Appointment

From: EMA [ema@emamail.org]
Sent: 7/2/2015 6:57:15 PM
To: EMA [ema@emamail.org]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Jed R. Mandel [jmandel@clpchicago.com]; Simon, Karl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=4d781d1ad595415db3a4e768c2d2b3fc-Simon, Karl]; eb@acea.be; hj.stein@daimler.com; Rich Wagner (rich.s.wagner@cummins.com) [rich.s.wagner@cummins.com]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: July 17, 2015, Conference Call
Attachments: 2015 07 17 Conference Call Notice.pdf
Location: Personal Matters / Ex. 6 Chair: Bill Charmley

Start: 7/17/2015 10:30:00 AM
End: 7/17/2015 11:30:00 AM
Show Time As: Busy

Recurrence: (none)

TO: Erik Bergelin
Bill Charmley
Jed Mandel
Karl Simon
Juergen Stein
Rich Wagner

FROM: Timothy A. Blubaugh

DATE: July 2, 2015

RE: **July 17, 2015, Conference Call**

PBI / Ex. 4

Following is the call-in information:

DATE: Friday, July 17, 2015
TIME: 5:30 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFEREN
CHAIR: Bill Charmley

If you have any questions, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
Personal Phone / Ex. 6 direct ? (312) 929-1975 fax

tblubaugh@emamail.org

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Message

From: Andjelka Vujovic [AVujovic@emamail.org]
Sent: 2/9/2016 5:03:05 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard

(mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; NICHOLAS.BELLOVARY@sgs.com; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

Subject: EMA - EMTC, CARB, EPA & Others - January 19-20, 2016, EMTC Meeting Minutes and Attachments

Attachments: ITR_Presentation to EMTC_1-19-16.ppt; Marshik VOC ICAC EPA Roundtable FINAL.pptx; RoundRobinEngine-TestSchedule-20160107.xlsx; Test Plan Discussion for Revised Fuel Mapping Variability-20160120.pdf; Attendance List - 2016-01-19 EMTC Meeting.pdf; 2016-01-19 and 20 EMTC_meeting minutes - 2016-02-08.DOCX

TO: Engine Emissions Measurement & Testing Committee
(EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: February 9, 2016

RE: **January 19-20, 2016, EMTC Meeting Minutes and Attachments**

Attached are the January 19-20, 2016, EMTC meeting minutes and attachments. The next EMTC meeting will be held on March 29-30, 2016, at the Cummins, Inc.'s Technical Center in Columbus, Indiana. The meeting details will be sent in the near future.

If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave
Columbus, Indiana 47201
Office: (812) 377-7532
Cell: Personal Phone / Ex. 6

Andjelka Vujovic
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333 West Wacker Drive • Suite 810
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avujovic@emamail.org

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/28/2016 5:24:25 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: Cummins ISX Cycle Average Map 4-28-16.pdf

All – here are the ISX slides that Cummins will present on today's call.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, April 27, 2016 2:20 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>; Jon A Dickson <jon.a.dickson@cummins.com>; 'spears.matthew@epa.gov' <spears.matthew@epa.gov>; 'charmley.william@epa.gov' <charmley.william@epa.gov>; 'Sanchez.james@Epa.gov' <Sanchez.james@Epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; 'tom.sloane@paccar.com' <tom.sloane@paccar.com>; 'Cortney.Guzlas@Navistar.com' <Cortney.Guzlas@Navistar.com>; 'Zhang.Houshun@epa.gov' <Zhang.Houshun@epa.gov>; 'Matthew.Hunkler@Navistar.com' <Matthew.Hunkler@Navistar.com>; Manik Narula <manik.narula@cummins.com>; 'erin.luke@paccar.com' <erin.luke@paccar.com>; 'debbie.gordon@allisontransmission.com' <debbie.gordon@allisontransmission.com>; 'MihaiDorobantu@eaton.com' <MihaiDorobantu@eaton.com>; 'Jeffrey.shultz@allisontransmission.com' <Jeffrey.shultz@allisontransmission.com>; 'david.gardner@navistar.com' <david.gardner@navistar.com>; 'David.Majors@Navistar.com' <David.Majors@Navistar.com>; 'MatthewRBusdiecker@eaton.com' <MatthewRBusdiecker@eaton.com>; 'ErikDykes@eaton.com' <ErikDykes@eaton.com>; 'dan.kieffer@paccar.com' <dan.kieffer@paccar.com>; Anthony Greszler

(anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; 'He Yuesheng' <yuesheng.he@volvo.com>; 'Ricart-Ugaz, Laura M' <Laura.Ricart@Navistar.com>; 'Marley Jeffrey' <jeff.marley@volvo.com>; 'Mark Malowicki' <Mark.Malowicki@PACCAR.com>; 'Costi Nedelcu' <Costi.Nedelcu@PACCAR.com>; 'Miller Marc' <marc.miller@volvo.com>; 'donald.keski-hynnila@daimler.com' <donald.keski-hynnila@daimler.com>; 'aaron.neuman@daimler.com' <aaron.neuman@daimler.com>; 'gerald.freitag@daimler.com' <gerald.freitag@daimler.com>; 'steve.berry@volvo.com' <steve.berry@volvo.com>; 'tblubaugh@emamail.org' <tblubaugh@emamail.org>; 'david.kayes@daimler.com' <david.kayes@daimler.com>; 'Mark.Siddall@HMMUSA.COM' <Mark.Siddall@HMMUSA.COM>; 'LIN_GEORGE@cat.com' <LIN_GEORGE@cat.com>; 'inderpal.singh@daimler.com' <inderpal.singh@daimler.com>; 'Kaslavage Charles' <charles.kaslavage@volvo.com>; 'scott.mundy@allisontransmission.com' <scott.mundy@allisontransmission.com>; 'Thomas Manley' <Thomas.Manley@HMMUSA.COM>
Subject: Phase 2 Collaboration meeting agenda

Reminder of Thursday's call at 3:00 pm Eastern. (This call has been rescheduled from last week.)

Proposed agenda:
1. ISB and N13 testing at SwRI – Houshun
2. ISX test results – Jackie
3. Road grade evaluation – TBD
4. Other topics?
5. Plan next call – All

Call-in and Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

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For Cummins participants:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

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Regards,

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/27/2016 6:19:48 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of Thursday's call at 3:00 pm Eastern. (This call has been rescheduled from last week.)

Proposed agenda:

1. ISB and N13 testing at SwRI – Houshun
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Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/7/2016 1:46:52 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: Cummins ISL and N-V update 4-07-16.pdf

All – attached are slides that Cummins would like to review on today's call.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, April 6, 2016 2:50 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>; Jon A Dickson <jon.a.dickson@cummins.com>; 'spears.matthew@epa.gov' <spears.matthew@epa.gov>; 'charmley.william@epa.gov' <charmley.william@epa.gov>; 'Sanchez.james@Epa.gov' <Sanchez.james@Epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; 'tom.sloane@paccar.com' <tom.sloane@paccar.com>; 'Cortney.Guzlas@Navistar.com' <Cortney.Guzlas@Navistar.com>; 'Zhang.Houshun@epa.gov' <Zhang.Houshun@epa.gov>; 'Matthew.Hunkler@Navistar.com' <Matthew.Hunkler@Navistar.com>; Manik Narula <manik.narula@cummins.com>; 'erin.luke@paccar.com' <erin.luke@paccar.com>; 'debbie.gordon@allisontransmission.com' <debbie.gordon@allisontransmission.com>; 'MihaiDorobantu@eaton.com' <MihaiDorobantu@eaton.com>; 'Jeffrey.shultz@allisontransmission.com' <Jeffrey.shultz@allisontransmission.com>; 'david.gardner@navistar.com' <david.gardner@navistar.com>; 'David.Majors@Navistar.com' <David.Majors@Navistar.com>; 'MatthewRBusdiecker@eaton.com' <MatthewRBusdiecker@eaton.com>; 'ErikDykes@eaton.com' <ErikDykes@eaton.com>; 'dan.kieffer@paccar.com' <dan.kieffer@paccar.com>; Anthony Greszler

(anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; 'He Yuesheng' <yuesheng.he@volvo.com>; 'Ricart-Ugaz, Laura M' <Laura.Ricart@Navistar.com>; 'Marley Jeffrey' <jeff.marley@volvo.com>; 'Mark Malowicki' <Mark.Malowicki@PACCAR.com>; 'Costi Nedelcu' <Costi.Nedelcu@PACCAR.com>; 'Miller Marc' <marc.miller@volvo.com>; 'donald.keski-hynnila@daimler.com' <donald.keski-hynnila@daimler.com>; 'aaron.neuman@daimler.com' <aaron.neuman@daimler.com>; 'gerald.freitag@daimler.com' <gerald.freitag@daimler.com>; 'steve.berry@volvo.com' <steve.berry@volvo.com>; 'tblubaugh@emamail.org' <tblubaugh@emamail.org>; 'david.kayes@daimler.com' <david.kayes@daimler.com>; 'Mark.Siddall@HMMUSA.COM' <Mark.Siddall@HMMUSA.COM>; 'LIN_GEORGE@cat.com' <LIN_GEORGE@cat.com>; 'inderpal.singh@daimler.com' <inderpal.singh@daimler.com>; 'Kaslavage Charles' <charles.kaslavage@volvo.com>; 'scott.mundy@allisontransmission.com' <scott.mundy@allisontransmission.com>; 'Thomas Manley' <Thomas.Manley@HMMUSA.COM>
Subject: Phase 2 Collaboration meeting agenda

Reminder of tomorrow's call at 3:00 pm Eastern. Let me know if anyone has additional agenda topics or updates to share. In case there are any issues with the new version of Skype, you may want to email your slides to the group before the call.

Proposed agenda:
1. ISL engine test results – Manik
2. Road grade evaluation – TBD
3. Other topics?
4. Plan next call – All

Call-in and Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

For non-Cummins participants:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

For Cummins participants:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Join by phone

Personal Phone / Ex. 6 (Region)
Region)
Find a local number

Conference ID: personal phone / Ex. 6
Forgot your dial-in PIN? | Help

Skype Advanced

Audio for this Skype for Business meeting is available using a computer or the phone dial-in bridge. Cummins Skype Advanced users should select "Use Skype for Business (full audio and video experience)" when using their PCs to connect to the meeting audio. Cummins Skype Standard users should select "Don't Join Audio" and dial into the phone bridge.

Regards,

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 1/19/2016 2:36:32 AM
To: Brian C Mormino [brian.c.mormino@cummins.com]
CC: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: Re: Administrator Mtg Request

Thanks for the heads up

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

On Jan 18, 2016, at 7:30 AM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Good morning Chris and Bill. We updated our CEO Tom Linebarger on the meetings in December. He asked about meeting with Gina McCarthy when he is in DC next week. I informed him that we had all discussed this at a staff level and thought such a meeting was more appropriate for him – and that Janet McCabe had suggested such a meeting to Jen in December during their face-to-face. Thus, I am going to submit the meeting request this morning for January 26-27. I believe this is in line with our previous discussions. I will copy both of you on the meeting request. Please help facilitate through the process.
>
> Thanks in advance for your help and let me know if you need anything,
>
> Brian

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/14/2016 3:25:14 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com
Subject: 1/7 Collaboration Call Notes
Attachments: Work Planning 1-07-16 updated.pptx

Participants:

- Allison – Mike Howenstein
- Cummins – Jackie Yeager
- Daimler – Anirban Sett, Gerald Freitag
- Eaton – Erik Dykes
- EMA – Tim Blubaugh
- EPA – Houshun Zhang, James Sanchez
- Navistar – Cortney Guzlas, Dave Gardner
- PACCAR – Dan Kieffer, Erin Luke, Mark Malowicki, Tom Sloane, Costi Nedelcu
- Volvo – Marc Miller, Steve Berry, Yuesheng He, Tony Greszler

Discussion and follow-up items (with owner's name in **bold**):

- SwRI testing update – Houshun
  - Only testing not completed is the N13 child rating.
  - Asked SwRI to further investigate 55/65 mph results on ISB child rating.
- Open questions/work planning - All
  - Reviewed 2015 progress and began 2016 planning (see attached Powerpoint). Continue planning discussion next week – **All**
  - New road grade profile ("Profile D")
    - Volvo noted new road grade profile operates the engine at full load and no load ~3x more often than their logged vehicle data. Also saw 20% increase in fuel consumption. Consider sharing analysis in future call – **Tony**
    - EPA testing at ORNL did not show as much difference in fuel consumption. Summarize on a future call – **James**
- Other topics

- Use box.com to transmit debug version of GEM. Give access to box.com to newest members of the group – **Erik**
- Post past material on box.com – **Jackie**
- Let Jackie know ASAP if any concerns with posting old material – **All**

Topics for future calls:

- (Tentative) Volvo analysis of new road grade profile – Tony
- (TBD) – Summarize road grade results at ORNL – James
- (1/14) – Open questions/work planning – All

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/14/2016 3:11:12 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of today's call at 3:00 pm Eastern.

Proposed agenda:

1. Road grade evaluation update – Houshun/James
2. GEM release – All
3. Open questions/work planning – All
4. Other topics?
5. Plan next call – All

Call-in information:

US toll-free Personal Phone / Ex. 6
Access code Personal Phone / Ex. 6

Skype information:

Link for non-Cummins attendees (see additional instructions in the attachment):

→ Join Skype Meeting (web guest)

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
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jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 5/19/2016 5:37:20 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: RE: Phase 2 Collaboration meeting agenda - Cummins slides
Attachments: GEMShiftLogicSensitivity05192016.pdf

Here are slides that Cummins would like to review on today's call.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
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Cummins Inc.
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jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, May 18, 2016 8:51 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>; Jon A Dickson <jon.a.dickson@cummins.com>; 'spears.matthew@epa.gov' <spears.matthew@epa.gov>; 'charmley.william@epa.gov' <charmley.william@epa.gov>; 'Sanchez.james@Epa.gov' <Sanchez.james@Epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; 'tom.sloane@paccar.com' <tom.sloane@paccar.com>; 'Cortney.Guzlas@Navistar.com' <Cortney.Guzlas@Navistar.com>; 'Zhang.Houshun@epa.gov' <Zhang.Houshun@epa.gov>; 'Matthew.Hunkler@Navistar.com' <Matthew.Hunkler@Navistar.com>; Manik Narula <manik.narula@cummins.com>; 'erin.luke@paccar.com' <erin.luke@paccar.com>; 'debbie.gordon@allisontransmission.com' <debbie.gordon@allisontransmission.com>; 'MihaiDorobantu@eaton.com' <MihaiDorobantu@eaton.com>; 'Jeffrey.shultz@allisontransmission.com' <Jeffrey.shultz@allisontransmission.com>; 'david.gardner@navistar.com' <david.gardner@navistar.com>; 'David.Majors@Navistar.com' <David.Majors@Navistar.com>; 'MatthewRBusdiecker@eaton.com' <MatthewRBusdiecker@eaton.com>; 'ErikDykes@eaton.com' <ErikDykes@eaton.com>; 'dan.kieffer@paccar.com' <dan.kieffer@paccar.com>; Anthony Greszler

(anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; 'He Yuesheng' <yuesheng.he@volvo.com>; 'Ricart-Ugaz, Laura M' <Laura.Ricart@Navistar.com>; 'Marley Jeffrey' <jeff.marley@volvo.com>; 'Mark Malowicki' <Mark.Malowicki@PACCAR.com>; 'Costi Nedelcu' <Costi.Nedelcu@PACCAR.com>; 'Miller Marc' <marc.miller@volvo.com>; 'donald.keski-hynnila@daimler.com' <donald.keski-hynnila@daimler.com>; 'aaron.neuman@daimler.com' <aaron.neuman@daimler.com>; 'gerald.freitag@daimler.com' <gerald.freitag@daimler.com>; 'steve.berry@volvo.com' <steve.berry@volvo.com>; 'tblubaugh@emamail.org' <tblubaugh@emamail.org>; 'david.kayes@daimler.com' <david.kayes@daimler.com>; 'Mark.Siddall@HMMUSA.COM' <Mark.Siddall@HMMUSA.COM>; 'LIN_GEORGE@cat.com' <LIN_GEORGE@cat.com>; 'inderpal.singh@daimler.com' <inderpal.singh@daimler.com>; 'Kaslavage Charles' <charles.kaslavage@volvo.com>; 'scott.mundy@allisontransmission.com' <scott.mundy@allisontransmission.com>; 'Thomas Manley' <Thomas.Manley@HMMUSA.COM>
Subject: Phase 2 Collaboration meeting agenda

Reminder of tomorrow's call at 3:00 pm Eastern.

Proposed agenda:
1. Shifting sensitivity to generic steady state map – Manik, Matt H.
2. 55/65 cycle average map speed/load coverage – Matt H.
3. Other topics?
4. Plan next call – All

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(Region)
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Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director

Environmental Strategy and Compliance
Cummins Inc.
Phone: Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/6/2016 6:49:55 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of tomorrow's call at 3:00 pm Eastern. Let me know if anyone has additional agenda topics or updates to share. In case there are any issues with the new version of Skype, you may want to email your slides to the group before the call.

Proposed agenda:

1. ISL engine test results – Manik
2. Road grade evaluation – TBD
3. Other topics?
4. Plan next call – All

Call-in and Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

For non-Cummins participants:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

For Cummins participants:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Join by phone

Personal Phone / Ex. 6 (Region)
(Region)
Find a local number

Conference ID: Personal Phone / Ex. 6
Forgot your dial-in PIN? | Help

Skype Advanced

Audio for this Skype for Business meeting is available using a computer or the phone dial-in bridge. Cummins Skype Advanced users should select "Use Skype for Business (full audio and video experience)" when using their PCs to connect to the meeting audio. Cummins Skype Standard users should select "Don't Join Audio" and dial into the phone bridge.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone: personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/6/2016 6:28:52 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: 3/24 Collaboration Call Notes

Participants:

- Allison – Mike Howenstein
- Caterpillar –
- Cummins – Manik Narula
- Daimler – Gerald Freitag, David Kayes, Inderpal Singh
- Eaton –
- EMA – Tim Blubaugh
- EPA – Houshun Zhang, James Sanchez
- Hino – Mark Siddall
- Navistar – Dave Gardner, Cortney Guzlas, Matt Hunkler
- PACCAR – Mark Malowicki, Erin Luke, Dan Kieffer
- Volvo – Marc Miller, Tim Connors, Steve Berry

Discussion and follow-up items (with owner's name in **bold**):

- Road grade evaluation - James
  - James presented analysis looking at the effect of vehicle overspeed on engine operation
  - James proposed a modified Profile D and showed the effect of modification on engine operation
  - Evaluate modified Profile D and provide feedback to EPA as soon as possible – **All**
  - Slides and profile have been shared with the group in a separate email

Topics for future calls:

- (TBD) SwRI results (N13 365, gasoline engine) – Houshun
- (4/7) Road grade evaluation – TBD

Regards,

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/4/2016 8:19:01 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; Brian C Mormino [brian.c.mormino@cummins.com]; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Jon A Dickson [jon.a.dickson@cummins.com]; Kaslavage Charles [charles.kaslavage@volvo.com]; Scott.Mundy@allisontransmission.com
Subject: Collaboration meeting invitations

Hi all,

I have been migrated to a new version of Skype, so I need to set up a new Skype meeting link for our Thursday bi-weekly Phase 2 Collaboration Group calls. I will send a new repeating invitation and cancel the old one. I apologize for any inconvenience.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone: Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 1/8/2016 6:55:02 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Silverman, Steven [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=2cabad28b2394fbda8c047cdc4ef3fdc-SSILVE02]; 'ryan.posten@dot.gov' [ryan.posten@dot.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: Sponsored advertising by Fitzgerald in Overdrive
Attachments: Fitzgeral ad.pdf

Hell to all

Attached is sponsored advertising in December 2015 edition of Overdrive magazine from Fitzgerald Gliders. Interesting that, contrary to statements from select members of Congress, Fitzgerald makes no attempt to masquerade glider-based vehicles as used trucks: "Even being the leaders in the industry, they still occasionally get asked the very basic question, "What is a Glider Kit"? Luckily, the answer to that question is incredibly simple. A Glider Kit is a *brand new truck* [italics mine] from the manufacturer without an engine and transmission." They go on to say, "Fitzgerald Glider Kits offers customers the option to purchase a *brand new 2016 tractor* [italics mine], in any configuration offered by the manufacturer. Next comes the option of several pre emission engines to choose from."

Business is thriving: "Currently, they are averaging 80-90 completed trucks per week." We will be very pleased in 2018 when they will be limited to 6 per week, thanks to the Agencies' actions under the Phase 2 rulemaking. Would be interesting to get an update on NHTSA's enforcement actions under current regulation if possible.

Best regards,
Steve Berry

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/7/2016 2:30:23 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: EPA Testing overview - 7-23-2015 v2.pdf; Work Planning 1-07-16.pdf

Here are a couple background documents for today's call. The first is a test plan overview that EPA shared previously. The second is a quick review of last year's work. Together these can hopefully set the stage for our work planning discussion.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone: Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, January 6, 2016 3:38 PM
To: 'spears.matthew@epa.gov' <spears.matthew@epa.gov>; 'charmley.william@epa.gov' <charmley.william@epa.gov>; 'Sanchez.james@Epa.gov' <Sanchez.james@Epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; 'tom.sloane@paccar.com' <tom.sloane@paccar.com>; 'Cortney.Guzlas@Navistar.com' <Cortney.Guzlas@Navistar.com>; 'Zhang.Houshun@epa.gov' <Zhang.Houshun@epa.gov>; 'Matthew.Hunkler@Navistar.com' <Matthew.Hunkler@Navistar.com>; Manik Narula <manik.narula@cummins.com>; 'erin.luke@paccar.com' <erin.luke@paccar.com>; 'debbie.gordon@allisontransmission.com' <debbie.gordon@allisontransmission.com>; 'MihaiDorobantu@eaton.com' <MihaiDorobantu@eaton.com>; 'michael.j.howenstein@allisontransmission.com' <michael.j.howenstein@allisontransmission.com>; 'Jeffrey.shultz@allisontransmission.com' <Jeffrey.shultz@allisontransmission.com>; 'david.gardner@navistar.com' <david.gardner@navistar.com>; 'David.Majors@Navistar.com' <David.Majors@Navistar.com>; 'MatthewRBusdiecker@eaton.com' <MatthewRBusdiecker@eaton.com>; 'ErikDykes@eaton.com' <ErikDykes@eaton.com>; 'dan.kieffer@paccar.com' <dan.kieffer@paccar.com>; Anthony Greszler

(anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; He Yuesheng <yuesheng.he@volvo.com>; Ricart-Ugaz, Laura M <Laura.Ricart@Navistar.com>; 'Marley Jeffrey' <jeff.marley@volvo.com>; 'Mark Malowicki' <Mark.Malowicki@PACCAR.com>; Costi Nedelcu <Costi.Nedelcu@PACCAR.com>; Miller Marc <marc.miller@volvo.com>; 'donald.keski-hynnila@daimler.com' <donald.keski-hynnila@daimler.com>; 'aaron.neuman@daimler.com' <aaron.neuman@daimler.com>; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino <brian.c.mormino@cummins.com>; 'steve.berry@volvo.com' <steve.berry@volvo.com>; 'tblubaugh@emamail.org' <tblubaugh@emamail.org>; 'david.kayes@daimler.com' <david.kayes@daimler.com>
Subject: Phase 2 Collaboration meeting agenda

Reminder of tomorrow's call at 3:00 pm Eastern.

Proposed agenda:
1. SwRI testing update (if needed) – Houshun
2. Open questions/work planning – All
3. Other topics?
4. Plan next call – All

Call-in information:
US toll-free Personal Phone / Ex. 6
Access code Personal Phone / Ex. 6

Skype information:

Link for non-Cummins attendees (see additional instructions in the attachment):

→ Join Skype Meeting (web guest)

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
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Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 11/11/2015 8:25:51 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group

(FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard (mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Carnegie [william.carnegie@ge.com]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

Subject: EMA - EMTC, EPA, CARB & Others - Cycle Average Fuel Map Procedure

Attachments: 1036 540 Cycle Average Fuel Maps ver3.pdf

TO: Engine Emissions Measurement & Testing Committee
(EMA Members, CARB, EPA & Others)

CC: CVEC GHG Subcommittee
Timothy A. French

FROM: Timothy A. Blubaugh

DATE: November 11, 2015

RE: **Cycle Average Fuel Map Procedure**

Attached is a draft cycle average fuel mapping test procedure for the GHG Phase 2 rule. We are circulating the draft procedure so it can be discussed during the EMTC meeting that will take place on Tuesday and Wednesday, November 17th & 18th, in Ann Arbor.

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
Personal Phone / Ex. 6 ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 11/10/2015 8:35:27 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; Brian C Mormino [brian.c.mormino@cummins.com]; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; Morgan Andreae [morgan.andreae@cummins.com]; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of Thursday's call at 3:00 pm Eastern. Let me know if anyone has agenda topics to add.

I'll try again this week to use Skype for Business (not the same as the regular Skype) for presenting any data. Our IT group tells me that in order to access the meeting through the guest link below, you may need to first install a web app plug-in according to the instructions in the attached PDF. Sorry for the inconvenience.

Proposed agenda:

1. ISB child rating results – Houshun (Houshun, you may want to email your slides to the group in advance if possible, in case we have Skype issues again.)
2. Other topics?
3. Plan next call – All

Call-in information:

Teleconference:
US toll-free Personal Phone / Ex. 6
Access code Personal Phone / Ex. 6

Skype information:

Link for non-Cummins attendees (see additional instructions in the attachment):

Join Skype Meeting (web guest)

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Personal Phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/25/2015 9:15:24 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: david.majors@navistar.com
Subject: RE: Attendees, EPA meetings with Volvo and Navistar, Sept 29th

Hi Bill
I owed you a topics list. It's very simple as you understood:

- Manufacturers are seeking a rule that works for the environment and customers
- Concerns we have about procedures and compliance protocol
- How we can best move forward from here, to allow a credible feedback to the Agencies on stringency than is possible today

We'll also just touch very quickly on our appreciation for what the Agency did to address gliders.
Have a good weekend.
Steve

From: Berry Steve
Sent: Wednesday, September 23, 2015 9:37 AM
To: Charmley.william@Epa.gov
Cc: david.majors@navistar.com
Subject: Attendees, EPA meetings with Volvo and Navistar, Sept 29th

Hi Bill
Here is the list of attendees to the meeting with the Administrator at 10:00, and for the pre-meeting with Chris Grundler at 9:00 as well:

For Volvo Group

- Mr. Niklas Gustavsson, Chief Sustainability Officer, Volvo Group
- Mr. Dennis Slagle, President, Volvo Group Trucks North America
- Mrs. Susan Alt, Sr Vice President Public Affairs, Volvo Group NA
- Mr. Anthony Greszler, Vice President Government and Industry Affairs, Volvo Group NA
- Mr. Steve Berry, Director, Regulatory Affairs, Volvo Group

And for Navistar

- Mr. Troy Clarke, CEO, Navistar [Administrator meeting only]
- Mr. James Spangler, Vice President Corporate Affairs and Chief Communications Officer
- ~~Mr. Dennis Mooney, Sr. Vice President Global Product Development~~
- Mr. David Majors, Vice President Engineering and Compliance

Steve

Steve Berry
Volvo Group Trucks Product Planning
2900 K St NW
South Building, Suite 401
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Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 9/24/2015 8:43:44 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Baker (bbaker@aanddtech.com) [bbaker@aanddtech.com]; Bill Martin (w.t.martin7019@outlook.com) [w.t.martin7019@outlook.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group

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CC: shirish.a.shimpi@cummins.com

Subject: EMA - EMTC, CARB, EPA & Others - Rescheduled - November 2015 EMTC Meeting

TO: Engine Emissions Measurement & Testing Committee
(EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: September 24, 2015

RE: **Rescheduled - November 2015 EMTC Meeting**

Please note that the November 11-12, 2015, EMTC meeting has been rescheduled due to November 11th being a government holiday. The new meeting dates are November 17-18, 2015, and will be held at EPA Offices in Ann Arbor, MI. The meeting will start at 9:00 a.m. on both days and end at 5:00 p.m. on the first day (November 17th) and end at 2:00 p.m. on the second day (November 18th). A meeting notice will be sent out in the near future.

If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave
Columbus, Indiana 47201
Office: (812) 377-7532

Cell: Personal Phone / Ex. 6

Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 11/9/2015 4:04:54 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group

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CC: shirish.a.shimpi@cummins.com

Subject: EMA - EMTC, CARB, EPA & Others - 1065 Working Document

Attachments: 40 CFR Part 1065 Engine Test Procedures Working Document 11-6-15 Staff Draft.pdf; Duty Cycle Generation Issue - FEV.pdf

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: November 9, 2015

RE: **1065 Working Document**

Please see the following email and attachments from EPA's Chris Laroo.

If you have any questions, please do not hesitate to contact me.

From: Laroo, Chris [mailto:laroo.chris@epa.gov]
Sent: Friday, November 06, 2015 1:43 PM
Subject: 1065 Working Document for Circulation to EMTC

Please note that there are extensive editorial changes to 1065.340, CVS calibration. When drafting the CVS calibration section in 40 CFR 1066, 1065.340 was used as the template. The resulting 1066 procedure contained many editorial changes. It was felt that these changes would also benefit 1065, so we are moving forward with making the changes in 1065 as well.

Also attached is an issue that came in from FEV regarding duty-cycle generation that I would like to discuss at the meeting.

Regards,

Chris Laroo
Environmental Protection Specialist
US Environmental Protection Agency
Office of Transportation and Air Quality
Assessment and Standards Division
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(734) 214-4937
(734) 214-4055 (fax)
Email: laroo.chris@epa.gov

Laroo, Chris

From: Sanchez, James
Sent: Thursday, November 05, 2015 11:51 AM
To: Laroo, Chris
Subject: RE: Duty Cycle Generation - Maximum Test Speed Calculation

Deliberative Process / Ex. 5

James

From: Laroo, Chris
Sent: Thursday, November 05, 2015 10:37 AM
To: Sanchez, James <sanchez.james@epa.gov>
Subject: FW: Duty Cycle Generation - Maximum Test Speed Calculation

Any thoughts?

Regards,

Chris Laroo
Environmental Protection Specialist
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Email: laroo.chris@epa.gov

From: Baddam, Praveen [mailto:Baddam@FEV.COM]
Sent: Wednesday, November 04, 2015 4:34 PM
To: Laroo, Chris <laroo.chris@epa.gov>
Subject: Duty Cycle Generation - Maximum Test Speed Calculation

Dear Mr. Laroo,

PBI / Ex. 4

PBI / Ex. 4

Thank you

Praveen Baddam
Regulations & Gov't Relations Engineer
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Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 11/5/2015 9:37:09 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group

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CC: shirish.a.shimpi@cummins.com
Subject: EMA - EMTC, CARB, EPA & Others - November 17-18, 2015, EMTC Meeting Agenda
Attachments: 2015-11-17 to 18 EMTC Meeting - Agenda.docx

TO: Engine Emissions Measurement & Testing Committee
(EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: November 5, 2015

RE: **November 17-18, 2015, EMTC Meeting Agenda**

Attached is the agenda for the upcoming EMTC meeting that will take place on November 17-18, in Ann Arbor.

If you have any questions, please do not hesitate to contact me.

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Andjelka Vujovic
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Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 8/4/2015 6:53:56 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; Brian C Mormino [brian.c.mormino@cummins.com]; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; Morgan Andreae [morgan.andreae@cummins.com]; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]

Subject: Phase 2 Collaboration Meeting
Location: US toll-free Personal Phone / Ex. 6 Access code Personal Phone / Ex. 6

Start: 8/7/2015 7:00:00 PM
End: 8/7/2015 8:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Rescheduling this week due to conflict with Phase 2 public hearing on 8/6.

Background:

Joint sessions to exchange information on the development and validation of engine/powertrain test cycles and information going into the vehicle simulation for Phase 2.

Teleconference call-in number:

US toll-free Personal Phone / Ex. 6
Access code Personal Phone / Ex. 6

Webex information:

Topic: Phase 2 Collaboration Mtg
Date: Every Thursday, from Thursday, December 18, 2014, to no end date
Time: 3:00 pm, Eastern Standard Time (New York, GMT-05:00)
Meeting number: Personal Phone / Ex. 6
Meeting password: Personal Phone / Ex. 6
Please click the link below to see more information about the meeting, including its agenda, or to join the meeting.

internal web link / Ex. 6

To contact Jackie Yeager, call personal phone / Ex. 6 or

send a message to this address: jackie.m.yeager@cummins.com<MAILTO:JACKIE.M.YEAGER@CUMMINS.COM< U>>

To update this meeting to your calendar program (for example, Microsoft Outlook or Lotus Notes), do the following:

- For all calendar programs (except Lotus Notes), click the following link, or copy the link and paste it into your Web browser: Ex. 6

NOTE: Release 6 will be available with PowerSweep II
*For Lotus Notes (Release 6), follow these steps:
1. Right-click the attached iCalendar format (*.ics) file, and then choose View.
2. Click Import All. A new broadcast email message is added to your Inbox.
3. Open the new message.
4. Click Update Calendar.

The playback of UCF (Universal Communications Format) rich media files requires appropriate players. To view this type of rich media files in the meeting, please check whether you have the players installed on your computer by going to

Ex. 6

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 7/27/2015 11:12:52 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: Re: Meeting with Chris

Go ahead and call me at 10 pm tonight on my cell. I will still be on a call with Japan at 8 am tomorrow.

Sent from my iPhone

> On Jul 27, 2015, at 7:08 PM, Charmley, William <charmley.william@epa.gov> wrote:
>
> Brian
>
> Chris has 30 minutes between noon and 1 that I will nail down in the am.
>
>
> I would like to/ need to talk with you before then.
>
> Can I call you at either 10pm this evening, or 8am tomorrow morning?
>
> Thanks
> Bill
>
>
> Bill Charmley
> Assessment and Standards Division
> Office of Transportation and Air Quality
> National Vehicle & Fuel Emissions Laboratory
> US Environmental Protection Agency
> Ann Arbor, Michigan
> Desk phone 734-214-4466
> Mobile phone 734-545-0333
> Email charmley.william@epa.gov

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 11/4/2015 1:52:07 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Lemieux, Stephan@ARB [stephan.lemieux@arb.ca.gov]
CC: Brian C Mormino [brian.c.mormino@cummins.com]
Subject: Cummins slides from 10/29/15 - Confidential Business Information
Attachments: message.html

Encrypted email message from Cummins Inc. Office 365 Message Encryption (OME) system
To view your message
Save and open the attachment (message.html), and follow the instructions.
Sign in using the following email address: **charmley.william@epa.gov**

This email, including any attachments, is for the exclusive and confidential use of the intended recipient(s). If you are not an intended recipient, please do not read, distribute or take action in reliance upon this message. If you have received this in error, please notify the sender immediately by return email and promptly delete this message and its attachments from your computer system.

Message encryption by Microsoft Office 365

Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 7/17/2015 2:04:02 AM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Brian C Mormino [brian.c.mormino@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew Psota [matthew.psota@cummins.com]; Michael J Ruth [michael.j.ruth@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]

Subject: Cummins/EPA meeting
Location: EPA Ann Arbor office

Start: 7/28/2015 1:00:00 PM
End: 7/28/2015 8:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Discuss Phase 2 GHG NPRM.

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 7/16/2015 3:03:46 AM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: GEM source code available

All,

EPA asked me pass along that the GEM source code, executable(s), and support information from the EPA HD Phase 2 NPRM Public Docket are available in the Box.com location we have been using to share files on the alternative mapping project. Go to this link and look for the GEM power user zip file in the Phase II GHG Collaboration folder:

Ex. 6

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 7/14/2015 5:14:39 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 7/9 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Gary Salemme, Jackie Yeager
- Eaton – (Erik on vacation)
- EPA – Matt Spears, Houshun Zhang, James Sanchez
- Navistar – David Gardner, Cortney Guzlas
- PACCAR – Erin Luke, Dan Kieffer
- Allison – Mike Howenstein, Debbie Gordon

Discussion and follow-up items (with owner's name in **bold**):

- NPRM update
  - Federal Register notice on July 13 (http://www.gpo.gov/fdsys/pkg/FR-2015-07-13/pdf/2015-15500.pdf); comments due September 11
  - Public hearing dates will be finalized soon; tentatively during weeks of August 3 and 17
- Next steps
  - Areas for additional work
    - Continued engine and powertrain testing at ORNL, SwRI, EPA
    - Refine generic vehicle definition, interpolation/extrapolation routines
    - Ideas for reducing test burden
  - Check with SwRI on whether ISB engine and/or Allison transmission should be updated – **Houshun**
  - Consider "hybrid" concept of using alternative mapping for ARB transient cycle and smaller steady state map on 55, 65 mph cruise cycles as way of reducing test time, for discussion on next call – **All**
  - Summarize completed and planned testing for next call – **Houshun**
  - Summarize how to generate engine cycles from GEM for next call **– James**
- Plan next call, frequency
  - Extend invitation for additional calls every other week starting 7/23 – **Jackie**
- Other
  - SAE paper drafts are receiving good ratings from reviewers
  - Presenter needed for industry paper at SAE COMVEC (Oct. 6-8)
  - Still working to setup EMA discussion on alternate mapping

Topics for future calls:

- (7/23) "Hybrid" concept of alt map + ss map – All

- (7/23) Summary of completed and planned testing – Houshun
- (7/23) Generating engine cycles from GEM – James

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 7/13/2015 8:31:22 PM
To: Andjelka Vujovic [avujovic@emamail.org]; Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Baker (bbaker@aanddtech.com) [bbaker@aanddtech.com]; Bill Martin (w.t.martin7019@outlook.com) [w.t.martin7019@outlook.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Meyerkord [daniel.j.meyerkord@emdiesels.com]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com)

[mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard (mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Carnegie [william.carnegie@ge.com]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

CC: Shirish A Shimpi [shirish.a.shimpi@cummins.com]

Subject: RE: EMA - EMTC, CARB, EPA & Others - June 10-11, 2015, EMTC Meeting Minutes and Attachments

Attachments: 2015-06-10 and 11 EMTC_meeting minutes - draft final.docx

PLEASE NOTE:

Attached are the meeting minutes that were inadvertently omitted in the previous email.

From: Andjelka Vujovic
Sent: Monday, July 13, 2015 11:48 AM
Subject: EMA - EMTC, CARB, EPA & Others - June 10-11, 2015, EMTC Meeting Minutes and Attachments

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: July 13, 2015

RE: **June 10-11, EMTC Meeting Minutes and Attachments**

Attached are the June 10-11, EMTC meeting minutes and attachments.

If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave
Columbus, Indiana 47201
Office: (812) 377-7532
Cell: personal phone / Ex. 6

Andjelka Vujovic
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
personal phone / Ex. 6 • (312) 929-1975 fax
avujovic@emamail.org

Please consider the environment before printing this email.

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 7/13/2015 5:19:23 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: FW: House Glider amendment language

Hi Bill

According to the July 10 Successful Dealer article mentioned below, there could be as many as 10,000 glider kits per year. I'm sure you're aware of the amendment in the House last week by Rep Black from TN to block action against glider-based vehicles.

Please let me know if you'd prefer I not forward such items to you.

Steve B
==========

"As long as you're taking a donor truck off the road of equal EPA emission standards, you really shouldn't have an issue with that," he adds.

"They're trying to get all these old engines off the road," Harrison says. "Over time, engines are going to weed themselves off the road. Just not as fast as they want."

Roughly 10,000 glider kits are sold annually, and Harrison says failing to offer an exemption for glider kits removes any incentive to purchase or manufacture them, which basically would kill glider kit and related industries.

"You're talking about thousands of jobs affected, several thousands," he says. "The assemblers, the manufacturing plants, the rebuild people … That's a lot of jobs. Gone."

http://www.successfuldealer.com/without-amendment-phase-2-mandates-could-kill-glider-kit-industry/?utm_source=daily&utm_medium=email&utm_content=07-13-2015&utm_campaign=SD&ust_id=6ddc6abb71&

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/6/2016 8:37:41 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of tomorrow's call at 3:00 pm Eastern.

Proposed agenda:

1. SwRI testing update (if needed) – Houshun
2. Open questions/work planning – All
3. Other topics?
4. Plan next call – All

Call-in information:

US toll-free personal phone / Ex. 6
Access code personal phone / Ex. 6

Skype information:

Link for non-Cummins attendees (see additional instructions in the attachment):

→ Join Skype Meeting (web guest)

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/5/2016 3:41:16 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com
Subject: 12/17 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – Houshun Zhang, James Sanchez
- Navistar – Cortney Guzlas, Dave Gardner, Matt Hunkler
- PACCAR – Dan Kieffer, Erin Luke, Mark Malowicki
- Allison –
- Volvo – Marc Miller, Steve Berry, Yuesheng He
- Daimler – Don Keski, David Kayes, Gerald Freitag

Discussion and follow-up items (with owner's name in **bold**):

- SwRI testing update – Houshun
  - Regression model analysis – SwRI looking into why Model 2 (bsfc) and Model 8 (fuel mass) do not look as good for child ratings on 55 and 65 mph cycles
  - Testing – Only N13 child rating testing has not been completed
- EMTC update – James
  - James reported on November EMTC discussions pertaining to cycle average map
  - Pre-conditioning was a big focus; drafting language to prescribe test order to reduce variability
  - Discussion on fuel calculations from emissions measurements
  - Discussion on measurement techniques and variability for potential SwRI study
- Other topics
  - January version of GEM will incorporate elements to handle cycle average map, including regression Model 8 (fuel mass)
  - Number of required data points in SS map not finalized yet
  - How will NOx measurements during cycle average map be used?
  - Can we identify various work tasks that still need to be done, and by when? For next call, everyone be prepared to discuss open questions that still need work – **All**

- For example, after bug fixes and other changes are implemented in GEM, does any validation testing, regression model analysis, etc. need to be re-visited?

Topics for future calls:

- (1/7) SwRI update – Houshun
- (1/7) Open questions/work remaining – All

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 5/17/2016 9:09:06 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: 5/5 Collaboration Call Notes

Participants:

- Allison – Scott Mundy
- Caterpillar –
- Cummins – Manik Narula, Jackie Yeager
- Daimler – Gerald Freitag, Inderpal Singh
- Eaton – Erik Dykes
- EMA – Tim Blubaugh
- EPA – Houshun Zhang, Matt Spears, James Sanchez
- Hino – Mark Siddall
- Navistar – Cortney Guzlas, Matt Hunkler, Laura Ricart-Ugaz
- PACCAR – Mark Malowicki, Dan Kieffer, Erin Luke
- Volvo – Marc Miller, Tim Connors, Tony Greszler

Discussion and follow-up items (with owner's name in **bold**):

- Generic vehicle definition – All
    - Discussion about impact of assuming automatic transmission on N/V coverage
- Cycle average map option – All
    - Discussion about GEM shift algorithm and using an EPA default (generic) steady state fuel map for shifting if manufacturer chooses to use a cycle average map for all 3 GEM cycles
        - Shape (not absolute values) of default map matters for shifting, also engine torque curve
        - Actual engine torque curve still used
    - Discussion about confirmatory testing scenarios

Topics for future calls:

- (TBD) SwRI results (gasoline engine) – Houshun

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/5/2016 3:39:13 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; Brian C Mormino [brian.c.mormino@cummins.com]; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com
Subject: 12/3 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – Houshun Zhang, James Sanchez
- Navistar – Cortney Guzlas, Dave Gardner
- PACCAR – Dan Kieffer, Erin Luke, Mark Malowicki
- Allison –
- Volvo – Tony Greszler, Marc Miller
- Daimler – Anirban Sett, David Kayes, Gerald Freitag

Discussion and follow-up items (with owner's name in **bold**):

- SwRI testing update – Houshun
    - See slides sent previously by Houshun
    - Analyzing 12 regression models each for bsfc and fuel flow, using various combinations of N/V, work, T, N for ISB and N13 engines on parent and child ratings
    - Models using N and T terms so far have better correlations than N/V and cycle work, and fuel flow might be better than bsfc
    - Most promising regression model will be built into 'debug version' of GEM
- Half-hill cycle results – Erik
    - See slides previously sent by Erik
    - Evaluated latest road grade profiles from NREL on ISX engine + 10 speed Eaton FAS transmission running in test cell
    - New steeper % grades are more realistic, but not the hill shapes – similar conclusion from Volvo simulations comparing to logged vehicle data

Topics for future calls:

- (12/17) SwRI update – Houshun

- (12/17) EMTC update – James

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 12/21/2015 8:53:30 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
CC: Manik Narula [manik.narula@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Matthew Psota [matthew.psota@cummins.com]
Subject: Re: Request for ISB data

I am following up on this note as both Volvo and Navistar just approved sharing the data from their engines. We also approve Shari g the data from our engine.

Houshun, I will forward you their emails. It is very important that we move quickly. All the companies seem unified in generating and sharing data. Thanks for your help.

Sent from my iPhone

On Dec 18, 2015, at 6:31 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Chris, it was very good to see you today. Thanks for making the time, and we look forward to continuing to work together on Phase 2. Please see below on our email requests tied to data surrounding the cycle average map as we discussed with you and Janet today. We want to be able to perform some analyses over the next few weeks as we prepare for the next meeting with EPA in January on this topic as well as the questions around engine platforms. Thanks in advance for your consideration,
>
> Brian
>
> ---
>
> **From:** Jackie M Yeager
> **Sent:** Friday, December 18, 2015 6:19 PM
> **To:** Zhang, Houshun <Zhang.Houshun@epa.gov>
> **Cc:** Manik Narula <manik.narula@cummins.com>; Gary C Salemme <gary.c.salemme@cummins.com>; Brian C Mormino <brian.c.mormino@cummins.com>
> **Subject:** FW: Request for ISB data
>
> Hello Houshun,
>
> I wanted to follow up with you to check whether EPA will be able to share the ISB data we requested? We would also like to request the same data for the other engines EPA has tested (ISX, Navistar, and Volvo). Our interest is in doing additional analysis to understand issues you are seeing with the cycle average map on the 55 and 65 mph cycles. Please let me know if EPA can share the data.
>
> Thanks,
> Jackie Yeager
> GHG/Fuel Efficiency Policy Director
> Environmental Strategy and Compliance
> Cummins Inc.

Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Friday, December 4, 2015 3:59 PM
To: 'Zhang.Houshun@epa.gov' <Zhang.Houshun@epa.gov>
Cc: Manik Narula <manik.narula@cummins.com>
Subject: Request for ISB data

Hi Houshun,

As follow up to our discussion earlier this week, attached is a description of the ISB data from SwRI testing that we would like to request. We are ok if you need to share the data with the whole collaboration group that has been working on the cycle average mapping approach. Please let us know if EPA can accommodate the request, or if you have any questions.

Thanks,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 12/17/2015 11:38:23 AM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; Brian C Mormino [brian.c.mormino@cummins.com]; MihaiDorobantu@eaton.com; michael.j.howenstein@allisontransmission.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of today's call at 3:00 pm Eastern. Sorry I haven't issued meeting notes yet for the last call. These are the agenda topics we agreed on last time – any others?

Proposed agenda:

1. SwRI testing update – Houshun
2. EMTC update – James
3. Other topics?
4. Plan next call – All

Call-in information:

US toll-free personal phone / Ex. 6
Access code personal phone / Ex. 6

Skype information:

Link for non-Cummins attendees (see additional instructions in the attachment):

→ Join Skype Meeting (web guest)

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/23/2015 1:37:05 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: david.majors@navistar.com
Subject: Attendees, EPA meetings with Volvo and Navistar, Sept 29th

Hi Bill
Here is the list of attendees to the meeting with the Administrator at 10:00, and for the pre-meeting with Chris Grundler at 9:00 as well:

For Volvo Group

- Mr. Niklas Gustavsson, Chief Sustainability Officer, Volvo Group
- Mr. Dennis Slagle, President, Volvo Group Trucks North America
- Mrs. Susan Alt, Sr Vice President Public Affairs, Volvo Group NA
- Mr. Anthony Greszler, Vice President Government and Industry Affairs, Volvo Group NA
- Mr. Steve Berry, Director, Regulatory Affairs, Volvo Group

And for Navistar

- Mr. Troy Clarke, CEO, Navistar
- Mr. James Spangler, Vice President Corporate Affairs and Chief Communications Officer
- Mr. Dennis Mooney, Sr. Vice President Global Product Development
- Mr. David Majors, Vice President Engineering and Compliance

Steve

Steve Berry
Volvo Group Trucks Product Planning
2900 K St NW
South Building, Suite 401
Washington, DC 20007
Office 202-536-1557
Cell: personal phone / Ex. 6
steve.berry@volvo.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/22/2015 9:04:17 AM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: RE: time for a call later today?

Bill,
I'm on my way to Chicago for EMA meeting. You may still try to call, but I just wanted you to know I'll be out of pocket for certain times.
Good to hear about the reschedule. It's 5 OEMs (CAT was planning to attend as well)
Steve

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Monday, September 21, 2015 8:55 PM
To: Berry Steve
Subject: Re: time for a call later today?

Steve

Yes, please reach out to Gwen directly

I will let Chris know that you all are meeting with the administrator and you are going to see if there is an opportunity to meet with Chris as well.

As a follow up to our discussion earlier today, I had a chance to circle back with Chris at the end of today, and I will call you Tuesday morning regarding rescheduling the meeting with the 4 OEMs.

Thanks
Bill

Bill Charmley
Assessment and Standards Division
Office of Transportation and Air Quality
National Vehicle & Fuel Emissions Laboratory
US Environmental Protection Agency
Ann Arbor, Michigan
Desk phone 734-214-4466
Mobile phone personal phone / Ex. 6
Email charmley.william@epa.gov

On Sep 21, 2015, at 2:46 PM, Berry Steve <steve.berry@volvo.com> wrote:

> Hi Bill
> I intended to mention to you Volvo's meeting with Administrator McCarthy on Sep 29, 10:00. You had expressed an interest that Niklas Gustavsson and Denny Slagle have a pre-meeting with Chris Grundler. Shall I arrange this directly with Gwen Stewart?
> Steve
>
> ---
>
> **From:** Charmley, William [mailto:charmley.william@epa.gov]
> **Sent:** Monday, September 21, 2015 12:03 PM

To: Berry Steve
Subject: RE: time for a call later today?

Steve –

I will call you in a few minutes.

Bill Charmley
Director
Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Vehicle and Fuel Emissions Laboratory
2000 Traverwood Drive
Ann Arbor, MI 48105

desk ph. 734-214-4466
cell ph. 734-545-0333
e-mail: charmley.william@epa.gov

From: Berry Steve [mailto:steve.berry@volvo.com]
Sent: Monday, September 21, 2015 11:33 AM
To: Charmley, William
Subject: RE: time for a call later today?

Hi Bill
Tried a couple of times. Will call you a few minutes after 12.
Steve

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Monday, September 21, 2015 11:01 AM
To: Berry Steve
Subject: time for a call later today?

Steve,

Do you have time later today for a call?

I am open from 12-1pm eastern time, and then also late today at about 5pm.

Thanks
Bill

Bill Charmley
Director

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Vehicle and Fuel Emissions Laboratory
2000 Traverwood Drive
Ann Arbor, MI 48105

desk ph. 734-214-4466
cell ph. 734-545-0333
e-mail: charmley.william@epa.gov

Appointment

From: jeannie.carpenter@cummins.com [jeannie.carpenter@cummins.com]
Sent: 9/17/2015 5:29:44 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Jackie M Yeager [jackie.m.yeager@cummins.com]; John C Wall [john.c.wall@cummins.com]

Subject: Pren Mtg for EPA-CMI Ann Arbor Disc on Oct 29
Location: personal phone / Ex. 6 with code personal phone / Ex. 6 & Conf. Room L207/CTC

Start: 9/21/2015 12:30:00 PM
End: 9/21/2015 1:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Message

From: Manik Narula [manik.narula@cummins.com]
Sent: 9/17/2015 1:10:58 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: Parent_Child_AltMethod_analysis_v3.pdf

All,

Regarding agenda # 2 (child rating analysis), I plan to go through the attached presentation.

Thanks

Manik Narula
Technical Advisor,
Advanced Engineering Systems Integration

Cummins Inc.
Cummins Technical Center, MC 50030
1900 Mckinley Ave
Columbus, IN 47201
U.S.A.

Phone 1-812-341-1460
Fax 1-812-377-7226
cummins.com
manik.narula@cummins.com

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From: Jackie M Yeager
Sent: Thursday, September 17, 2015 7:34 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>; charmley.william@epa.gov; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com; David.Majors@Navistar.com; Gary C Salemme <gary.c.salemme@cummins.com>; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae <morgan.andreae@cummins.com>; spears.matthew@epa.gov; Zhang.Houshun@epa.gov; david.gardner@navistar.com;

debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula <manik.narula@cummins.com>; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez.james@Epa.gov; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; He Yuesheng <yuesheng.he@volvo.com>
Subject: Phase 2 Collaboration meeting agenda

Reminder of today's call at 3:00 pm Eastern.

Proposed agenda:
1. Volvo summary of observations on cycle average approach – Yuesheng
2. Child ratings analysis – Manik
3. Other topics?
4. Plan next call – All

Call-in and Webex information:
Teleconference:
US toll-free personal phone / Ex. 6
Access code personal phone / Ex. 6

Topic: Phase 2 Collaboration Mtg
Date: Every Thursday, from Thursday, December 18, 2014, to no end date
Time: 3:00 pm, Eastern Standard Time (New York, GMT-05:00)
Meeting number: personal phone / Ex. 6
Meeting password: personal phone / Ex. 6

Please click the link below to see more information about the meeting, including its agenda, or to join the meeting.

Ex. 6

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 9/16/2015 3:08:36 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]
Subject: 9/3 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – Houshun Zhang, James Sanchez
- Navistar –Cortney Guzlas, Matt Hunkler, Brad Carlson, Laura Richart
- PACCAR – Dan Kieffer, Erin Luke
- Allison – Mike Howenstein, Jeff Shultz
- Volvo – Tony Greszler, Yuesheng He

Discussion and follow-up items (with owner's name in **bold**):

- Update on Volvo testing – Yuesheng/Tony
  - Volvo shared in-progress results from engine dyno testing on GEM-generated cycles – observations:
    - Did not get expected spread of N/V on 55 mph cycle
    - Vehicle struggling to hit vehicle speed target on ARB transient cycle
    - Houshun – could be issue with auto shift in GEM, which will be re-calibrated once more data available from SwRI and ORNL tests
    - Saw high cycle work on the config with low axle ratio
  - Houshun requested comparison of interpolation scheme from Excel file vs. surface fit from SAE paper – **Yuesheng**
- Other topics
  - Question about transfer case efficiency losses in GEM missing from vehicle sub-categories other than Class 8 tractor
  - New grade profiles
    - Some vehicles can't follow trace – will +/- constraint on vehicle speed target be retained? Yes, but could be improved, need some metric to constrain how driver model is tuned for powertrain test
    - Test won't be invalidated for not meeting speed target if at max effort/full pedal
    - Some technologies intentionally don't follow the trace (for example, predictive technologies) – how to account for in powertrain testing and in GEM?
    - Will powertrain protocol allow grade inputs to ECM or transmission? Could consider it
  - Houshun requested comparison of interpolation scheme vs. surface fit – **Manik**

Topics for future calls:

- (9/17) – Update on engine testing – Yuesheng
- (9/17) – Child ratings analysis – Manik
- (9/17?) – Comparison of interpolation vs. surface fit – Manik

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone Ex. 6
jackie.m.yeager@cummins.com

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 9/16/2015 1:26:26 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Jeannie Carpenter [jeannie.carpenter@cummins.com]
Subject: RE: Oct 29

Correct! We're good.

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Wednesday, September 16, 2015 9:26 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Cc: Spears, Matthew <spears.matthew@epa.gov>; Jackie M Yeager <jackie.m.yeager@cummins.com>; Jeannie Carpenter <jeannie.carpenter@cummins.com>
Subject: Re: Oct 29

Oops

I just realized you were talking probably about a pre-meeting call next week on Monday at 8:30am. That sounds good

Bill Charmley
Assessment and Standards Division
Office of Transportation and Air Quality
National Vehicle & Fuel Emissions Laboratory
US Environmental Protection Agency
Ann Arbor, Michigan
Desk phone 734-214-4466
Mobile phone 734-545-0333
Email charmley.william@epa.gov

On Sep 16, 2015, at 9:24 AM, Charmley, William <charmley.william@epa.gov> wrote:

> Brian
>
> Oct 29 is a Thursday
>
> Just want to make sure we are talking about he same date
>
> Thanks
> Bill
>
> Bill Charmley
> Assessment and Standards Division
> Office of Transportation and Air Quality
> National Vehicle & Fuel Emissions Laboratory

US Environmental Protection Agency
Ann Arbor, Michigan
Desk phone 734-214-4466
Mobile phone 734-545-0333
Email charmley.william@epa.gov

On Sep 16, 2015, at 9:08 AM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

Let's go with Monday. I will send invite.

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Wednesday, September 16, 2015 6:21 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Cc: Spears, Matthew <spears.matthew@epa.gov>; Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: Oct 29

Dear Brian,

Thank you for being willing to come to Ann Arbor on October 29. I realize my voice my was wandering around a little, but I think you got the main point – we are going to be very busy in October and November, so I really appreciate Cummins coming to EPA for this.

Matt and I caught up on this yesterday, and we are all set – we will plan on meeting with you, Jackie and others on October 29 in Ann Arbor.

Regarding a pre-meeting call, I could do a call any day next week if the start time is 8:30am eastern – just let me know which day.

Best regards,

Bill

Bill Charmley
Director
Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Vehicle and Fuel Emissions Laboratory
2000 Traverwood Drive
Ann Arbor, MI 48105

desk ph. 734-214-4466
cell ph. 734-545-0333
e-mail: charmley.william@epa.gov

From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Friday, September 11, 2015 12:06 PM
To: Charmley, William
Cc: Spears, Matthew; Jackie M Yeager
Subject: Oct 29

Bill, I got your voicemail. We will come to Ann Arbor on October 29. It would be very helpful if you could lay out what you want to hear from us. Maybe have a call to discuss in the next week or so?

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 9/8/2015 10:12:36 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: Jackie M Yeager [jackie.m.yeager@cummins.com]
Subject: RE: New Date - Oct 29?

Bill, will October 29 work for a visit to Columbus?

From: Brian C Mormino
Sent: Thursday, September 03, 2015 6:54 PM
To: 'Spears, Matthew' <spears.matthew@epa.gov>; Charmley, William <charmley.william@epa.gov>
Cc: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: New Date - Oct 29?

I will also be at Integer so thought this date could work. Bill, what about you and Chris?

From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Thursday, September 03, 2015 10:20 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>; Charmley, William <charmley.william@epa.gov>
Cc: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: New Date - Oct 29?

Hi Brian,

That could potentially work for me. I would be traveling directly from the DEF Integer conference in Chicago the day before.

From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Thursday, September 03, 2015 7:46 AM
To: Charmley, William; Spears, Matthew
Cc: Jackie M Yeager
Subject: New Date - Oct 29?

Bill and Matt – Given the extension on the comments deadline, we are looking for a date in October for you to come to Columbus. We can make October 29th work. Could that work for you?

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Tuesday, August 25, 2015 12:08 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Cc: Spears, Matthew <spears.matthew@epa.gov>; Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: Sept 30?

Brian and Jackie

I have not had a chance to catch up with Matt on this request, and it's already Tuesday.

I do know that both Chris and I have an all-day meeting with a light-duty OEM on that day, but I don't think we both have to attend it. It is possible that I could go to Columbus, and Chris could cover the other meeting. However, it's also very important that I check with Matt and a few others on the staff to understand if they can attend, as they are more important than me for a meeting like this.

For now, please put a place holder on September 30, but it may be another week before you hear back from Matt or I on this (unless Matt has already given you some feedback).

Thanks
Bill

Bill Charmley
Director
Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Vehicle and Fuel Emissions Laboratory
2000 Traverwood Drive
Ann Arbor, MI 48105

desk ph. 734-214-4466
cell ph. 734-545-0333
e-mail: charmley.william@epa.gov

From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Friday, August 21, 2015 9:56 PM
To: Charmley, William
Cc: Spears, Matthew; Jackie M Yeager
Subject: Sept 30?

Bill, I am following up on our discussion on Phase 2 and the need for a deep dive on technologies and technical issues. I have checked and my schedule lines up with both John and Jen on September 30th. We could get into the whole suite of issues that we discussed as well as show you directly the latest on Waste Heat Recovery. Could that work for you and the team to come down to Columbus for the day? How about Chris?

Brian C. Mormino
Executive Director -- Worldwide Environmental Strategy & Compliance
Cummins Inc.
MC 60203, 500 Jackson Street
Columbus, IN 47201
Ex. 6 (p)

Ex. 6 (c)
brian.c.mormino@cummins.com

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Message

From: Michael J Ruth [michael.j.ruth@cummins.com]
Sent: 9/8/2015 1:27:54 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Olechiw, Michael [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9f564b92ff96459ab606eb66e5892e2d-Olechiw, Michael]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]
CC: Brian C Mormino [brian.c.mormino@cummins.com]
Subject: RE: Follow-up with Cummins on Light-duty vehicle diesel engine technologies

We would be willing to bring the vehicle as a show and tell. If you would like to test our vehicle at your facility, we would need to do some level of negotiation of what we would allow as some of the technology is still pending IP concerns.

Michael J Ruth
Director – Advanced Systems Integration
Chassis Certified Products

Cummins Technical Center
M/C 50030
1900 McKinley Ave
Columbus, IN 47201-3005
USA

personal phone / Ex. 6
cummins.com
michael.j.ruth@cummins.com

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From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Tuesday, September 08, 2015 8:19 AM
To: Michael J Ruth <michael.j.ruth@cummins.com>; Jackie M Yeager <jackie.m.yeager@cummins.com>; Olechiw, Michael <olechiw.michael@epa.gov>; McDonald, Joseph <McDonald.Joseph@epa.gov>
Cc: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: RE: Follow-up with Cummins on Light-duty vehicle diesel engine technologies

Mike –

Thanks for the response. Yes, this would be lucky for me, two interactions in one month, but unfortunately I'm going to have to hand this one off to Mike Olechiw and Joe McDonald on my team.

Mike and Joe will be tied up this week with me at a series of meetings with some of the light-duty OEMs, but I know that Joe is very interested in learning more about the ATLAS project. I believe Joe went to the DOE merit reviews this past June and was probably on a review panel for the project, but I believe he has a number of more detailed questions.

Joe – can you follow up with Mike Ruth directly?

Thanks
Bill

From: Michael J Ruth [mailto:michael.j.ruth@cummins.com]
Sent: Friday, August 28, 2015 7:53 AM
To: Jackie M Yeager; Charmley, William; Olechiw, Michael
Cc: Brian C Mormino
Subject: RE: Follow-up with Cummins on Light-duty vehicle diesel engine technologies

Bill, Lucky you. Another opportunity for you to interact with me.

Michael J Ruth
Director – Advanced Systems Integration
Chassis Certified Products

Cummins Technical Center
M/C 50030
1900 McKinley Ave
Columbus, IN 47201-3005
USA

personal phone / Ex. 6
cummins.com
michael.j.ruth@cummins.com

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From: Jackie M Yeager
Sent: Friday, August 28, 2015 6:26 AM
To: Charmley, William <charmley.william@epa.gov>; Olechiw, Michael <olechiw.michael@epa.gov>

Cc: Brian C Mormino <brian.c.mormino@cummins.com>; Michael J Ruth <michael.j.ruth@cummins.com>
Subject: RE: Follow-up with Cummins on Light-duty vehicle diesel engine technologies

Bill,

Cummins would be happy to discuss the 2.8L engine which was part of the ATLAS project with DOE. Mike Ruth, whom I have cc'ed here, was the Principal Investigator for the project. We look forward to hearing from Mike O. and Joe.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Wednesday, August 26, 2015 9:03 AM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>; Olechiw, Michael <olechiw.michael@epa.gov>
Cc: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: Follow-up with Cummins on Light-duty vehicle diesel engine technologies

Dear Jackie,

Thanks for your response, I had thought maybe you would be sticking around today for the rest of the EMA meeting, but given the focus on tractor aerodynamics for today I can understand why you choose not to.

I had wanted to introduce you to Matt's light-duty counterpart in my Division, Mike Olechiw.

Mike is leading up the technical analysis for the EPA light-duty vehicle GHG Mid-term Evaluation team. This is the regulatory commitment EPA made in the final rule for the 2017-2025 light-duty vehicle GHG/Fuel Economy rule with NHTSA, where we committed to a process to re-assess the appropriateness of the 2022-2025 standards.

I am sure that Cummins will be interested in participating at some level in this multi-year review, and I wanted to take the opportunity to introduce you to Mike. I will still do that, but it will now be via email.

One near-term request that Mike and his staff have for Cummins is regarding the Cummins light-duty 2.8 L project. Mike's subject matter expert on his staff for this project for engine technologies is Joe McDonald, who many of your colleagues at Cummins probably know. Joe attended this past spring/summer the DOE merit reviews (which he has done for many, many years), and I believe he heard the update from the Cummins folks.

Mike and Joe would like to follow up with you and Brian very soon regarding our interest in this engine.

At this point I will leave it to Mike and Joe to follow up with you on this topic.

Thanks
Bill

From: Jackie M Yeager [mailto:jackie.m.yeager@cummins.com]
Sent: Wednesday, August 26, 2015 8:47 AM
To: Charmley, William
Cc: Iffland, JoNell
Subject: RE: Jackie - if you get to the EPA office's before 9am, can you ask the guards to call me, I wanted to talk with you regarding a Light-duty Diesel topic. Thanks, Bill Charmley

Hi Bill – I am actually back in Columbus today. I did not stay in town for the aero discussion. Would you like to call me on the LD topic?

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Wednesday, August 26, 2015 8:45 AM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Cc: Iffland, JoNell <Iffland.JoNell@epa.gov>
Subject: Jackie - if you get to the EPA office's before 9am, can you ask the guards to call me, I wanted to talk with you regarding a Light-duty Diesel topic. Thanks, Bill Charmley

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/3/2015 12:53:10 AM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: RE: Gliders OK until Jan 2022 ?

Hello Bill and Chuck

Regarding EPA and NHTSA's proposal wrt glider vehicles, we read in the Preamble (p. 839 of the pre-issue):
EPA is proposing that this requirement for gliders to meet engine and vehicle standards applicable to other new vehicles and engines take effect on January 1, **2018.**

Yet, upon further review, and considering proposed 1037.150 (c)
(c) Provisions for small manufacturers. .... Qualifying manufacturers are not subject to the greenhouse gas standards of §§ 1037.105 and 1037.106 for vehicles built before January 1, **2022,**

...and 1037.150(j),
(j) Limited prohibition related to early model year engines. The provisions of this paragraph (j) apply only for vehicles that have a date of manufacture before January 1, **2018.** See § 1037.635 for related provisions that apply in later model years. The prohibition in § 1037.601 against introducing into U.S. commerce a vehicle containing an engine not certified to the standards applicable for the calendar year of installation does not apply for vehicles using model year 2014 or 2015 spark-ignition engines, or any model year 2013 or earlier engines.

Our interpretation is that:

1) SMALL BUSINESSES have until Jan 1, 2022 to comply with vehicle and engine GHG standards, and SMALL BUSINESS glider vehicle manufacturers also have until Jan 1, 2022 to comply, but at that time they are entitled to an annual exemption for 300 units or 2010-2014 annual volume peak, whichever is less.
2) Glider vehicle manufacturers that are NOT small businesses are already subject to the GHG *vehicle* standards today (the NPRM mentions that you know of only one such manufacturer), yet, according to (j), the vehicles they build before Jan 1, 2018 need not have engines whose model year is corresponding to the vehicle year of manufacture. After Jan 1, 2018, this non-small business glider vehicle manufacturer must comply with all vehicle GHG standards, and all engine GHG & criteria standards (that is, the engine's model year must correspond to the vehicle year of manufacture), *without* any exemptions.

As 1037.105 (j) is written, there is no qualifier as to what kind of manufacturer we're talking about. Even Volvo could build vehicles with 2013 or earlier diesel engines up to Jan 1, 2018. As well, I find the provision somewhat circular, essentially: *Your vehicle's engine model year must match the vehicle year of manufacture (1037.601) unless the engine model year doesn't match the vehicle year of manufacture (1037.150(j)).*

My question is: Can you tell us, please, if you agree with our interpretation with respect to #1 and #2 above, and if it was what the Agencies had intended? (I'm confused about the mismatch on the preamble dates and the reg language dates.)

Thanks
Steve B

Steve Berry
Volvo Group Trucks Product Planning
2900 K St NW

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Cell: personal phone / Ex. 6
steve.berry@volvo.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 9/2/2015 3:13:06 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]
Subject: 8/20 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton –
- EPA – Houshun Zhang, James Sanchez
- Navistar – David Gardner, Cortney Guzlas, Matt Hunkler
- PACCAR – Dan Kieffer, Erin Luke
- Allison – Mike Howenstein
- Volvo – Tony Greszler, Yuesheng He, Jeff Marley

Discussion and follow-up items (with owner's name in **bold**):

- Vehicle configs with similar cycle work and N/V – Manik
  - Reviewed the slides prepared by Manik (emailed to the group after the call)
  - Re-send the EPA spreadsheet with details of the vehicle configurations used in the simulations – **James** (DONE, emailed to the group after the call)
  - Next step is to see if testing confirms the spread in CO2 for similar N/V and cycle work values is acceptable
- Engine testing issues – Tony/Yuesheng
  - Discussed issues trying to run engine speeds and torques generated by GEM: test cell can't follow drastic torque changes on ARB cycle; lower cycle work in test cell; engine speed going below idle because GEM only moves 1 gear at a time (no skip shifting)
  - GEM engine transient response not representative of real engine and needs improvement
  - Use Part 1065 regression criteria for now
  - Volvo may be ready with some test results to share on next call
- Questions on entering powertrain map into GEM – Hunkler
  - Question on why GEM does not use the specific powertrain you are testing (to determine N/V and cycle work for entering the powertrain map??) – Needed a general approach that would cover transmissions GEM can't simulate, such as CVT, so using a generic powertrain

Topics for future calls:

- (9/3?) – Update on engine testing – Yuesheng

Regards,

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/1/2015 4:25:18 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: Your voicemail

Hi Bill
I got your vmail. I think it's a great idea and I'll inform Denny and Niklas of the interest and do what I can on my end to make it happen.
Steve

Steve Berry
Volvo Group Trucks Product Planning
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Washington, DC 20007
Office 202-536-1557
Cell. personal phone / Ex. 6
steve.berry@volvo.com

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 8/28/2015 9:00:22 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: RE: Sustainability and Efficiency Awards Given Out at Fleet Technology Expo

Thanks, Bill. I hadn't seen that. We'll see what their formal comments say. Anyway, it sounds like they plan to make hay while the sun is shining. That's their definition of "transition"

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Friday, August 28, 2015 3:59 PM
To: Berry Steve
Subject: FW: Sustainability and Efficiency Awards Given Out at Fleet Technology Expo

Steve,

Thanks for your earlier email on gliders. I don't know if you saw the article below from Preston Freight at Kenworth, but you may want to read it. In it he discusses Kenworths views on glider kits in the context of the HD Phase 2 proposal.

Thanks

Bill

Begin forwarded message:

From: "HDT Headline News" <hdtheadlinenews@bobitnews.com>
Date: August 27, 2015 at 6:02:28 AM EDT
To: <charmley.william@epa.gov>
Subject: Sustainability and Efficiency Awards Given Out at Fleet Technology Expo
Reply-To: "HDT Headline News" <reply-fec51170706c057a-12457_HTML-127575834-1079685-116@bobitnews.com>

Heavy-Duty Fleet Technology Expo Awards Announced Click to view online

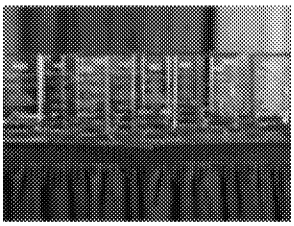
HDT HEADLINE NEWS

August 27, 2015

ATA Puts Support Behind Driver Hair Testing Option

In a letter, the ATA urged congress to move forward with legislation that would allow fleets to use hair samples in a federally mandated drug screening program for drivers.

Heavy-Duty Fleet Technology Expo Awards Announced



Many fleets were honored but only six took the top honors of the HDT Efficiency and Sustainability awards at the 2015 Fleet Technology Expo at an Aug. 26 ceremony.

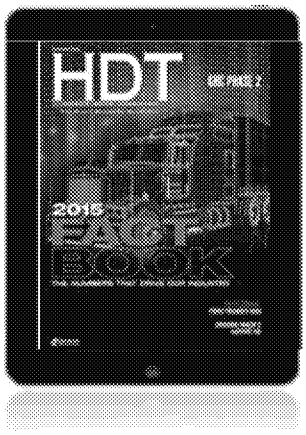
Kenworth Execs Talk Trucks and Trucking

In a wide-ranging discussion with trucking journalists at its headquarters Tuesday, Kenworth executives shared their insights on topics ranging from autonomous trucks to the safety of the industry.

Economic Watch: Capital Goods Orders Shine in Manufacturing Report

Shipments and new orders of manufactured durable goods, including a key economic indicator inside this sector, posted impressive gains in July, according to a new Commerce Department report, but it's hardly a long-term trend.

TABLET EDITION



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BLOG

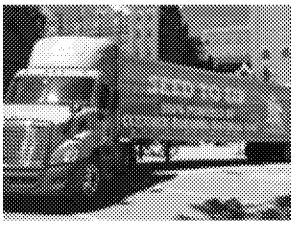
Replacing Rivets with Adhesives Yields Smoother Sides That Could Save Fuel

Lord Corp., which makes bonding adhesives, has done research that indicates eliminating rivets from a trailer's walls might cut aerodynamic drag by about 1%.

Ladies, Gentlemen; Please Meet THE Dumbest Truck Driver in the World

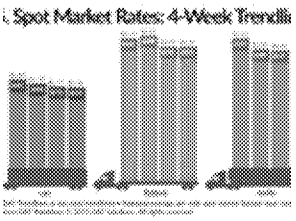
You simply won't believe your eyes when you see what some dumb-*ss truck driver is doing in this YouTube video. Equipment editor Jim Park is just glad he was kind enough to leave behind this bit of

Anheuser-Busch Converts St. Louis Fleet to CNG



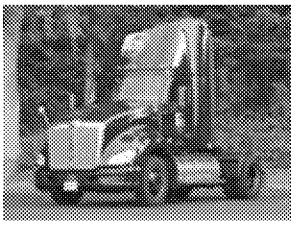
Anheuser-Busch has replaced all 97 diesel-fueled tractors in its St. Louis fleet with new compressed natural gas (CNG)-fueled tractors, the brewing company announced. By transitioning to CNG technology, Anheuser-Busch expects to reduce carbon dioxide emissions by 2,500 tons per year.

Spot Freight Rates Stable, Available Loads Drop



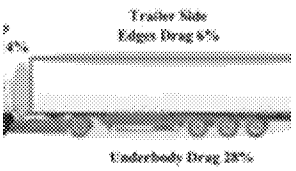
Spot truckload rates, including fuel surcharges, remained nearly unchanged over the past week as overall load availability fell 5.5% during the week ending Aug. 22, according to DAT Solutions.

UPS Gets 50,000th Paccar MX Engine Installed in a Kenworth



UPS received the milestone 50,000th Paccar MX series engine installed in a Kenworth truck at a ceremony at Kenworth headquarters Wednesday.

Replacing Rivets with Adhesives Yields Smoother Sides That Could Save Fuel



Lord Corp., which makes bonding adhesives, has done research that indicates eliminating rivets from a trailer's walls might cut aerodynamic drag by about 1%.

evidence. Does anybody have any idea who this guy is?

Crash Argues for Better Impact Guards, and Better Driving

Senior Editor Tom Berg ponders fatal rear-end crashes -- a type of crash that killed a college buddy many years ago.

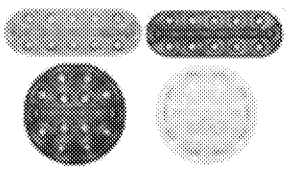
East Manufacturing Appoints Dealer Liaison

East Manufacturing has named Tom Welch as its dealer liaison, a newly created position responsible for dealer network growth, improvement and support activities.

Industry Leaders to Share Insight at Trucking Efficiency Workshop

The NACFE's Trucking Efficiency Workshop is a one-day event for fleets where industry leaders will share their insights on some of the best efficiency technologies.

HD 500 Series Lights Designed to Stand Out



Optitronics' HD 500 Series LED stop, tail, turn lamps are designed with a three-dimensional lens feature and brighter illumination for improved ability to stand out compared with other lighting.

GOTQUESTIONS? Sponsored By: CITGO

Q. Is it practical to switch to synthetic lubes after running mineral oils for a long time?

A. Yes - equipment owners have changed to synthetic lubricants without problems. **READ MORE**

GOTQUESTIONS? Sponsored By: HENDRICKSON

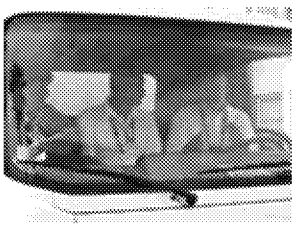
Q. Is it a special Hendrickson axle that uses the PSI system?

A. The axle is only unique from the perspective that if specified in advance by the OEM or dealer, Hendrickson pre-drills the axle for the tire inflation system. **READ MORE**

DOWNLOAD WHITEPAPER

- Is Your Business Ready for the ELD Mandate?
- Quantifying the Costs of Unsafe Drivers
- West Air Gases Case Study
- Continuous Driver Monitoring Made Easy
- Assessing Bumper Technology for a No-Compromise Solution
- Learn How Micron Filtration Will Benefit Your Fleet
- Transportation Operations Needs. Today and Tomorrow.
- What do today's fleet professionals think of GPS tracking technology?

PHOTO GALLERIES



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Being Evel Documentary Premiere

Ford Plant Celebrates F-650/750 Rollout

Hirschbach's Fuel-Saving Strategies

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 8/28/2015 6:43:11 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; james.tamm@dot.gov
CC: ryan.posten@dot.gov; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Kenworth Icon 900 glider kit now available from Fitzgerald's
Attachments: removed.txt

Hello Bill and Jim

Another interesting article about the expansion of the glider business. The reader comment really sums things up, copied here:

Snowball 2 minutes ago
We just picked up our first of what may be many Fitzgerald Glider Kit 389/386 tractors yesterday. This is an awesome truck and the workmanship in the engine compartment is 2nd to none!!! As long as the government and EPA don't quash this set up we will never buy another truck with a manufacturer's engine. I bet our new truck runs as clean or cleaner than all these others with all the emissions crap on them. Fitzgerald's is now our new truck dealer!! Thanks Tommy and crew!

http://www.ccjdigital.com/kenworth-900-icon-glider-kit-now-available-from-fitzgeralds/?utm_source=daily&utm_medium=email&utm_content=08-28-2015&utm_campaign=Commercial%20Carrier%20Journal&ust_id=590da236f0&

We're very pleased the agencies are taking action to address this issue within the HD market.

Regards,

Steve Berry

Steve Berry
Volvo Group Trucks Product Planning
2900 K St NW
South Building, Suite 401
Washington, DC 20007
Office 202-636-1557
Cell personal phone / Ex. 6
steve.berry@volvo.com

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 8/25/2015 6:57:06 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Jackie M Yeager [jackie.m.yeager@cummins.com]
Subject: RE: Sept 30?

Have not heard back from Matt yet. Yes, I think it would be good for you and Matt and the team to be present and I think it is ok if Chris is not able to attend. Please let us know as soon as you can about Sept 30.

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Tuesday, August 25, 2015 12:08 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Cc: Spears, Matthew <spears.matthew@epa.gov>; Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: Sept 30?

Brian and Jackie

I have not had a chance to catch up with Matt on this request, and it's already Tuesday.

I do know that both Chris and I have an all-day meeting with a light-duty OEM on that day, but I don't think we both have to attend it. It is possible that I could go to Columbus, and Chris could cover the other meeting. However, it's also very important that I check with Matt and a few others on the staff to understand if they can attend, as they are more important than me for a meeting like this.

For now, please put a place holder on September 30, but it may be another week before you hear back from Matt or I on this (unless Matt has already given you some feedback).

Thanks
Bill

Bill Charmley
Director
Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

National Vehicle and Fuel Emissions Laboratory
2000 Traverwood Drive
Ann Arbor, MI 48105

desk ph. 734-214-4466
cell ph. 734-545-0333
e-mail: charmley.william@epa.gov

From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Friday, August 21, 2015 9:56 PM
To: Charmley, William
Cc: Spears, Matthew; Jackie M Yeager
Subject: Sept 30?

Bill, I am following up on our discussion on Phase 2 and the need for a deep dive on technologies and technical issues. I have checked and my schedule lines up with both John and Jen on September 30th. We could get into the whole suite of issues that we discussed as well as show you directly the latest on Waste Heat Recovery. Could that work for you and the team to come down to Columbus for the day? How about Chris?

Brian C. Mormino
Executive Director -- Worldwide Environmental Strategy & Compliance
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personal phone / Ex. 6 (p)
(c)
brian.c.mormino@cummins.com

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From: Manik Narula [manik.narula@cummins.com]
Sent: 8/21/2015 1:31:26 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: EMA_VehicleConfigQuestion_analysis_v5.pdf

All,

The presentation related to agenda #1 which I went through yesterday is enclosed for your reference.

Thanks

Manik Narula
Technical Advisor,
Advanced Engineering Systems Integration

Cummins Inc.
Cummins Technical Center, MC 50030
1900 Mckinley Ave
Columbus, IN 47201
U.S.A.

Phone 1-812-341-1460
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manik.narula@cummins.com

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From: Jackie M Yeager
Sent: Thursday, August 20, 2015 8:45 AM
To: Brian C Mormino <brian.c.mormino@cummins.com>; charmley.william@epa.gov; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com; David.Majors@Navistar.com; Gary C Salemme <gary.c.salemme@cummins.com>; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae <morgan.andreae@cummins.com>; spears.matthew@epa.gov; Zhang.Houshun@epa.gov; david.gardner@navistar.com;

debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula <manik.narula@cummins.com>; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez.james@Epa.gov; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com; Anthony Greszler (anthony.greszler@volvo.com) <anthony.greszler@volvo.com>; He Yuesheng <yuesheng.he@volvo.com>
Subject: Phase 2 Collaboration meeting agenda

Reminder of today's call at 3:00 pm Eastern. Welcome to Volvo (Tony and Yuesheng) who will be joining the calls going forward and are cc:ed here. Please use the dist list from this email if you need to share info with the whole group. Note, Daimler was invited but declined to participate.

Proposed agenda:
1. Vehicle configs with similar cycle work and N/V – Manik
2. Engine testing issues – Tony
3. Questions on entering powertrain map into GEM – Hunkler
4. Other topics?
5. Plan next call – All

Call-in and Webex information:
Teleconference:
US toll-free personal phone / Ex. 6
Access code personal phone / Ex. 6

Topic: Phase 2 Collaboration Mtg
Date: Every Thursday, from Thursday, December 18, 2014, to no end date
Time: 3:00 pm, Eastern Standard Time (New York, GMT-05:00)
Meeting number: personal phone / Ex. 6
Meeting password: personal phone / Ex. 6

Please click the link below to see more information about the meeting, including its agenda, or to join the meeting.

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Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 8/20/2015 12:37:10 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 8/7 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – Houshun Zhang
- Navistar – David Gardner, Cortney Guzlas
- PACCAR – Dan Kieffer
- Allison – Jeff Shultz, Laverne Spears

Discussion and follow-up items (with owner's name in **bold**):

- "Hybrid" concept of alt map + ss map
  - EPA's objective with combining the two mapping approaches is to decrease test burden.
  - Discussed whether vocational would need more steady state points than tractor. Testing of ISB+Allison TX, gasoline engine may answer.
  - Discussed whether number of cycle average points could be reduced. Risk of reducing interpolation accuracy. Also being looked at by SwRI.
- Industry group comments
  - Might depend on where EMA ends up
  - Invite Volvo and Daimler to join these calls – **Jackie**
- EMA questions on cycle average map
  - How to define generic vehicle configurations – any need to normalize cycle work as has been done in engine speed space?
  - Can two different vehicle configs give same cycle work and N/V but different CO2?
    - Look in existing simulations from James – **Manik**
    - Any insight from testing (past or planned)?
- Other
  - Next GEM release will be around August 18
  - Road grade changes – intent is to keep cycle time the same

Topics for future calls:

- (8/20) – Data mining for different vehicle configs with similar cycle work and N/V – Manik
- (8/20) – How to enter powertrain map in GEM? – Hunkler

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 12/8/2015 8:51:19 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group

(FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard (mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; NICHOLAS.BELLOVARY@sgs.com; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Carnegie [william.carnegie@ge.com]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

Subject: EMA - EMTC, CARB, EPA & Others - Cycle Average Fuel Map Presentation

Attachments: Alternative Appraoch_Zhang-Final.pdf

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: December 8, 2015

RE: **Cycle Average Fuel Map Presentation**

Please see the following email and attachment from James Sanchez of EPA.

If you have any questions, please do not hesitate to contact me.

From: Sanchez, James [mailto:sanchez.james@epa.gov]
Sent: Tuesday, December 08, 2015 11:03 AM
To: Shirish A Shimpi <shirish.a.shimpi@cummins.com>
Cc: Timothy A. French <tfrench@clpchicago.com>
Subject: Cycle Average Fuel Map Presentation

Shirish,
Here is the presentation I went over at the last EMTC meeting. Please send it to the group. If people are interested in looking at some of the additional work we have done on the topic they can read our SAE publication. 2015-01-2768.

Thanks
James

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 3/18/2015 12:30:18 AM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; White, Erik@ARB [erik.white@arb.ca.gov]
CC: Iffland, JoNell [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=269c8731e7c6417482f8a8ddccfc4887-Iffland, JoNell]; Lange, Bryan@ARB [bryan.lange@arb.ca.gov]
Subject: Logistics for EPA and ARB visit to Cummins on March 23

Hello Bill and Erik,

We are looking forward to hosting you at Cummins in Columbus, Indiana next Monday, March 23. Here is a summary of logistical details.

- Time:
  2:00 – 5:30 pm Eastern
  (Bill arrives at 2:00 pm, Erik arrives at 4:00 pm)

- Location:
  Columbus Technical Center (CTC)
  Customer Visit Room A
  1900 McKinley Avenue
  Columbus, IN 47201

- Arrival/parking:
  We will have a parking spot reserved for each of you in the main aisle leading to the guard shack – look for orange cones. (You may need to drop in the guard shack before you park to alert a guard to move the cones out of your way.) Have the guard call me on my cell phone to come escort you into the building.

- Jackie Yeager's cell phone:
  Personal Address / Ex. 6
  Feel free to call me if you need anything.

- Dress:
  I suggest business casual. We are pretty informal.

Please let me know if you need any other details. I will send a finalized agenda later this week.

Regards,
Jackie Yeager
Global Energy Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 3/25/2015 9:05:25 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: Re: email address for Wane

Hi Bill, thanks again for stopping in to see us on Monday. Wayne's email is:

wayne.a.eckerle@cummins.com

Let me know if there are any other addresses you would like, or any follow up items I can help with.

Jackie Yeager
Sent from my iPhone

On Mar 25, 2015, at 4:53 PM, Charmley, William <charmley.william@epa.gov> wrote:

Jackie –

I would like to send a follow up email to you and your colleagues for the meeting on Monday, but I realized I don't have Wayne's email address.

Is that something you can send me on Thursday?

Thanks
Bill

This email has been scanned for Malware.

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 3/17/2015 11:45:17 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]
CC: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; John C Wall [john.c.wall@cummins.com]
Subject: Re: Motoring onward: part two of emissions regimes

Great stuff! I shared with Janet and Gina's press office

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

On Mar 17, 2015, at 10:16 AM, Jackie M Yeager <jackie.m.yeager@cummins.com> wrote:

> Chris, Bill, and Matt - here is an editorial today from the same author.
>
> Link: http://www.truckinginfo.com/article/story/2015/03/commentary-good-news-coming.aspx?utm_campaign=Headline-News-20150317&utm_source=Email&utm_medium=Enewsletter&btm_ea=Y2Fyb2wubGF2ZW5nb29kQGN1bW1pbnMuY29t
>
> # Commentary: Good News Coming?
>
> March 2015, TruckingInfo.com - Editorial
> By Rolf Lockwood
>
> You should hear some important news this month, and it might eventually save you a buck.
>
> A year ago, President Obama decreed that a new set of rules regarding greenhouse-gas emissions and fuel economy should be proposed, as of this month, covering medium- and heavy-duty trucks built in 2020 and beyond. Not sure I'd hold my breath about the timing, but he charged the U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration with figuring out how to go even further than we've already gone. And that's quite a way.
>
> The 2020 rules represent Phase 2 of an effort that began with another presidential decree back in 2010 demanding serious GHG and fuel consumption cuts for the 2014-2019 period. That was Phase 1 of the long-term plan, and it seemed complex and arbitrary. But if you've bought trucks in the last year, I'll bet you didn't even notice a change unless you examined what should be lower fuel bills.
>
> And that's a far cry from all the wrangling and arguing — not to mention the paying — that accompanied previous emissions regimes.
>
> The GHG targets are mainly carbon dioxide, but also methane and nitrous oxide. The thing is, when you cut CO2, you also increase fuel economy. Official projections tell us that Phase 1 will save 530 million barrels of oil, 270 million metric tons of GHGs, and $50 billion in fuel costs. Government

projections being what they are, who knows how accurate those estimates might actually be, but for the first time in recorded history, the EPA and NHTSA are sort of your friends.

Yes, as in the past, the cost of engines will rise, but this time there will be fuel savings to bring a fairly quick payback.

Things really have gone pretty quiet on the diesel front, and it hasn't been this way since the EPA started tinkering with things back in the 1990s.

In fact, they were at it as early as 1974, though the broad and heavy crunch came later. It really began in 1997 when the EPA set the standard for model years 2004-2006. But after all the trouble and woe brought on then and later with the 2007 emissions regime — which linger on for many of you — the 2010-spec heavy-duty diesel has proven to be a big improvement in terms of both reliability and fuel economy.

Are we back to where we were a dozen-plus years ago? No, but compared to EPA 2007, we're way ahead.

The present 2014-2019 rules say that tractors must achieve as much as a 20% reduction in CO2 emissions and fuel consumption by 2017, a little more by 2019. Mixers, refuse haulers, and other vocational machines have to get to a 10% reduction in fuel consumption by 2017.

None of this caused a stir last year, and targets were met with ordinary improvements of existing hardware and software. Things will get tougher as 2017 approaches, but radically new hardware such as waste-heat recovery won't be required.

Phase 2 will clearly demand even tougher CO2 and fuel-consumption reductions, and we know that the final regulation will appear some time in 2016. Our firm knowledge stops there.

I'm almost sitting on the edge of my seat, anxious to see the draft rules soon. And for the first time ever, I have the feeling that a major government intervention might actually bring good news.

Holy moly, did I just write that?

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From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Wednesday, March 04, 2015 11:02 PM
To: Brian C Mormino
Cc: Charmley, William; Spears, Matthew; Jackie M Yeager; John C Wall
Subject: Re: Motoring onward: part two of emissions regimes

Thanks for sharing this Brian!

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

On Mar 4, 2015, at 7:23 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

Chris, Bill and Matt – Thought you would be interested in seeing this recent article from Today's Trucking on Phase 2.

http://www.todaystrucking.com/motoring-onward-part-two-of-emissions-regimes?page=1

TODAY'S TRUCKING

Motoring onward: part two of emissions regimes

By Rolf Lockwood, Posted: Mar 3, 2015 4:35 PM | Last Updated: Mar 3, 2015 4:35 PM

TORONTO-- Apples and oranges. That's how Brian Mormino describes the difference between the emissions regimes of the previous decade and the one that was launched last year and will enter its second phase in 2020. Executive director, worldwide environmental strategy and compliance at Cummins, he says all the hard work and heartache of dealing with engine emissions from 2002 on to 2010 has left us well equipped for the next steps.

We've already taken the first of those steps, starting a year ago, with Phase 1 of the fuel economy and greenhouse gas regulations as decreed by President Obama. Back in 2010, with so-called 'criteria' pollutants like nitrogen oxide (NOx) under control, he ordered the Environmental Protection Agency (EPA) and the National Highway Traffic Administration to move on. He told them to cut carbon dioxide (CO2) emissions, along with other gases in lesser amounts, while improving fuel economy in medium- and heavy-duty trucks.

The challenge was anything but small, the timeline short, but the 2014 targets were met, largely because so much had already been achieved. And the next target in 2017 will be met as well.

"I'd like to help people understand that the industry is in a great place from the standpoint of technology and the future," Mormino told me in a lengthy recent interview. "What I mean by that is that we now have diesel particulate filters, we have SCR systems, we're taking care of emissions in the exhaust. And we have learned and improved on those systems.

"And so when we look at meeting the first GHG and fuel-consumption standard in 2013, a year early, how did Cummins do that? We did it by improving the engine architecture that we already had in place. And what are we going to do for 2017? We're going to improve on the engine architecture that we already have in place. And I would even venture to say that when we look at 2021, we're going to improve on the engine architecture that we already have in place."

The New Regime

Phase 1 of the GHG and fuel-economy regime does not involve just engines as in the past, but trucks as well, with tires and aerodynamic devices tested and taken into account. The present 2014-19 rules say that heavy-duty tractors must achieve as much as a 20-percent reduction in CO2 emissions and fuel consumption by 2017, a little more by 2019. Engines, tested separately, had to improve three percent by 2014, and six percent by 2017. Mixers, refuse haulers, and other vocational machines must get to a 10-percent reduction in fuel consumption by 2017.

None of this change caused a stir last year, and initial targets were met with ordinary improvements of existing hardware and software. Things will get tougher on engines in 2017 but radically new hardware -- like waste-heat recovery -- won't be required.

When these rules were announced it seemed to many observers that, with so many variations in commercial vehicles, it would be near impossible to find a standard that applies to all. But not so, apparently, and for reasons similar to those cited by Mormino.

"It's complicated but we've been able to manage all the configurations in Phase 1," said Sean Waters, director of compliance and regulatory affairs at Daimler Trucks North America. "Mostly we're able to manage all the differences because we spent a lot of money developing fuel-efficient technologies years ago. All those decisions that have paid off for our business and paid off for our customers, have also paid off in the regulatory world and enabled us to deal with all the different configurations out there."

Phase 2 Tougher

Phase 2 of the fuel-efficiency/greenhouse gas regulations will soon be unveiled. A draft rulemaking proposal was due to be released this month by the EPA and NHTSA, but I'm hearing there's a delay. Regardless, the final rule is due some time in 2016, affecting trucks built in 2020 and beyond.

We don't know much about it, and even the people I've talked to lately who keep track of what's going on in Washington can only guess. All we really know is that Phase 2 will demand even tougher, more stringent CO2 and fuel-consumption reductions. Much tougher, it seems. But our firm knowledge stops there.

Will trailers be added to the mix? It's almost certain, it seems, and there are suggestions that it will happen in 2018. At least for dry vans and reefers.

One test or two?

Engines and vehicles are tested separately in Phase 1, but there are those who urge that just one test, with engines rolled into the whole truck like any other component, is the better approach for Phase 2. Both sides are pretty vehement.

As things stand now engines are tested on a dynamometer as they have been all along, and Cummins thinks it should stay that way. Among other reasons, Mormino says that this would preserve spec'ing flexibility for truck buyers and ensure repeatability in the testing process.

Trucks, on the other hand, are tested by way of computer modelling in Phase 1, with some inputs coming from on-track trials using standard SAE protocols and that data then fed into the modelling software. Daimler and Volvo (including Mack), the only fully integrated OEMs, are arguing that a single all-inclusive test would be simpler and more cost-effective.

Mormino says the implementation of Phase 1 was pretty much seamless, and he attributes that success largely to the continued use of familiar regulatory tools and testing methods that had been in place for decades.

For 30 years engine makers have tested NOx and particulates on the dyno, and it was easy to include CO2 as well.

"We just added CO2," Mormino says, "which means that we allowed all that diversity to continue in the marketplace because the engine is certified to operate in a wide range of vehicles and applications. So customers and end-users still have all the choice that is

really, really important... in terms of all of their preferences and the types of work they have to do. The regulation didn't... limit their choices."

Perhaps a more compelling argument is the one he makes about the huge number of fuel-economy variables when a truck is put to use. Like driver skills, terrain, trailer type, highway or city, load, and countless others.

"That is a challenge for any type of regulation that tries to drive technology on vehicle aspects that are highly variable," Mormino says. "And the way that the regulation attempted to deal with that is that it separated out the most certain aspect, the engine, and provided a much brighter focus on something you can repeatably and accurately measure and do so in a way where it can be enforced."

On the other side of this argument sits DTNA's Sean Waters, as well as the Volvo Group's Tony Greszler.

"Our goal has always been to provide our customers with the lowest total operating costs to increase their revenues, and the most effective way to do that has been to provide better fuel efficiency," says Waters. "Regulations have interfered with this goal in the past where criteria-pollutant emissions control technology had a great negative impact on fuel economy.

"It's critical that regulations to reduce fuel consumption do not in actuality result in negative impacts on real-world fuel efficiency gains, and this is where the current separate engine standard program has failed. Engine test cycles are based on historical operating data and cannot reflect changes in engine size, powertrains, or vehicle power demand and do not accurately represent the fuel used in the real-world, nor were they ever designed to do so," Waters suggests.

"DTNA believes the best way to ensure that the Phase 2 regulation provides a total-cost-of-operation benefit to customers is to give manufacturers the ability to focus on improving the entire vehicle as it operates on the road and in the application for which its customers want to use the vehicle. Any regulation that doesn't give manufacturers the flexibility to meet it in the manner that works best for our customers, results in vehicles that customers can't afford, or doesn't provide sufficient real-world payback and risks creating a pre-buy prior to the regulation becoming effective."

Waters goes further, saying that the tests for criteria pollutants -- NOx and PM -- are based on a test designed in 1990 or 1991 "when trucks had higher horsepower, more torque. It was just a different way of operating an engine. The test was never designed for CO2." Nor was it designed to measure fuel economy, he adds.

He figures the test was used for convenience in Phase 1 to get a rule done quickly.

At Volvo Group North America, Tony Greszler is vice president of government and industry relations, and he's the point man on Phase 2 rules.

"The bottom line here is that the engine test doesn't test the engine the way it runs in the truck," he says. "It's impossible for any engine test to do that. And it also doesn't account for the impact of the engine on the rest of the truck.

Waste-heat Recovery

"The technology of most concern is what we call waste-heat recovery," Greszler goes on.

It's a tool that Cummins expects to deploy in 2020 or so, though Brian Mormino says some customers may get field-test units in 2017 or 2018. In fact all engine makers are

developing it, and a variation is even used in today's Formula One race cars where they add it to the standard V6 and call the package a hybrid. It recovers exhaust heat and turns it back into energy.

"It's essentially a second engine," says Greszler. "And it requires that you run the exhaust heat through a fluid, via a heat exchanger in the exhaust, and run it through an expansion machine to make power, and then condense that fluid again. Which means that you've got a lot more cooling demand. You've now got to cool most of the heat from the exhaust, because the process isn't very efficient, so most of that heat ends up in your condenser.

"And we end up having to add substantial weight, space, and cooling capacity into our trucks," he continues, "which means that we lose aerodynamic performance and we lose freight capacity because of weight. So we add efficiency to the engine but we take it away from the truck. That doesn't make sense.

"Why would you force us to do something like that? Give us the flexibility to look at the truck as a complete entity and make the best, most cost-effective decisions about how to improve the fuel efficiency in a way that meets the target," Greszler urges.

"I think it's also obvious that a system like that adds a lot of components, a lot of sensors, a lot of complexity, and potentially a lot of unreliability. Which customers don't want or need. And if you're not getting the full benefit from it anyway, you're really kidding yourself when you measure the efficiency of the engine in a test cell where weight, space, and cooling demand are not accounted for at all."

Waste heat recovery is just an example, of course, and there might be any number of similar examples that could come up in the future.

"A particular customer could well benefit from efficiency improvements that have nothing to do with the engine and hit the overall targets that EPA will establish," Greszler continues. "Are we going to force him into engine efficiency solutions that don't necessarily match his operational requirements because EPA structured a rule that said X amount had to come from the engine? It just doesn't make sense to us."

Depending on the stringency of the coming rules, and whether or not we have a separate engine test, waste-heat recovery may or may not be needed.

"If we have a fairly stringent engine efficiency requirement measured in a test cell, then WHR may be the only available technology to meet that target," Greszler says. "If it's not applied to the engine but to the truck, we may find quite a few other options.

"We're all developing waste-heat recovery," he adds, "don't get me wrong. I'm not saying it's a technology that shouldn't be explored and exploited when and where it makes sense, but it ought not be forced into production on a time schedule that doesn't allow adequate reliability development and it shouldn't be forced into applications where it doesn't really deliver."

So, much remains to be seen on this topic, and given how much information couldn't be packed into this space, a Part Three seems to be in order. Stay tuned.

This email has been scanned for Malware.

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/19/2016 5:34:23 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: 4/7 Collaboration Call Notes

Participants:

- Allison – Scott Mundy
- Caterpillar –
- Cummins – Manik Narula, Jackie Yeager
- Daimler – Gerald Freitag, Don Keski, Inderpal Singh
- Eaton –
- EMA – Tim Blubaugh
- EPA – Houshun Zhang, James Sanchez, Matt Spears
- Hino – Tom Manley
- Navistar – Dave Gardner
- PACCAR – Mark Malowicki, Erin Luke, Dan Kieffer, Costi Nedelcu
- Volvo – Marc Miller, Tim Connors, Tony Greszler, Chuck Kaslavage, Steve Berry

Discussion and follow-up items (with owner's name in **bold**):

- ISL engine test results – Manik
    - Cummins presented cycle average map test results for ISL 450 and 300 hp ratings – see slides emailed previously
    - Cycle average map performance matches that of steady state map on cruise cycles
- Addressing N/V overlap – Manik
    - Cummins presented example of how to revise generic vehicle definition to prevent N/V overlap – see slides emailed previously
    - EPA asked companies to consider options of 1) adding generic vehicle configurations, or 2) selecting custom vehicle configurations instead of generic
    - Discussion about how to certify vehicles not designed to reach 65 or 55 mph
- Road grade profiles – EPA

- Discussion about a couple options for further modifying the cycles to better match time at peak torque in-use:
  - Add miles at zero grade, or
  - Reduce grade by a fixed percentage (same effect as reducing vehicle mass)

Topics for future calls:

- (TBD) SwRI results (N13 365, gasoline engine) – Houshun
- (4/21) Road grade evaluation – TBD

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
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jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/20/2015 6:59:52 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 4/16 Phase 2 Collaboration Call Notes

Reminder, please review the SAE paper draft that Gary Salemme shared and provide feedback to him by Tuesday, April 21.

Participants:
- Cummins – Jackie Yeager, Manik Narula
- Eaton –
- EPA – James Sanchez, Houshun Zhang
- Navistar – Matt Hunkler
- PACCAR – Dan Kieffer
- Allison –

Discussion and follow-up items (with owner's name in **bold**):
- Group was small and meeting was short due to multiple conflicts with other meetings
- EPA draft SAE paper – Houshun
  - Undergoing internal EPA review
- Industry draft SAE paper – Cummins
  - Gary circulated draft earlier in the week. Please provide feedback by April 21 so he can start incorporating changes in order to submit the first draft to SAE by 4/28 – **All**
  - Check on possibility to include 1-2 paragraphs summarizing the Navistar generic vehicle analysis reviewed on 3/19 – **Matt H.**

Topics for future calls:
- (4/23) EPA draft SAE paper – Houshun
- (4/23) Industry draft SAE paper – Cummins
- (TBD) Update on Cummins fntest data – Jackie
- (TBD) Engine cert ideas – Cummins
- (TBD) Update on powertrain family concept – Matt S.
- (TBD) Update on transient correction factor in primary approach – Matt S.

Regards,
Jackie Yeager
Global Energy Policy Director

Environmental Strategy and Compliance
Cummins Inc.
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jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/19/2016 5:32:42 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: Phase 2 Collaboration meeting agenda
Attachments: Joining Skype for Business Meetings (External).pdf

Reminder of Thursday's call at 3:00 pm Eastern. I only heard from a couple people who had conflicts due to the EMA workshop, so let's stick with our regular day and time.

Proposed agenda:

1. ISB and N13 testing at SwRI – Houshun
2. Road grade evaluation – TBD
3. Other topics?
4. Plan next call – All

Call-in and Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

For non-Cummins participants:

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For Cummins participants:

→ Join Skype Meeting

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Audio for this Skype for Business meeting is available using a computer or the phone dial-in bridge. Cummins Skype Advanced users should select "Use Skype for Business (full audio and video experience)" when using their PCs to connect to the meeting audio. Cummins Skype Standard users should select "Don't Join Audio" and dial into the phone bridge.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
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jackie.m.yeager@cummins.com

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/16/2015 1:29:46 AM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 3/19 Phase 2 Collaboration Call Notes

(Just catching up on some meeting notes that I missed awhile back)

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton –
- EPA – James Sanchez, Houshun Zhang
- Navistar – Cortney Guzlas, Matt Hunkler, Dave Gardner
- PACCAR – Dan Kieffer, Tom Sloane
- Allison – Jeff Shultz, Mike Howenstein

Discussion and follow-up items (with owner's name in **bold**):

- Navistar vehicle analysis – Matt H.
    - Matt reviewed his analysis of different methods of selecting the 9 generic vehicle configurations – conclusions below:

Conclusions

NAVISTAR
Integrated Product Development

- The accuracy and error distribution of each of the different 9 point methods is relatively similar and it does not appear to be biased by point selection.
- The even selection method provided the best overall fit and coverage. (higher r^2, lower MSE)
- The method of point selection is not entirely straight forward when applied to a population at large and may require further refinement.
- The overall weighted average error of the EPA method has most values within plus-minus 1%.
- The neighborhood selection techniques had a high number of points requiring extrapolation. This may not be desired.
  - Even the EPA method has 10% extrapolation
- Might require more points for better fit, there are large sections of data with few points.

DRAFT NOT FOR PUBLICATION

- Error for generic vehicle selection using cycle composite – James
  - James compared errors using weighted cycle composites to errors of individual cycles (see Powerpoint emailed by James) – not significantly different

Topics for future calls:

- (TBD) Comparison of 1 Hz and 10 Hz – Manik
- (TBD) Update on Cummins fntest data – Jackie
- (TBD) Engine cert ideas – Cummins
- (TBD) Update on powertrain family concept – Matt S.
- (TBD) Update on transient correction factor in primary approach – Matt S.

Regards,

Jackie Yeager
Global Energy Policy Director
Environmental Strategy and Compliance
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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/16/2015 1:28:32 AM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 4/9 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – James Sanchez, Houshun Zhang, Matt Spears
- Navistar – Cortney Guzlas, Dave Gardner
- PACCAR – Erin Luke, Dan Kieffer
- Allison – Jeff Shultz

Discussion and follow-up items (with owner's name in **bold**):

- Analysis of 1 Hz, 5 Hz, 10 Hz – Erik
    - Erik presented a comparison of data analyzed at 10, 5, and 1 Hz, where the 5 Hz and 1 Hz data was an average of 2 and 10 points, respectively, to represent logging the data at lower frequency
    - Results support logging data at lower than 10 Hz – for example, command speed/torque at 10 or 5 Hz and log at 1 Hz – which would not drive a change to Part 1065
- Update on EPA SAE paper – Houshun
    - Discussed status of EPA and industry drafts
    - Will request a 2 week extension for turning in the first drafts (extension to April 28)
    - Share drafts with group by early next week to start reviewing – **Houshun, Gary**
    - Share latest draft of Eaton technical report – **Erik**

Topics for future calls:

- (4/16) EPA draft SAE paper – Houshun
- (4/16) Industry draft SAE paper – Gary/Cummins
- (TBD) Update on Cummins fntest data – Jackie
- (TBD) Engine cert ideas – Cummins
- (TBD) Update on powertrain family concept – Matt S.
- (TBD) Update on transient correction factor in primary approach – Matt S.

Regards,
Jackie Yeager
Global Energy Policy Director

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/16/2015 1:27:50 AM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: Phase 2 Collaboration meeting agenda

Reminder of tomorrow's call at 3:00-4:00 pm Eastern.

Proposed agenda:
1. EPA draft SAE paper – Houshun
2. Industry draft SAE paper – Jackie
3. Other topics?
4. Plan next week's call

Call-in and Webex information:
Teleconference:
US toll-free personal phone / Ex. 6
Access code personal phone / Ex. 6

Topic: Phase 2 Collaboration Mtg
Date: Every Thursday, from Thursday, December 18, 2014, to no end date
Time: 3:00 pm, Eastern Standard Time (New York, GMT-05:00)
Meeting number: personal phone / Ex. 6
Meeting password: personal phone / Ex. 6

Please click the link below to see more information about the meeting, including its agenda, or to join the meeting.

Ex. 6

Regards,
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Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 7/13/2015 4:49:12 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Baker (bbaker@aanddtech.com) [bbaker@aanddtech.com]; Bill Martin (w.t.martin7019@outlook.com) [w.t.martin7019@outlook.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Meyerkord [daniel.j.meyerkord@emdiesels.com]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com)

[mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard (mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Carnegie [william.carnegie@ge.com]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

CC: Shirish A Shimpi [shirish.a.shimpi@cummins.com]

Subject: EMA - EMTC, CARB, EPA & Others - June 10-11, 2015, EMTC Meeting Minutes and Attachments

Attachments: ITR_Presentation to EMTC_6-10-15.pdf; June 10-11 EMTC Meeting Attendance List.pdf; RoundRobinEngine-TestSchedule-20150608.xlsx; RRSummary-Combined-20150608.xlsx; SAE TEVEM Update (2015_06_11).pdf; Torque-Curve_Compare-RREngine-20150608.xlsx; 2015-06-10 to 11 EMTC - Agenda.pdf; EMA Round Robin Testing Results_Caterpillar.pdf; RR_Results_Navistar_ 06_11_15.pdf; EMTC-2014-VeryLowNOxProgram-20150609.pdf

TO: Engine Emissions Measurement & Testing Committee
(EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: July 13, 2015

RE: **June 10-11, EMTC Meeting Minutes and Attachments**

Attached are the June 10-11, EMTC meeting minutes and attachments.

If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave

Columbus, Indiana 47201
Office: (812) 377-7532
Cell: personnel / Ex. 6

Andjelka Vujovic
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333 West Wacker Drive ▪ Suite 810
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avujovic@emamail.org

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EMTC MEETING JUNE 11 2015

	NAME	AFFILIATION
1	SHIRISH SHIMPI	CUMMINS
2	PALAK PATEL	CUMMINS
3	CAROL SMITH	ISUZU
4	GRANVILLE HAYWORTH	TENNECO
5	Steve Mayotte	EPA
6	TUEBIN WU	Cummins
7	Costi Nedelcu	PACCAR
8	Steve Yarosz	ISUZU
9	Victor MIRANDA	NAVISTAR
10	HENRY NG	TxCEF
11	RYAN PARCELL	CAT
12	Joel Souire	Cat
13	DAVE MURDAY	HORIBA
14	Brian Mace	HORIBA
15	Kevin Reiss	John Deele
16	Mike Akard	Horiba
17	Doug Sobotka	Excel Engineering
18	MICHAEL TRAVER	ARAMCO
19	Bertrand Lauber	Sensors, Inc.
20	Zack Muter	Volvo
21	Chris Sharp	SWRI
22	Steve Klick	ACS
23	ANDREAS BURGER	MTU America
24	Matt Swanson	CAI
25	Sam Cao	Cummins
26	Chris Laroo	EPA

Attendance via Conference call:

Hector Maldonado; Mike May; Bill Martin; Dave Hortsman; Don Nagy; William Robertson, Radha Purushothaman - others not recorded.

EMTC Meeting June 10, 2015

	Name	Affiliation
1.	Shirish Shimpi	Cummins
2.	PALAK PATEL	CUMMINS
3.	Chet Mun Liew	Cummins
4.	GRANVILLE WAKWORTH	TENNECO
5	Steve Mayotte	EPA
6.	Yuebin Wu	Cummins
7.	ANDREAS BURGER	MTU America
8.	COSTI HEDUCU	PACCAR
9.	HENRY NG	TxCEF
10.	Brian Mace	HORIBA
11.	Kevin Reiss	John Deere
12.	RYAN PARCELL	CATERPILLAR
13.	Joel Squire	Caterpillar
14.	Mike Akard	Horiba Inst.
15.	VICTOR MIRANDA	NAVISTAR
16.	Doug Sobotka	Excel Engineering
17.	Bertrand Lauhar	Sensors, Inc.
18.	Zack Muter	Volvo
19.	Chris Sharp	SwRI
20.	Steve Klick	ACS
21.	Matt Swanson	CAI
22.	Tanfang (SAM) Cao	Cummins.
23.	CAROL SMITH	ISUZU
24.	Steve Yarosz	"
25.	Chris Laroo	EPA

	Facility	Planned Test Date	Status	Contact	Expected Engine Arrival	Notes
Year 1	EPA	March 2014	Complete	Ruonan Sun		
	SwRI	May 2014	Complete	Chris Sharp		
	Intertek	July 2014	Complete	Dave Horstman		
	SGS	August-Sep 2014	Complete	Keith Vertin		
	Cummins	Sep-Oct 2014	Complete	Shirish Shimpi / Bill Martin		
	IAV	Nov-Dec 2014	Complete	Paolo DiMartino	11/12/2014	testing after turbo damage with new turbo
	Original Isuzu test event postponed due to turbo damage				IAV testing completed by early Feb 1, 2015	
Planned Year 2	Caterpillar	mid March 2015	Complete	Ryan Parcell	3/4/2015	test cell avail 3/16/2015
	Navistar	mid April 2015	Complete	Victor Miranda	4/20/2015	arrived by May 2015
	EPA	mid May 2015	In Progress	Ruonan Sun	6/27/2015	
	Volvo	August 2015	Planned	Zack Murter	8/15/2015	
	Isuzu	Sep-Oct 2015	Planned	Carol Smith	9/26/2015	
	Ricardo	Nov-Dec 2015	Planned	Mike May	11/7/2015	

Note: Expected Engine Arrival is based on a 6 to 7-week turnaround at each facility from engine arrival, including shipping time to next facility.

Pending Requests (not yet officially added to the schedule)

Tenneco	Q4 2015 or Q1 2016	Requested	Granville Hayworth	now likely Q1 2016
Ford	Q4 2015 or Q1 2016	Requested	Travis Henney	Q1 2016 ?
Hino	?	Requested	Yukitake Kudo	

? Environment Canada
? Other International labs
? WVU
? CE-CERT

Vehicle and Engine Emissions Standards Committee (SAE TEVEM)

Update to EMA-EMTC
Ann Arbor, MI 6/11/2015

SAE J2992 - FTIR GAS ANALYZER – Performance Evaluation / Qualification for Automotive Testing

The standard is intended to offer best practices for the use of Fourier Transform Infrared (FTIR) spectrometry in engine exhaust emissions testing.

Published and now available at http://www.sae.org/technical/standards/J2992_201504

Thanks go out to Barb Marshik and Dan Sales for leading this effort.

SAE INTERNATIONAL

SURFACE VEHICLE STANDARD	J2992	APR2015
	Issued	2015-04

FTIR Gas Analyzer Performance Evaluation / Qualification for Automotive Testing

RATIONALE

Over the past several decades, manufacturers have made great strides in reducing emissions and improving fuel efficiency of the modern internal combustion engine. Integral to these improvements has been the use of various emissions monitoring equipment to test, verify and certify the improvements. As industry compliance standards become ever more stringent, the need for new capabilities has fueled automotive emissions engineers to utilize alternate technologies for monitoring gaseous emissions. The Fourier Transform Infrared (FTIR) gas analyzer is one example of a technology that shows much promise in meeting the needs of the modern emissions engineer. As use of FTIR analyzers become more widespread in both R&D and Certification, there is a growing need for an SAE standard to provide recommended practices and minimum performance standards for the analyzer in various automotive related applications.

This document is to be used as a guideline for the use of Fourier Transform Infrared (FTIR) spectrometry in engine exhaust certification testing as well as engine and vehicle development activities. The goal is to create a best practice that follows the concepts and procedures as laid out in EPA document 40 CFR Part 1065 for Engine emissions testing but applied to a multi-component FTIR analyzer. This document contains instructions on how to perform and certify the various stages of the verification testing as well as what needs to be done after major maintenance and other interruptions as defined by Part 1065. By using this procedure one can verify the ability of the FTIR and sampling system to measure multiple gases in the presence of interfering constituents such as high concentration components like water and carbon dioxide. The FTIR system chosen for this application should have the necessary sensitivity and linearity across the full range of concentration values for each of the selected exhaust species that will be seen for each particular engine test encountered. The full range is defined by the specific EPA standard for the test or the end user requirements whichever is greater.

Since the FTIR can monitor multiple components simultaneously, pre-validating procedures as described below are implemented and utilized to initially validate the technology as well as provide routine tests that ensure compliance after implementation of the integrated system. Because all the infrared (IR) active exhaust components are measured at the same time without any chemical reaction, any potential interference observed can normally be reduced or eliminated by modifying the analytical method recorded in the software and / or by reducing the internal pressure of the gas cell. If interference is noted during the verification process, all the data collected can be reprocessed against an updated method (provided the overall system pressure and concentrations remains the same) to demonstrate that the interference has been reduced or eliminated to acceptable levels.

Once the FTIR validation has been completed, there will be sufficient data to support the use of FTIR in order to meet the existing 1065 emission performance requirements.

Note that it is the responsibility of the user to ensure that the equipment used for certification testing is approved by the appropriate certification authorities.

SAE values your input. To provide feedback on this Technical Report, please visit

J2943 Particulate Filter Weigh Room Recommended Practice

- Development Status:
  - Substantial portion of document in place
  - <u>Seeking input and experience from active laboratories</u>
  - Experts with knowledge of Weigh Room construction and Weighing Procedures sought for input to standard
- Schedule:
  - Draft document targeted for Q4 2015
  - Possible standard publication in 2016

J2943 Particulate Filter Weigh Room Standard

Section	Description	% complete
1	**Scope**	100%
2	**Background**	100%
3	**Filter Conditioning and Weighing Requirements**	
3.1	Filter Storage	100%
3.2	Filter Conditioning	100%
3.3	Filter Handling	100%
3.3.1	Filter Inspection	100%
3.3.2	Filter Handling Procedures	100%
3.3.3	Static Neutralization Procedures	100%
3.4	Weigh Room Operating Procedures	
3.4.1	Operator Wardrobe	90%
3.4.2	Operator Procedures	70%
3.5	Weighing Process	
3.5.1	Weighing Techniques	90%
3.5.2	Reference Filter Weighing	90%
3.5.3	Traceable Reference Weighing	90%
3.5.4	Sample Filter Weighing	90%
3.5.5	Auto Filter Weighing	60%
4	**Microbalance Requirements / Recommendations**	
4.1	Microbalance Specifications	90%
4.2	Microbalance Calibration	
4.2.1	Calibration Procedures	90%
4.2.2	Calibration Intervals	90%
5	**Management System/Quality Control**	
5.1	Data Acquisition	100%
5.2	Documentation Control	100%
5.2.1	Data	100%
5.2.2	Reports and Documents	100%
5.2.3	Update of Reports and Modification of Document	100%
5.3	Filter Tracking	
5.3.1	Serialized Tracking	100%
5.3.2	Positive Identification for Filters	100%
5.3.3	Transportation/Possession of Filters after Sampling	100%
5.3.4	Environmental Stabilization Time and Certification	100%
5.4	Data Validation/Uncertainty	
5.4.1	Data Validation	100%
5.4.2	Measurement Error	100%
5.4.3	Recommendations of Practices	100%
6	**Particulate Filter Weigh Room**	
6.1	Room Layout	
6.1.1	Functional Separation	70%
6.1.2	Equipment Placement	90%
6.2	Room Design Specifications	
6.2.1	Design considerations	90%
6.2.2	Materials of construction	0%
6.2.3	Vibration Specifications	5%
6.2.4	Static Charge Specifications	50%
6.2.5	Lighting	0%
6.2.6	Flooring	0%
6.3	Environmental Specifications	
6.3.1	Temperature Specifications	0%
6.3.2	Humidity Specifications	0%
6.3.3	Ambient Particulate Specifications	0%
6.3.4	Air Velocity	0%
6.3.5	Sound Specification (?)	0%
7	**Weigh Room Maintenance Recommendations**	
7.1	Temperature Calibration	
7.1.3	Calibration intervals	90%
7.1.4	Calibration Reference Equipment	90%
7.2	Humidity Calibration	
7.2.3	Calibration intervals	90%
7.2.4	Calibration Reference Equipment	90%
7.3	Pressure Calibration	
7.3.3	Calibration intervals	90%
7.3.4	Calibration Reference Equipment	90%
7.4	HVAC	
7.4.1	HVAC Air System	
a.	System down maintenance	90%
b.	Change HEPA filter	90%
7.4.2	HVAC Water System	90%
7.4.3	Filter Change criteria	90%
7.4.4	Temperature Control System Maintenance	90%
7.5	Maintenance	
7.5.1	Floor	90%
7.5.2	Walls/ Tables	90%
7.5.3	Anti-Static Floor	90%

New Activities

- Soot Measurement Calibration
  - Review of latest technologies for measuring particulate and defining what is being measured
  - Initial concept under consideration with focus on device calibration method and/or definition tied to elemental carbon

- Particle Number Calibration
  - Review of latest regulatory and procedural information from Europe
  - Activities in Europe focused on minimizing variability in measurement process
  - Possible need for Standard/Recommended Practice on setup procedure to improve confidence in measurement

- EMA, EPA and ARB will be invited to provide comments on PM/PN methods prior to any SAE standard initiation process

New Activities

- Zero Air Generator Standard
  - Inquiries to manufacturers underway including SPX and Parker regarding level of interest and willingness to participate
  - Seeking comments from industry on possible scope of Recommended Practice or Standard
  - Information on System Providers and related contact information requested

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 2/5/2015 9:31:28 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: RE: GHG Phase II

Flag: Follow up

Hi Bill,

Do you have some potential dates for the meetings?

Thanks and regards,

Tim

From: Charmley, William [mailto:charmley.william@epa.gov]
Sent: Thursday, January 29, 2015 4:22 AM
To: Timothy A. Blubaugh
Subject: Re: GHG Phase II

Tim,

The answer to both questions is yes.

Give me a few days and we will get back with you on some potential dates and times.

Do you think the TEMA members are willing to come to Michigan for these two discussions?

Thanks
Bill

Sent from my BlackBerry 10 smartphone on the Verizon Wireless 4G LTE network.

From: Timothy A. Blubaugh
Sent: Wednesday, January 28, 2015 5:54 PM
To: Charmley, William
Subject: GHG Phase II

Hi Bill,

Deliberative Process / Ex. 5

Deliberative Process / Ex. 5

If it would be easier to chat over the telephone, please give me a call. Office: (312) 929-1972. Mobile: personnel / Ex. 6

Best,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
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Message

From: Andjelka Vujovic [AVujovic@emamail.org]
Sent: 3/18/2016 3:29:03 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Martin (bmartin@cybermetrix.com) [bmartin@cybermetrix.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov;

Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard (mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; NICHOLAS.BELLOVARY@sgs.com; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni (thomaslanni@gmail.com) [thomaslanni@gmail.com]; Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]

Subject: EMA - EMTC, CARB, EPA & Others - Part 1065 and Standard Setting Part Documents

Attachments: 40 CFR Part 1065 Engine Test Procedures Working Document 3-14-16 Staff Draft.pdf; Standard Setting Part Sections Draft 3-14-16.pdf

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: March 18, 2016

RE: **Part 1065 and Standard Setting Part Documents**

Please see the attached documents from EPA's Chris Laroo. If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave
Columbus, Indiana 47201
Office: (812) 377-7532
Cell: personnel / Ex. 6

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 3/5/2015 7:28:26 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: RE: Phase 2 Collaboration meeting agenda
Attachments: Industry paper outline v0.docx

One more document for discussion on today's call – draft outline for industry paper.

From: Jackie M Yeager
Sent: Thursday, March 05, 2015 9:08 AM
To: 'Brian C Mormino'; 'charmley.william@epa.gov'; 'Cortney.Guzlas@Navistar.com'; 'dan.kieffer@paccar.com'; 'David.Majors@Navistar.com'; 'Gary C Salemme'; 'Matthew.Hunkler@Navistar.com'; 'MihaiDorobantu@eaton.com'; 'Morgan Andreae'; 'spears.matthew@epa.gov'; 'Zhang.Houshun@epa.gov'; 'david.gardner@navistar.com'; 'debbie.gordon@allisontransmission.com'; 'ErikDykes@eaton.com'; 'erin.luke@paccar.com'; 'Manik Narula'; 'MatthewRBusdiecker@eaton.com'; 'michael.j.howenstein@allisontransmission.com'; 'Sanchez.james@Epa.gov'; 'tom.sloane@paccar.com'; 'Jeffrey.shultz@allisontransmission.com'
Subject: Phase 2 Collaboration meeting agenda

Reminder of today's call at 3:00-4:00 pm Eastern.

Proposed agenda:
1. Regression analysis update – Erik
2. Comparison of 1 Hz and 10 Hz – Manik
3. Results with adding 10th point to map – James
4. Industry paper outline – Jackie
5. Other topics?
6. Plan next week's call

Call-in and Webex information:
Teleconference:
US toll-free Personal Phone / Ex. 6
Access code

Topic: Phase 2 Collaboration Mtg
Date: Every Thursday, from Thursday, December 18, 2014, to no end date
Time: 3:00 pm, Eastern Standard Time (New York, GMT-05:00)
Meeting number: personnel / Ex. 6
Meeting password: personnel / Ex. 6

Please click the link below to see more information about the meeting, including its agenda, or to join the meeting.

Ex. 6

Regards,
Jackie Yeager
Global Energy Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personnel / Ex. 6
jackie.m.yeager@cummins.com

Outline of Industry Paper
March 5, 2015

- **Paper Number** – 2015-xx-xxxx (15CV-0222)
- **Title** – Alternative Engine/Powertrain Mapping Approach for Simulation of Vehicle CO_2 Emissions
- **Author List**
  - Gary Salemme, Cummins Inc.
  - Erik Dykes, Eaton
  - Daniel Kieffer, PACCAR Inc.
  - Michael Howenstein, Allison Transmission Inc.
  - Matthew Hunkler, Navistar
- **Abstract** (see draft below)
- **Introduction**
  - Traditional Steady-State Fuel Map Approach
  - Challenges with Traditional Approach
  - Alternative Cycle Average Map Approach
  - Related Work (reference to EPA paper)
  - Overview of Paper
- **[Body of paper]**
  - Experimental Results
    - Engine Mapping
      - Hardware
      - Test Procedure (including test cycles)
      - Test Results (engine cycle average map)
      - Analysis (accuracy vs. steady-state map)
    - Powertrain Mapping
      - Hardware
      - Test Procedure (including test cycles)
      - Results (powertrain cycle average map)
      - Analysis
  - Procedure for Simulating Vehicle CO_2
    - Definition of Generic Vehicles
    - Generating Test Cycles
    - Mapping the Engine/Powertrain (test time estimates)
    - Simulating Specific Vehicle CO_2 (refer to interpolation/extrapolation in EPA paper)
- **Summary/Conclusions**
  - Summary
  - Advantages of Alternative Approach in CO_2 Regulation
  - Future Work
- **References**
- **Contact Information** (optional section per SAE guidelines)
- **Acknowledgements** (optional section per SAE guidelines)
- **Definitions/Abbreviations** (optional section per SAE guidelines)
- **Appendices** (optional section per SAE guidelines)

Draft abstract:

Simulations used to estimate carbon dioxide (CO_2) emissions and fuel consumption of medium- and heavy-duty vehicles over prescribed drive cycles often employ engine fuel maps consisting of engine measurements at numerous steady-state operating conditions. However, simulating the engine in this way has limitations as engine controls become more complex, particularly when attempting to use steady-state measurements to represent transient operation. This paper explores an alternative approach to vehicle simulation that uses a "cycle average" engine map rather than a steady state engine fuel map. The map contains engine CO_2 values measured on an engine dynamometer on cycles derived from vehicle drive cycles for a range of generic vehicles. A similar cycle average mapping approach is developed for a powertrain (engine and transmission) tested together in order to show the specific CO_2 improvements due to powertrain integration and optimization that would not otherwise be recognized in simulation, engine testing, or full vehicle evaluation. While a related paper entitled "Alternative Vehicle Certification Procedure" focuses primarily on simulation results, this paper summarizes the associated experimental results. Test results for an engine and a powertrain demonstrate the cycle average map is a smooth, continuous surface in each case. The paper also compares accuracy of using the steady-state engine map versus the cycle average engine map, with the cycle average map performing similarly or better, depending on drive cycle. Advantages of using the cycle average map for vehicle simulation in the context of CO_2 regulations are also discussed.

Key SAE dates:

Review Ready Manuscript Date:	Apr 14, 2015
Organizer Approval Date:	Jul 21, 2015
Final Manuscript Due Date:	Aug 03, 2015

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 5/5/2016 4:46:59 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; scott.mundy@allisontransmission.com; Thomas Manley [Thomas.Manley@HMMUSA.COM]
Subject: FW: Draft Final Road Grade Profile for HD Phase 2, please distribute
Attachments: Road Grade Profile Draft Final.xlsx

All – EPA has asked me to share this draft road grade file with the Collaboration Group distribution list. Please see attached.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone personal phone / Ex. 6
jackie.m.yeager@cummins.com

From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Thursday, May 5, 2016 12:18 PM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>; Timothy A. Blubaugh <TBlubaugh@emamail.org>
Cc: Sanchez, James <sanchez.james@epa.gov>; Zhang, Houshun <Zhang.Houshun@epa.gov>
Subject: Draft Final Road Grade Profile for HD Phase 2, please distribute

Hi Jackie and Tim,

Please find attached an Excel spreadsheet depicting our draft final road grade profile for the Phase 2 55 and 65 mph cycles.

Jackie, would you please distribute this file to your list of participants on our Thursday cycle-average coordination calls? Tim, would you please distribute this file to any EMA members who are not participants on the coordination calls?

If anyone has any individual feedback on this information, please have them reply directly to James, Houshun and me. I should emphasize that we are not seeking any consensus views on this information.

If you receive any requests for an EPA version of this information in a format for use in GEM, please let others know that EPA is currently working toward another GEM debugging release to expert users and that the debugging release will have this road grade information.

We do not yet have a target date set for the next GEM debugging release. Personally, I would guess that a GEM debugging release could be ready within about two weeks from today, but that all depends on how EPA decides to prioritize completing all of our other tasks toward the Final Rule.

Please let me know if you have any questions, thanks.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
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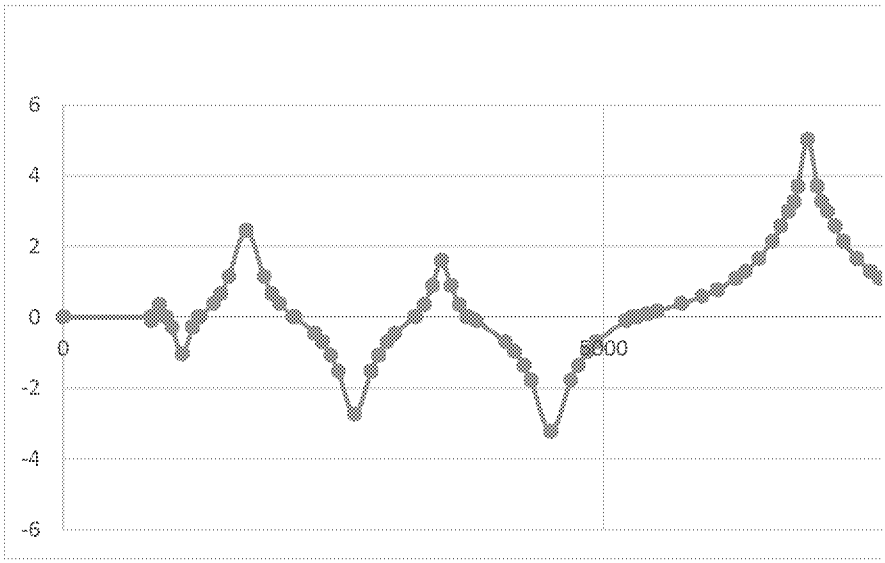
w. 734-214-4921
m. 734-276-7079

Distance (m)	Grade (%)
0	0
804	0
808	0
820	-0.1
832	0
842	0
892	0.36
942	0
952	0
1006	-0.28
1102	-1.04
1198	-0.28
1252	0
1264	0
1390	0.39
1458	0.66
1534	1.15
1696	2.44
1858	1.15
1934	0.66
2002	0.39
2128	0
2146	0
2330	-0.46
2398	-0.69
2478	-1.08
2546	-1.53
2698	-2.75
2850	-1.53
2918	-1.08
2998	-0.69
3066	-0.46
3250	0
3264	0
3340	0.35
3416	0.9
3502	1.59
3588	0.9
3664	0.35
3740	0
3756	0
3822	-0.1
4094	-0.69
4176	-0.97
4262	-1.36
4330	-1.78



4514	-3.23
4698	-1.78
4766	-1.36
4852	-0.97
4934	-0.69
5206	-0.1
5272	0
5322	0
5406	0.1
5498	0.17
5720	0.38
5912	0.58
6052	0.77
6226	1.09
6312	1.29
6436	1.66
6562	2.14
6638	2.57
6710	3
6762	3.27
6800	3.69
6890	5.01
6980	3.69
7018	3.27
7070	3
7142	2.57
7218	2.14
7344	1.66
7468	1.29
7554	1.09
7728	0.77
7868	0.58
8060	0.38
8282	0.17
8374	0.1
8458	0
8502	0
8608	-0.38
8668	-0.69
8852	-2.13
9036	-0.69
9096	-0.38
9202	0
9214	0
9262	0.26
9316	0.7
9370	0.26

9418	0
9428	0
9496	-0.34
9622	-1.33
9748	-0.34
9816	0
9826	0
9914	0.37
9968	0.7
10112	1.85
10256	0.7
10310	0.37
10398	0
10410	0
10498	-0.37
10552	-0.7
10696	-1.85
10840	-0.7
10894	-0.37
10982	0
10992	0
11060	0.34
11186	1.33
11312	0.34
11380	0
11390	0
11438	-0.26
11492	-0.7
11546	-0.26
11594	0
11606	0
11712	0.38
11772	0.69
11956	2.13
12140	0.69
12200	0.38
12306	0
12350	0
12434	-0.1
12526	-0.17
12748	-0.38
12940	-0.58
13080	-0.77
13254	-1.09
13340	-1.29
13464	-1.66
13590	-2.14

13666	-2.57
13738	-3
13790	-3.27
13828	-3.69
13918	-5.01
14008	-3.69
14046	-3.27
14098	-3
14170	-2.57
14246	-2.14
14372	-1.66
14496	-1.29
14582	-1.09
14756	-0.77
14896	-0.58
15088	-0.38
15310	-0.17
15402	-0.1
15486	0
15536	0
15602	0.1
15874	0.69
15956	0.97
16042	1.36
16110	1.78
16294	3.23
16478	1.78
16546	1.36
16632	0.97
16714	0.69
16986	0.1
17052	0
17068	0
17144	-0.35
17220	-0.9
17306	-1.59
17392	-0.9
17468	-0.35
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17558	0
17742	0.46
17810	0.69
17890	1.08
17958	1.53
18110	2.75
18262	1.53
18330	1.08

18410	0.69
18478	0.46
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18680	0
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18950	-1.15
19112	-2.44
19274	-1.15
19350	-0.66
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19556	0
19610	0.28
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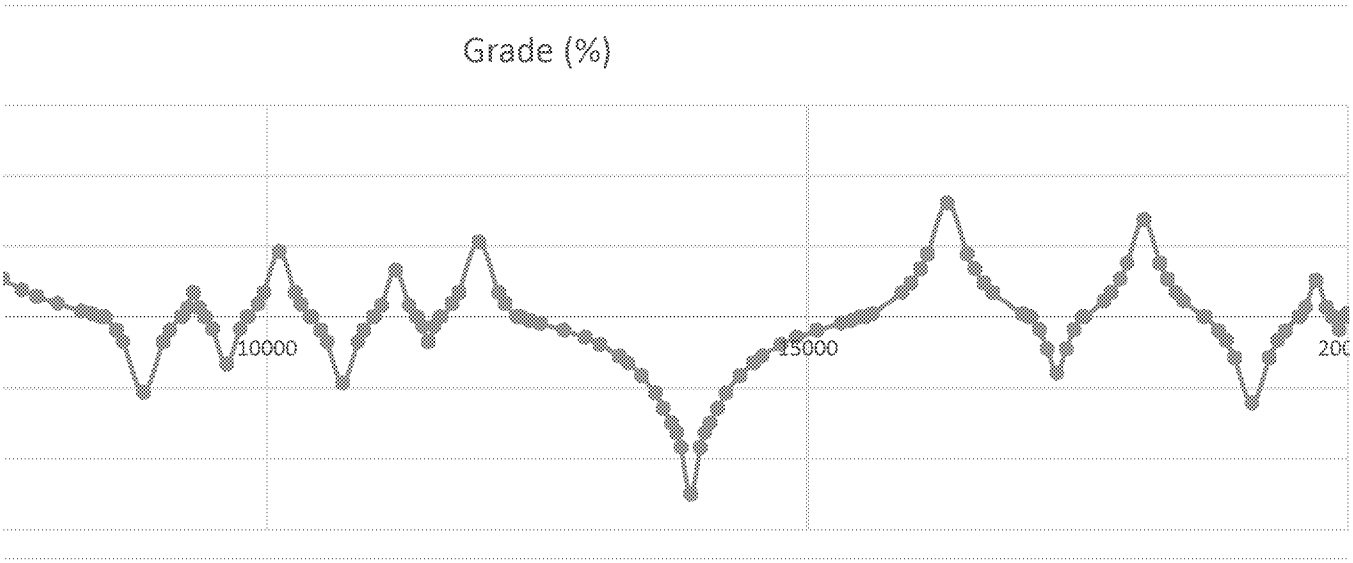
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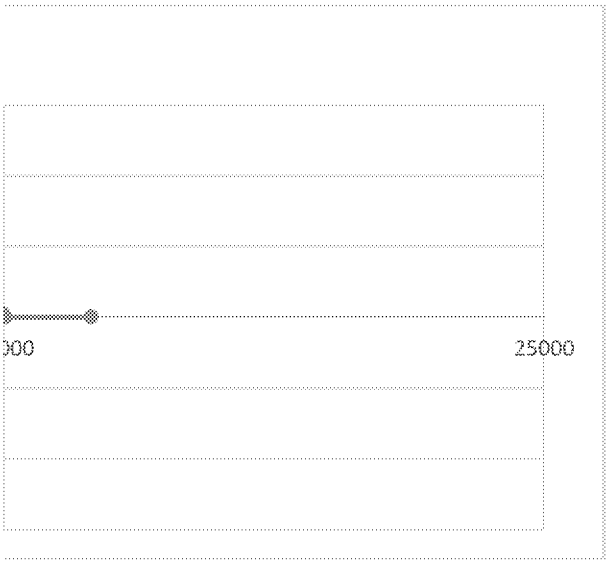
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Message

From: Andjelka Vujovic [avujovic@emamail.org]
Sent: 3/31/2015 2:15:37 PM
To: Schrodt, Thomas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff95d8e17858450682eed1dd06d6abd6-Schrodt, Thomas]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade (bshade@tenneco.com) [bshade@tenneco.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Baker (bbaker@aanddtech.com) [bbaker@aanddtech.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brendan Sherry (brendan.sherry@iav-usa.com) [brendan.sherry@iav-usa.com]; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Meyerkord [daniel.j.meyerkord@emdiesels.com]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; John R Briggs (John.Briggs@procat-testing.com) [John.Briggs@procat-testing.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov;

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Subject: EMA - EMTC, CARB, EPA & Others - Draft 1065 Working Document for Tomorrow's Meeting

Attachments: 40 CFR Part 1065 Engine Test Procedures Working Document 3-27-15 Staff Draft.pdf

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish A. Shimpi

DATE: March 31, 2015

RE: **Draft 1065 Working Document for Tomorrow's Meeting**

Please see the following email and attachment from EPA's Chris Laroo.

If you have any questions, please do not hesitate to contact me.

From: Laroo, Chris [mailto:laroo.chris@epa.gov]
Sent: Friday, March 27, 2015 2:00 PM
To: Shirish A Shimpi
Cc: Sanchez, James; Bill T Martin
Subject: Draft 1065 Working Document for Next Week's Meeting

Shirish,

Attached please find an updated draft 1065 working document for circulation to EMTC members. Members should specifically pay attention to 1065.655 and 1065.680, as changes were made to address dual-fuel engines and IRAF respectively.

Regards,

Chris Laroo
Environmental Protection Specialist
US Environmental Protection Agency
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Assessment and Standards Division
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Ann Arbor, MI 48105
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This email has been scanned for Malware.

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40 CFR Part 1065

Engine-Testing Procedures

DRAFT Working Document

(Change Tracking – HD GHG Phase 2 NPRM, Non-Road HDIUT NPRM)

3/27/15

TITLE 40—Protection of Environment

CHAPTER I—ENVIRONMENTAL PROTECTION AGENCY (CONTINUED)

SUBCHAPTER U—AIR POLLUTION CONTROLS

Part 1065—ENGINE-TESTING PROCEDURES

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PART 1065—ENGINE-TESTING PROCEDURES

Subpart A—APPLICABILITY AND GENERAL PROVISIONS

§ 1065.1 Applicability.

(a) This part describes the procedures that apply to testing we require for the following engines or for vehicles using the following engines:
(1) Locomotives we regulate under 40 CFR part 1033. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 92 according to § 1065.10.
(2) Model year 2010 and later heavy-duty highway engines we regulate under 40 CFR part 86. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 86, subpart N, according to § 1065.10.
(3) Nonroad diesel engines we regulate under 40 CFR part 1039 and stationary diesel engines that are certified to the standards in 40 CFR part 1039 as specified in 40 CFR part 60, subpart IIII. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 89 according to § 1065.10.
(4) Marine diesel engines we regulate under 40 CFR part 1042. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 94 according to § 1065.10.
(5) Marine spark-ignition engines we regulate under 40 CFR part 1045. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 91 according to § 1065.10.
(6) Large nonroad spark-ignition engines we regulate under 40 CFR part 1048, and stationary engines that are certified to the standards in 40 CFR part 1048 or as otherwise specified in 40 CFR part 60, subpart JJJJ.
(7) Vehicles we regulate under 40 CFR part 1051 (such as snowmobiles and off-highway motorcycles) based on engine testing. See 40 CFR part 1051, subpart F, for standards and procedures that are based on vehicle testing.
(8) Small nonroad spark-ignition engines we regulate under 40 CFR part 1054 and stationary engines that are certified to the standards in 40 CFR part 1054 as specified in 40 CFR part 60, subpart JJJJ. For earlier model years, manufacturers may use the test procedures in this part or those specified in 40 CFR part 90 according to § 1065.10.
(b) The procedures of this part may apply to other types of engines, as described in this part and in the standard-setting part.
(c) The term "you" means anyone performing testing under this part other than EPA.
(1) This part is addressed primarily to manufacturers of engines, vehicles, equipment, and vessels, but it applies equally to anyone who does testing under this part for such manufacturers.
(2) This part applies to any manufacturer or supplier of test equipment, instruments, supplies, or any other goods or services related to the procedures, requirements, recommendations, or options in this part.
(d) Paragraph (a) of this section identifies the parts of the CFR that define emission standards and other requirements for particular types of engines. In this part, we refer to each of these other parts generically as the "standard-setting part." For example, 40 CFR part 1051 is always the standard-setting part for snowmobiles. Note that while 40 CFR part 86 is the standard-setting

part for heavy-duty highway engines, this refers specifically to 40 CFR part 86, subpart A, and to certain portions of 40 CFR part 86, subpart N, as described in 40 CFR 86.1301.
(e) Unless we specify otherwise, the terms "procedures" and "test procedures" in this part include all aspects of engine testing, including the equipment specifications, calibrations, calculations, and other protocols and procedural specifications needed to measure emissions.
(f) For vehicles, equipment, or vessels subject to this part and regulated under vehicle-based, equipment-based, or vessel-based standards, use good engineering judgment to interpret the term "engine" in this part to include vehicles, equipment, or vessels, where appropriate.
(g) For additional information regarding these test procedures, visit our Web site at www.epa.gov, and in particular http://www.epa.gov/nvfel/testing/regulations.htm.
(h) This part describes procedures and specifications for measuring an engine's exhaust emissions. While the measurements are geared toward engine-based measurements (in units of g/kW·hr), many of these provisions apply equally to vehicle-based measurements (in units of g/mile or g/kilometer). 40 CFR part 1066 describes the analogous procedures for vehicle-based emission measurements, and in many cases states that specific provisions of this part 1065 also apply for those vehicle-based measurements. Where material from this part 1065 applies for vehicle-based measurements under 40 CFR part 1066, it is sometimes necessary to include parenthetical statements in this part 1065 to properly cite secondary references that are different for vehicle-based testing. See 40 CFR part 1066 and the standard-setting part for additional information.

§ 1065.2 Submitting information to EPA under this part.
(a) You are responsible for statements and information in your applications for certification, requests for approved procedures, selective enforcement audits, laboratory audits, production-line test reports, field test reports, or any other statements you make to us related to this part 1065. If you provide statements or information to someone for submission to EPA, you are responsible for these statements and information as if you had submitted them to EPA yourself.
(b) In the standard-setting part and in 40 CFR 1068.101, we describe your obligation to report truthful and complete information and the consequences of failing to meet this obligation. See also 18 U.S.C. 1001 and 42 U.S.C. 7413(c)(2). This obligation applies whether you submit this information directly to EPA or through someone else.
(c) We may void any certificates or approvals associated with a submission of information if we find that you intentionally submitted false, incomplete, or misleading information. For example, if we find that you intentionally submitted incomplete information to mislead EPA when requesting approval to use alternate test procedures, we may void the certificates for all engines families certified based on emission data collected using the alternate procedures. This would also apply if you ignore data from incomplete tests or from repeat tests with higher emission results.
(d) We may require an authorized representative of your company to approve and sign the submission, and to certify that all the information submitted is accurate and complete. This includes everyone who submits information, including manufacturers and others.
(e) See 40 CFR 1068.10 for provisions related to confidential information. Note however that under 40 CFR 2.301, emission data are generally not eligible for confidential treatment.
(f) Nothing in this part should be interpreted to limit our ability under Clean Air Act section 208 (42 U.S.C. 7542) to verify that engines conform to the regulations.

§ 1065.5 Overview of this part 1065 and its relationship to the standard-setting part.
(a) This part specifies procedures that apply generally to testing various categories of engines. See the standard-setting part for directions in applying specific provisions in this part for a particular type of engine. Before using this part's procedures, read the standard-setting part to answer at least the following questions:
(1) What duty cycles must I use for laboratory testing?
(2) Should I warm up the test engine before measuring emissions, or do I need to measure cold-start emissions during a warm-up segment of the duty cycle?
(3) Which exhaust constituents do I need to measure? Measure all exhaust constituents that are subject to emission standards, any other exhaust constituents needed for calculating emission rates, and any additional exhaust constituents as specified in the standard-setting part. Alternatively, you may omit the measurement of N_2O and CH_4 for an engine, provided it is not subject to an N_2O or CH_4 emission standard. If you omit the measurement of N_2O and CH_4, you must provide other information and/or data that will give us a reasonable basis for estimating the engine's emission rates.
(4) Do any unique specifications apply for test fuels?
(5) What maintenance steps may I take before or between tests on an emission-data engine?
(6) Do any unique requirements apply to stabilizing emission levels on a new engine?
(7) Do any unique requirements apply to test limits, such as ambient temperatures or pressures?
(8) Is field testing required or allowed, and are there different emission standards or procedures that apply to field testing?
(9) Are there any emission standards specified at particular engine-operating conditions or ambient conditions?
(10) Do any unique requirements apply for durability testing?
(b) The testing specifications in the standard-setting part may differ from the specifications in this part. In cases where it is not possible to comply with both the standard-setting part and this part, you must comply with the specifications in the standard-setting part. The standard-setting part may also allow you to deviate from the procedures of this part for other reasons.
(c) The following table shows how this part divides testing specifications into subparts:

TABLE 1 OF § 1065.5—DESCRIPTION OF PART 1065 SUBPARTS

This subpart	Describes these specifications or procedures
Subpart A	Applicability and general provisions.
Subpart B	Equipment for testing.
Subpart C	Measurement instruments for testing.
Subpart D	Calibration and performance verifications for measurement systems.
Subpart E	How to prepare engines for testing, including service accumulation.
Subpart F	How to run an emission test over a predetermined duty cycle.
Subpart G	Test procedure calculations.
Subpart H	Fuels, engine fluids, analytical gases, and other calibration standards.
Subpart I	Special procedures related to oxygenated fuels.
Subpart J	How to test with portable emission measurement systems (PEMS).

§ 1065.10 Other procedures.
(a) Your testing. The procedures in this part apply for all testing you do to show compliance with emission standards, with certain exceptions noted in this section. In some other sections in

this part, we allow you to use other procedures (such as less precise or less accurate procedures) if they do not affect your ability to show that your engines comply with the applicable emission standards. This generally requires emission levels to be far enough below the applicable emission standards so that any errors caused by greater imprecision or inaccuracy do not affect your ability to state unconditionally that the engines meet all applicable emission standards.
(b) Our testing. These procedures generally apply for testing that we do to determine if your engines comply with applicable emission standards. We may perform other testing as allowed by the Act.
(c) Exceptions. We may allow or require you to use procedures other than those specified in this part in the following cases, which may apply to laboratory testing, field testing, or both. We intend to publicly announce when we allow or require such exceptions. All of the test procedures noted here as exceptions to the specified procedures are considered generically as "other procedures." Note that the terms "special procedures" and "alternate procedures" have specific meanings; "special procedures" are those allowed by § 1065.10(c)(2) and "alternate procedures" are those allowed by § 1065.10(c)(7).
(1) The objective of the procedures in this part is to produce emission measurements equivalent to those that would result from measuring emissions during in-use operation using the same engine configuration as installed in a vehicle, equipment, or vessel. However, in unusual circumstances where these procedures may result in measurements that do not represent in-use operation, you must notify us if good engineering judgment indicates that the specified procedures cause unrepresentative emission measurements for your engines. Note that you need not notify us of unrepresentative aspects of the test procedure if measured emissions are equivalent to in-use emissions. This provision does not obligate you to pursue new information regarding the different ways your engine might operate in use, nor does it obligate you to collect any other in-use information to verify whether or not these test procedures are representative of your engine's in-use operation. If you notify us of unrepresentative procedures under this paragraph (c)(1), we will cooperate with you to establish whether and how the procedures should be appropriately changed to result in more representative measurements. While the provisions of this paragraph (c)(1) allow us to be responsive to issues as they arise, we would generally work toward making these testing changes generally applicable through rulemaking. We will allow reasonable lead time for compliance with any resulting change in procedures. We will consider the following factors in determining the importance of pursuing changes to the procedures:
(i) Whether supplemental emission standards or other requirements in the standard-setting part address the type of operation of concern or otherwise prevent inappropriate design strategies.
(ii) Whether the unrepresentative aspect of the procedures affect your ability to show compliance with the applicable emission standards.
(iii) The extent to which the established procedures require the use of emission-control technologies or strategies that are expected to ensure a comparable degree of emission control under the in-use operation that differs from the specified procedures.
(2) You may request to use special procedures if your engine cannot be tested using the specified procedures. For example, this may apply if your engine cannot operate on the specified duty cycle. In this case, tell us in writing why you cannot satisfactorily test your engine using this part's procedures and ask to use a different approach. We will approve your request if we determine that it would produce emission measurements that represent in-use operation and we determine that it can be used to show compliance with the requirements of the standard-setting part. Where we approve special procedures that differ substantially from the specified

procedures, we may preclude you from participating in averaging, banking, and trading with the affected engine families.
(3) In a given model year, you may use procedures required for later model year engines without request. If you upgrade your testing facility in stages, you may rely on a combination of procedures for current and later model year engines as long as you can ensure, using good engineering judgment, that the combination you use for testing does not affect your ability to show compliance with the applicable emission standards.
(4) In a given model year, you may ask to use procedures allowed for earlier model year engines. We will approve this only if you show us that using the procedures allowed for earlier model years does not affect your ability to show compliance with the applicable emission standards.
(5) You may ask to use emission data collected using other procedures, such as those of the California Air Resources Board or the International Organization for Standardization. We will approve this only if you show us that using these other procedures does not affect your ability to show compliance with the applicable emission standards.
(6) During the 12 months following the effective date of any change in the provisions of this part 1065(and 40 CFR part 1066 for vehicle testing), you may use data collected using procedures specified in the previously applicable version of this part 1065 (and 40 CFR part 1066 for vehicle testing). This also applies for changes to test procedures specified in the standard-setting part to the extent that these changes are not related to new emission standards. This paragraph (c)(6) does not restrict the use of carryover certification data otherwise allowed by the standard-setting part.
(7) You may request to use alternate procedures that are equivalent to the specified procedures, or procedures that are more accurate or more precise than the specified procedures. We may perform tests with your engines using either the approved alternate procedures or the specified procedures. The following provisions apply to requests for alternate procedures:
(i) Applications. Follow the instructions in § 1065.12.
(ii) Submission. Submit requests in writing to the Designated Compliance Officer.
(iii) Notification. We may approve your request by telling you directly, or we may issue guidance announcing our approval of a specific alternate procedure, which would make additional requests for approval unnecessary.
(d) Advance approval. If we require you to request approval to use other procedures under paragraph (c) of this section, you may not use them until we approve your request.

§ 1065.12 Approval of alternate procedures.
(a) To get approval for an alternate procedure under § 1065.10(c), send the Designated Compliance Officer an initial written request describing the alternate procedure and why you believe it is equivalent to the specified procedure. Anyone may request alternate procedure approval. This means that an individual engine manufacturer may request to use an alternate procedure. This also means that an instrument manufacturer may request to have an instrument, equipment, or procedure approved as an alternate procedure to those specified in this part. We may approve your request based on this information alone, whether or not it includes all the information specified in this section. Where we determine that your original submission does not include enough information for us to determine that the alternate procedure is equivalent to the specified procedure, we may ask you to submit supplemental information showing that your alternate procedure is consistently and reliably at least as accurate and repeatable as the specified procedure.

(b) We may make our approval under this section conditional upon meeting other requirements or specifications. We may limit our approval, for example, to certain time frames, specific duty cycles, or specific emission standards. Based upon any supplemental information we receive after our initial approval, we may amend a previously approved alternate procedure to extend, limit, or discontinue its use. We intend to publicly announce alternate procedures that we approve.

(c) Although we will make every effort to approve only alternate procedures that completely meet our requirements, we may revoke our approval of an alternate procedure if new information shows that it is significantly not equivalent to the specified procedure. If we do this, we will grant time to switch to testing using an allowed procedure, considering the following factors:

(1) The cost, difficulty, and availability to switch to a procedure that we allow.

(2) The degree to which the alternate procedure affects your ability to show that your engines comply with all applicable emission standards.

(3) Any relevant factors considered in our initial approval.

(d) If we do not approve your proposed alternate procedure based on the information in your initial request, we may ask you to send additional information to fully evaluate your request. While we consider the information specified in this paragraph (d) and the statistical criteria of paragraph (e) of this section to be sufficient to demonstrate equivalence, it may not be necessary to include all the information or meet the specified statistical criteria. For example, systems that do not meet the statistical criteria in paragraph (e) of this section because they have a small bias toward high emission results could be approved since they would not adversely affect your ability to demonstrate compliance with applicable standards.

(1) Theoretical basis. Give a brief technical description explaining why you believe the proposed alternate procedure should result in emission measurements equivalent to those using the specified procedure. You may include equations, figures, and references. You should consider the full range of parameters that may affect equivalence. For example, for a request to use a different NO_x measurement procedure, you should theoretically relate the alternate detection principle to the specified detection principle over the expected concentration ranges for NO, NO_2, and interference gases. For a request to use a different PM measurement procedure, you should explain the principles by which the alternate procedure quantifies particulate mass similarly to the specified procedures.

(2) Technical description. Describe briefly any hardware or software needed to perform the alternate procedure. You may include dimensioned drawings, flowcharts, schematics, and component specifications. Explain any necessary calculations or other data manipulation.

(3) Procedure execution. Describe briefly how to perform the alternate procedure and recommend a level of training an operator should have to achieve acceptable results. Summarize the installation, calibration, operation, and maintenance procedures in a step-by-step format. Describe how any calibration is performed using NIST-traceable standards or other similar standards we approve. Calibration must be specified by using known quantities and must not be specified as a comparison with other allowed procedures.

(4) Data-collection techniques. Compare measured emission results using the proposed alternate procedure and the specified procedure, as follows:

(i) Both procedures must be calibrated independently to NIST-traceable standards or to other similar standards we approve.

(ii) Include measured emission results from all applicable duty cycles. Measured emission results should show that the test engine meets all applicable emission standards according to specified procedures.
(iii) Use statistical methods to evaluate the emission measurements, such as those described in paragraph (e) of this section.
(e) Absent any other directions from us, use a *t*-test and an *F*-test calculated according to § 1065.602 to evaluate whether your proposed alternate procedure is equivalent to the specified procedure. We may give you specific directions regarding methods for statistical analysis, or we may approve other methods that you propose. Such alternate methods may be more or less stringent than those specified in this paragraph (e). In determining the appropriate statistical criteria, we will consider the repeatability of measurements made with the reference procedure. For example, less stringent statistical criteria may be appropriate for measuring emission levels being so low that they adversely affect the repeatability of reference measurements. We recommend that you consult a statistician if you are unfamiliar with these statistical tests. Perform the tests as follows:
(1) Repeat measurements for all applicable duty cycles at least seven times for each procedure. You may use laboratory duty cycles to evaluate field-testing procedures. Be sure to include all available results to evaluate the precision and accuracy of the proposed alternate procedure, as described in § 1065.2.
(2) Demonstrate the accuracy of the proposed alternate procedure by showing that it passes a two-sided *t*-test. Use an unpaired *t*-test, unless you show that a paired *t*-test is appropriate under both of the following provisions:
(i) For paired data, the population of the paired differences from which you sampled paired differences must be independent. That is, the probability of any given value of one paired difference is unchanged by knowledge of the value of another paired difference. For example, your paired data would violate this requirement if your series of paired differences showed a distinct increase or decrease that was dependent on the time at which they were sampled.
(ii) For paired data, the population of paired differences from which you sampled the paired differences must have a normal (i.e., Gaussian) distribution. If the population of paired difference is not normally distributed, consult a statistician for a more appropriate statistical test, which may include transforming the data with a mathematical function or using some kind of non-parametric test.
(3) Show that t is less than the critical t value, t_{crit}, tabulated in § 1065.602, for the following confidence intervals:
(i) 90 % for a proposed alternate procedure for laboratory testing.
(ii) 95 % for a proposed alternate procedure for field testing.
(4) Demonstrate the precision of the proposed alternate procedure by showing that it passes an *F*-test. Use a set of at least seven samples from the reference procedure and a set of at least seven samples from the alternate procedure to perform an F-test. The sets must meet the following requirements:
(i) Within each set, the values must be independent. That is, the probability of any given value in a set must be unchanged by knowledge of another value in that set. For example, your data would violate this requirement if a set showed a distinct increase or decrease that was dependent upon the time at which they were sampled.
(ii) For each set, the population of values from which you sampled must have a normal (i.e., Gaussian) distribution. If the population of values is not normally distributed, consult a

statistician for a more appropriate statistical test, which may include transforming the data with a mathematical function or using some kind of non-parametric test.
(iii) The two sets must be independent of each other. That is, the probability of any given value in one set must be unchanged by knowledge of another value in the other set. For example, your data would violate this requirement if one value in a set showed a distinct increase or decrease that was dependent upon a value in the other set. Note that a trend of emission changes from an engine would not violate this requirement.
(iv) If you collect paired data for the paired *t*-test in paragraph (e)(2) in this section, use caution when selecting sets from paired data for the *F*-test. If you do this, select sets that do not mask the precision of the measurement procedure. We recommend selecting such sets only from data collected using the same engine, measurement instruments, and test cycle.
(5) Show that F is less than the critical F value, F_{crit}, tabulated in § 1065.602. If you have several F-test results from several sets of data, show that the mean F-test value is less than the mean critical F value for all the sets. Evaluate F_{crit}, based on the following confidence intervals:
(i) 90 % for a proposed alternate procedure for laboratory testing.
(ii) 95 % for a proposed alternate procedure for field testing.

§ 1065.15 Overview of procedures for laboratory and field testing.
This section outlines the procedures to test engines that are subject to emission standards.
(a) In the standard-setting part, we set brake-specific emission standards in g/(kW·hr) (or g/(hp·hr)), for the following constituents:
(1) Total oxides of nitrogen, NO_x.
(2) Hydrocarbons, HC, which may be expressed in the following ways:
(i) Total hydrocarbons, THC.
(ii) Nonmethane hydrocarbons, NMHC, which results from subtracting methane, CH_4, from THC. You may choose to measure NMOG emissions to demonstrate compliance with NMHC standards.
(iii) Total hydrocarbon-equivalent, THCE, which results from adjusting THC mathematically to be equivalent on a carbon-mass basis.
(iv) Nonmethane hydrocarbon-equivalent, NMHCE, which results from adjusting NMHC mathematically to be equivalent on a carbon-mass basis. You may choose to measure NMOG emissions to demonstrate compliance with NMHCE standards.
(3) Particulate matter, PM.
(4) Carbon monoxide, CO.
(5) Carbon dioxide, CO_2.
(6) Methane, CH_4.
(7) Nitrous oxide, N_2O.
(b) Note that some engines are not subject to standards for all the emission constituents identified in paragraph (a) of this section. Note also that the standard-setting part may include standards for pollutants not listed in paragraph (a) of this section.
(c) We generally set brake-specific emission standards over test intervals and/or duty cycles, as follows:
(1) Engine operation. Testing may involve measuring emissions and work in a laboratory-type environment or in the field, as described in paragraph (f) of this section. For most laboratory testing, the engine is operated over one or more duty cycles specified in the standard-setting part. However, laboratory testing may also include non-duty cycle testing (such as simulation of field

testing in a laboratory). For field testing, the engine is operated under normal in-use operation. The standard-setting part specifies how test intervals are defined for field testing. Refer to the definitions of "duty cycle" and "test interval" in § 1065.1001. Note that a single duty cycle may have multiple test intervals and require weighting of results from multiple test intervals to calculate a composite brake-specific emissions value to compare to the standard.

(2) Constituent determination. Determine the total mass of each constituent over a test interval by selecting from the following methods:

(i) Continuous sampling. In continuous sampling, measure the constituent's concentration continuously from raw or dilute exhaust. Multiply this concentration by the continuous (raw or dilute) flow rate at the emission sampling location to determine the constituent's flow rate. Sum the constituent's flow rate continuously over the test interval. This sum is the total mass of the emitted constituent.

(ii) Batch sampling. In batch sampling, continuously extract and store a sample of raw or dilute exhaust for later measurement. Extract a sample proportional to the raw or dilute exhaust flow rate. You may extract and store a proportional sample of exhaust in an appropriate container, such as a bag, and then measure NO_x, HC, CO, CO_2, CH_4, N_2O, and CH_2O concentrations in the container after the test interval. You may deposit PM from proportionally extracted exhaust onto an appropriate substrate, such as a filter. In this case, divide the PM by the amount of filtered exhaust to calculate the PM concentration. Multiply batch sampled concentrations by the total (raw or dilute) flow from which it was extracted during the test interval. This product is the total mass of the emitted constituent.

(iii) Combined sampling. You may use continuous and batch sampling simultaneously during a test interval, as follows:

(A) You may use continuous sampling for some constituents and batch sampling for others.

(B) You may use continuous and batch sampling for a single constituent, with one being a redundant measurement. See § 1065.201 for more information on redundant measurements.

(3) Work determination. Determine work over a test interval by one of the following methods:

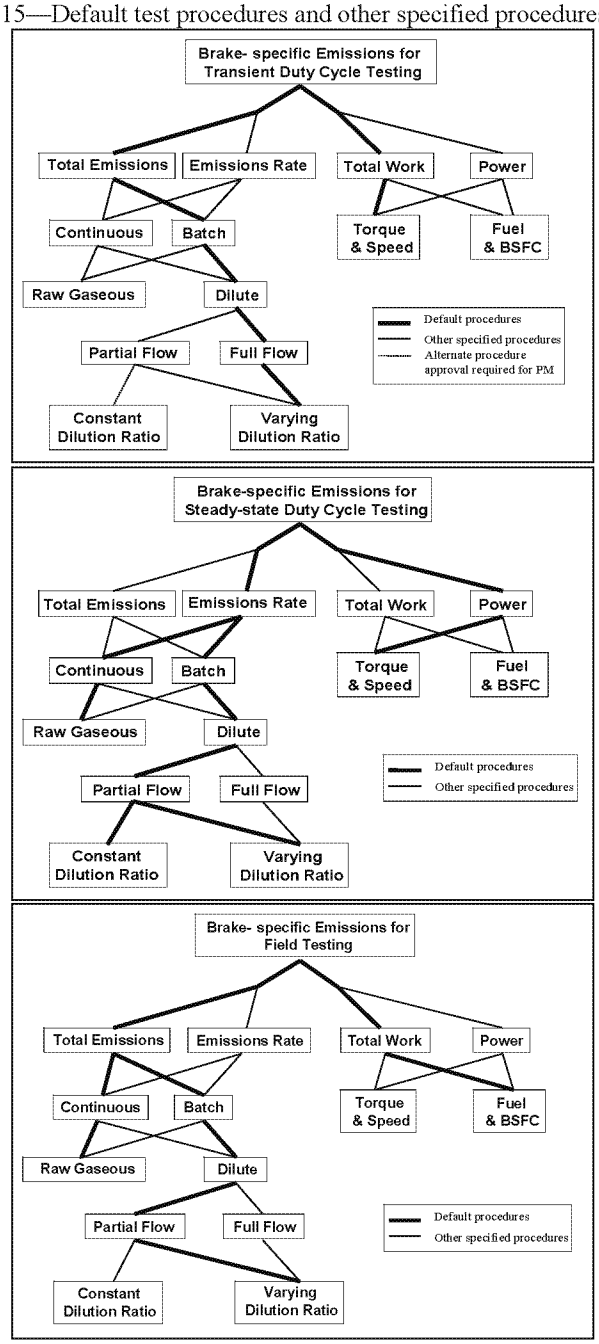
(i) Speed and torque. Synchronously multiply speed and brake torque to calculate instantaneous values for engine brake power. Sum engine brake power over a test interval to determine total work.

(ii) Fuel consumed and brake-specific fuel consumption. Directly measure fuel consumed or calculate it with chemical balances of the fuel, intake air, and exhaust. To calculate fuel consumed by a chemical balance, you must also measure either intake-air flow rate or exhaust flow rate. Divide the fuel consumed during a test interval by the brake-specific fuel consumption to determine work over the test interval. For laboratory testing, calculate the brake-specific fuel consumption using fuel consumed and speed and torque over a test interval. For field testing, refer to the standard-setting part and § 1065.915 for selecting an appropriate value for brake-specific fuel consumption.

(d) Refer to § 1065.650 for calculations to determine brake-specific emissions.

(e) The following figure illustrates the allowed measurement configurations described in this part 1065:

Figure 1 of § 1065.15—Default test procedures and other specified procedures.



(f) This part 1065 describes how to test engines in a laboratory-type environment or in the field.
(1) This affects test intervals and duty cycles as follows:
(i) For laboratory testing, you generally determine brake-specific emissions for duty-cycle testing by using an engine dynamometer in a laboratory or other environment. This typically consists of one or more test intervals, each defined by a duty cycle, which is a sequence of modes, speeds, and/or torques (or powers) that an engine must follow. If the standard-setting part allows it, you may also simulate field testing with an engine dynamometer in a laboratory or other environment.
(ii) Field testing consists of normal in-use engine operation while an engine is installed in a vehicle, equipment, or vessel rather than following a specific engine duty cycle. The standard-setting part specifies how test intervals are defined for field testing.
(2) The type of testing may also affect what test equipment may be used. You may use "lab-grade" test equipment for any testing. The term "lab-grade" refers to equipment that fully conforms to the applicable specifications of this part. For some testing you may alternatively used "field-grade" equipment. The term "field-grade" refers to equipment that fully conforms to the applicable specifications of subpart J of this part, but does not fully conform to other specifications of this part. You may use "field-grade" equipment for field testing. We also specify in this part and in the standard-setting parts certain cases in which you may use "field-grade" equipment for testing in a laboratory-type environment. (Note: Although "field-grade" equipment is generally more portable than "lab-grade" test equipment, portability is not relevant to whether equipment is considered to be "field-grade" or "lab-grade".)

§ 1065.20 Units of measure and overview of calculations.
(a) System of units. The procedures in this part generally follow the International System of Units (SI), as detailed in NIST Special Publication 811, which we incorporate by reference in § 1065.1010. The following exceptions apply:
(1) We designate angular speed, f_n, of an engine's crankshaft in revolutions per minute (r/min), rather than the SI unit of radians per second (rad/s). This is based on the commonplace use of r/min in many engine dynamometer laboratories.
(2) We designate brake-specific emissions in grams per kilowatt-hour (g/(kW·hr)), rather than the SI unit of grams per megajoule (g/MJ). In addition, we use the symbol *hr* to identify hour, rather than the SI convention of using *h*. This is based on the fact that engines are generally subject to emission standards expressed in g/kW·hr. If we specify engine standards in grams per horsepower·hour (g/(hp·hr)) in the standard-setting part, convert units as specified in paragraph (d) of this section.
(3) We generally designate temperatures in units of degrees Celsius (°C) unless a calculation requires an absolute temperature. In that case, we designate temperatures in units of Kelvin (K). For conversion purposes throughout this part, 0 °C equals 273.15 K. Unless specified otherwise, always use absolute temperature values for multiplying or dividing by temperature.
(b) Concentrations. This part does not rely on amounts expressed in parts per million. Rather, we express such amounts in the following SI units:
(1) For ideal gases, μmol/mol, formerly ppm (volume).
(2) For all substances, cm^3/m^3, formerly ppm (volume).
(3) For all substances, mg/kg, formerly ppm (mass).

(c) Absolute pressure. Measure absolute pressure directly or calculate it as the sum of atmospheric pressure plus a differential pressure that is referenced to atmospheric pressure. Always use absolute pressure values for multiplying or dividing by pressure.
(d) Units conversion. Use the following conventions to convert units:
(1) Testing. You may record values and perform calculations with other units. For testing with equipment that involves other units, use the conversion factors from NIST Special Publication 811, as described in paragraph (a) of this section.
(2) Humidity. In this part, we identify humidity levels by specifying dewpoint, which is the temperature at which pure water begins to condense out of air. Use humidity conversions as described in § 1065.645.
(3) Emission standards. If your standard is in g/(hp·hr) units, convert kW to hp before any rounding by using the conversion factor of 1 hp (550 ft·lbf/s) = 0.7456999 kW. Round the final value for comparison to the applicable standard.
(e) Rounding. You are required to round certain final values, such as emission values. You may round intermediate values when transferring data as long as you maintain at least six significant digits (which requires more than six decimal places for values less than 0.1), or all significant digits if fewer than six digits are available. Unless the standard-setting part specifies otherwise, do not round other intermediate values. Round values to the number of significant digits necessary to match the number of decimal places of the applicable standard or specification as described in this paragraph (e). Note that specifications expressed as percentages have infinite precision (as described in paragraph (e)(7) of this section). Use the following rounding convention, which is consistent with ASTM E29 and NIST SP 811:
(1) If the first (left-most) digit to be removed is less than five, remove all the appropriate digits without changing the digits that remain. For example, 3.141593 rounded to the second decimal place is 3.14.
(2) If the first digit to be removed is greater than five, remove all the appropriate digits and increase the lowest-value remaining digit by one. For example, 3.141593 rounded to the fourth decimal place is 3.1416.
(3) If the first digit to be removed is five with at least one additional non-zero digit following the five, remove all the appropriate digits and increase the lowest-value remaining digit by one. For example, 3.141593 rounded to the third decimal place is 3.142.
(4) If the first digit to be removed is five with no additional non-zero digits following the five, remove all the appropriate digits, increase the lowest-value remaining digit by one if it is odd and leave it unchanged if it is even. For example, 1.75 and 1.750 rounded to the first decimal place are 1.8; while 1.85 and 1.850 rounded to the first decimal place are also 1.8. Note that this rounding procedure will always result in an even number for the lowest-value digit.
(5) This paragraph (e)(5) applies if the regulation specifies rounding to an increment other than decimal places or powers of ten (to the nearest 0.01, 0.1, 1, 10, 100, etc.). To round numbers for these special cases, divide the quantity by the specified rounding increment. Round the result to the nearest whole number as described in paragraphs (e)(1) through (4) of this section. Multiply the rounded number by the specified rounding increment. This value is the desired result. For example, to round 0.90 to the nearest 0.2, divide 0.90 by 0.2 to get a result of 4.5, which rounds to 4. Multiplying 4 by 0.2 gives 0.8, which is the result of rounding 0.90 to the nearest 0.2.
(6) The following tables further illustrate the rounding procedures specified in this paragraph (e):

Quantity	Rounding Increment			
	10	1	0.1	0.01
3.141593	0	3	3.1	3.14
123,456.789	123,460	123,457	123,456.8	123,456.79
5.500	10	6	5.5	5.50
4.500	0	4	4.5	4.50

Quantity	Rounding Increment			
	25	3	0.5	0.02
229.267	225	228	229.5	229.26
62.500	50	63	62.5	62.50
87.500	100	87	87.5	87.50
7.500	0	6	7.5	7.50

(7) This paragraph (e)(7) applies where we specify a limit or tolerance as some percentage of another value (such as ±2 % of a maximum concentration). You may show compliance with such specifications either by applying the percentage to the total value to calculate an absolute limit, or by converting the absolute value to a percentage by dividing it by the total value.

(i) Do not round either value (the absolute limit or the calculated percentage), except as specified in paragraph (e)(7)(ii) of this section. For example, assume we specify that an analyzer must have a repeatability of ±1 % of the maximum concentration or better, the maximum concentration is 1059 ppm, and you determine repeatability to be ±6.3 ppm. In this example, you could calculate an absolute limit of ±10.59 ppm (1059 ppm × 0.01) or calculate that the 6.3 ppm repeatability is equivalent to a repeatability of 0.5949008498584 %.

(ii) Prior to July 1, 2013, you may treat tolerances (and equivalent specifications) specified in percentages as having fixed rather than infinite precision. For example, 2 % would be equivalent to 1.51 % to 2.50 % and 2.0 % would be equivalent to 1.951 % to 2.050 %. Note that this allowance applies whether or not the percentage is explicitly specified as a percentage of another value.

(8) You may use measurement devices that incorporate internal rounding, consistent with the provisions of this paragraph (e)(8). You may use devices that use any rounding convention if they report six or more significant digits. You may use devices that report fewer than six digits, consistent with good engineering judgment and the accuracy, repeatability, and noise specifications of this part. Note that this provision does not necessarily require you to perform engineering analysis or keep records.

(f) Interpretation of ranges. Interpret a range as a tolerance unless we explicitly identify it as an accuracy, repeatability, linearity, or noise specification. See § 1065.1001 for the definition of tolerance. In this part, we specify two types of ranges:

(1) Whenever we specify a range by a single value and corresponding limit values above and below that value (such as X ±Y), target the associated control point to that single value (X). Examples of this type of range include "±10 % of maximum pressure", or "(30 ±10) kPa". In these examples, you would target the maximum pressure or 30 kPa, respectively.

(2) Whenever we specify a range by the interval between two values, you may target any associated control point to any value within that range. An example of this type of range is "(40 to 50) kPa".

(g) Scaling of specifications with respect to an applicable standard. Because this part 1065 is applicable to a wide range of engines and emission standards, some of the specifications in this part are scaled with respect to an engine's applicable standard or maximum power. This ensures that the specification will be adequate to determine compliance, but not overly burdensome by requiring unnecessarily high-precision equipment. Many of these specifications are given with respect to a "flow-weighted mean" that is expected at the standard or during testing. Flow-weighted mean is the mean of a quantity after it is weighted proportional to a corresponding flow rate. For example, if a gas concentration is measured continuously from the raw exhaust of an engine, its flow-weighted mean concentration is the sum of the products (dry-to-wet corrected, if applicable) of each recorded concentration times its respective exhaust flow rate, divided by the sum of the recorded flow rates. As another example, the bag concentration from a CVS system is the same as the flow-weighted mean concentration, because the CVS system itself flow-weights the bag concentration. Refer to § 1065.602 for information needed to estimate and calculate flow-weighted means. Wherever a specification is scaled to a value based upon an applicable standard, interpret the standard to be the family emission limit if the engine is certified under an emission credit program in the standard-setting part.

§ 1065.25 Recordkeeping.

(a) The procedures in this part include various requirements to record data or other information. Refer to the standard-setting part and § 1065.695 regarding specific recordkeeping requirements.

(b) You must promptly send us organized, written records in English if we ask for them. We may review them at any time.

(c) We may waive specific reporting or recordkeeping requirements we determine to be unnecessary for the purposes of this part and the standard-setting part. Note that while we will generally keep the records required by this part, we are not obligated to keep records we determine to be unnecessary for us to keep. For example, while we require you to keep records for invalid tests so that we may verify that your invalidation was appropriate, it is not necessary for us to keep records for our own invalid tests.

Subpart B—EQUIPMENT SPECIFICATIONS

§ 1065.101 Overview.

(a) This subpart specifies equipment, other than measurement instruments, related to emission testing. The provisions of this subpart apply for all engine dynamometer testing where engine speeds and loads are controlled to follow a prescribed duty cycle. See subpart J of this part to determine which of the provisions of this subpart apply for field testing. This equipment includes three broad categories—dynamometers, engine fluid systems (such as fuel and intake-air systems), and emission-sampling hardware.

(b) Other related subparts in this part identify measurement instruments (subpart C), describe how to evaluate the performance of these instruments (subpart D), and specify engine fluids and analytical gases (subpart H).

(c) Subpart J of this part describes additional equipment that is specific to field testing.

(d) Figures 1 and 2 of this section illustrate some of the possible configurations of laboratory equipment. These figures are schematics only; we do not require exact conformance to them. Figure 1 of this section illustrates the equipment specified in this subpart and gives some references to sections in this subpart. Figure 2 of this section illustrates some of the possible configurations of a full-flow dilution, constant-volume sampling (CVS) system. Not all possible CVS configurations are shown.

(e) Dynamometer testing involves engine operation over speeds and loads that are controlled to a prescribed duty cycle. Field testing involves measuring emissions over normal in-use operation of a vehicle or piece of equipment. Field testing does not involve operating an engine over a prescribed duty cycle.

Figure 1 of § 1065.101—Engine dynamometer laboratory equipment.

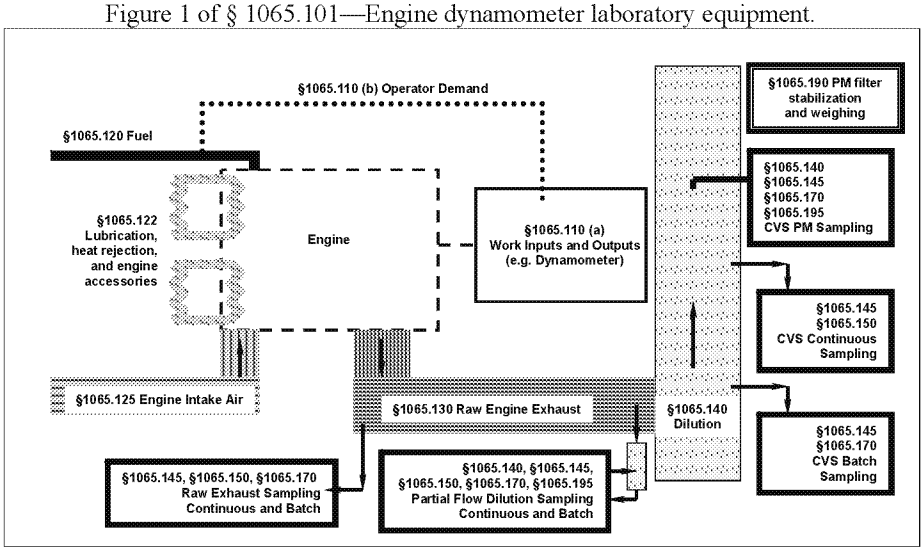
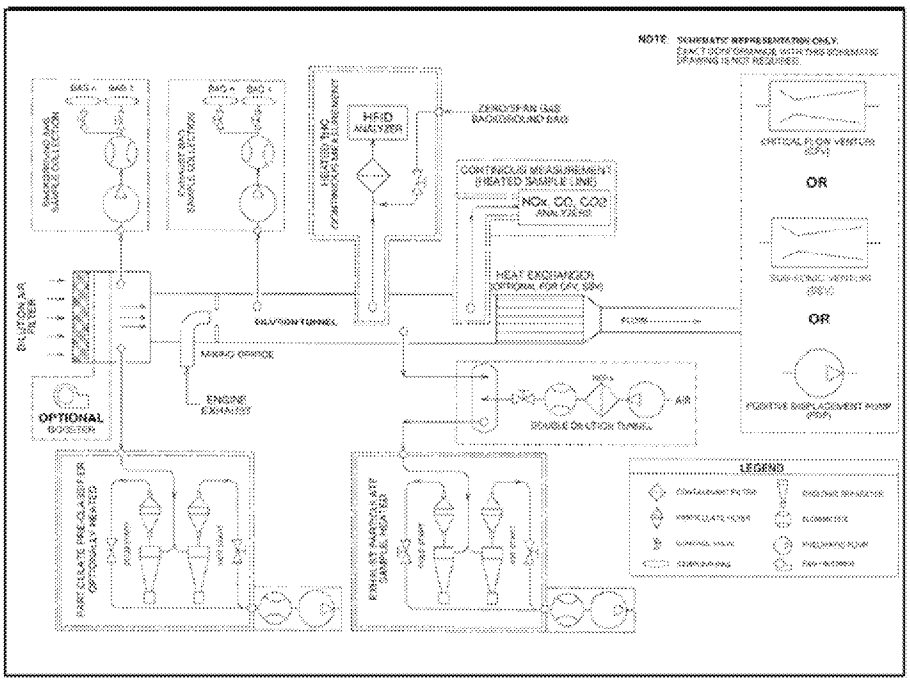


Figure 2 of § 1065.101—Examples of some full-flow dilution sampling configurations.



§ 1065.110 Work inputs and outputs, accessory work, and operator demand.

(a) Work. Use good engineering judgment to simulate all engine work inputs and outputs as they typically would operate in use. Account for work inputs and outputs during an emission test by measuring them; or, if they are small, you may show by engineering analysis that disregarding them does not affect your ability to determine the net work output by more than ±0.5 % of the net expected work output over the test interval . Use equipment to simulate the specific types of work, as follows:

(1) Shaft work. Use an engine dynamometer that is able to meet the cycle-validation criteria in § 1065.514 over each applicable duty cycle.

(i) You may use eddy-current and water-brake dynamometers for any testing that does not involve engine motoring, which is identified by negative torque commands in a reference duty cycle. See the standard setting part for reference duty cycles that are applicable to your engine.

(ii) You may use alternating-current or direct-current motoring dynamometers for any type of testing.

(iii) You may use one or more dynamometers.

(iv) You may use any device that is already installed on a vehicle, equipment, or vessel to absorb work from the engine's output shaft(s). Examples of these types of devices include a vessel's propeller and a locomotive's generator.

(2) Electrical work. Use one or more of the following to simulate electrical work:

(i) Use storage batteries or capacitors that are of the type and capacity installed in use.

(ii) Use motors, generators, and alternators that are of the type and capacity installed in use.

(iii) Use a resistor load bank to simulate electrical loads.
(3) Pump, compressor, and turbine work. Use pumps, compressors, and turbines that are of the type and capacity installed in use. Use working fluids that are of the same type and thermodynamic state as normal in-use operation.
(b) Laboratory work inputs. You may supply any laboratory inputs of work to the engine. For example, you may supply electrical work to the engine to operate a fuel system, and as another example you may supply compressor work to the engine to actuate pneumatic valves. We may ask you to show by engineering analysis your accounting of laboratory work inputs to meet the criterion in paragraph (a) of this section.
(c) Engine accessories. You must either install or account for the work of engine accessories required to fuel, lubricate, or heat the engine, circulate coolant to the engine, or to operate aftertreatment devices. Operate the engine with these accessories installed or accounted for during all testing operations, including mapping. If these accessories are not powered by the engine during a test, account for the work required to perform these functions from the total work used in brake-specific emission calculations. For air-cooled engines only, subtract externally powered fan work from total work. We may ask you to show by engineering analysis your accounting of engine accessories to meet the criterion in paragraph (a) of this section.
(d) Engine starter. You may install a production-type starter.
(e) Operator demand for shaft work. Operator demand is defined in § 1065.1001. Command the operator demand and the dynamometer(s) to follow a prescribed duty cycle with set points for engine speed and torque as specified in § 1065.512. Refer to the standard-setting part to determine the specifications for your duty cycle(s). Use a mechanical or electronic input to control operator demand such that the engine is able to meet the validation criteria in § 1065.514 over each applicable duty cycle. Record feedback values for engine speed and torque as specified in § 1065.512. Using good engineering judgment, you may improve control of operator demand by altering on-engine speed and torque controls. However, if these changes result in unrepresentative testing, you must notify us and recommend other test procedures under § 1065.10(c)(1).
(f) Other engine inputs. If your electronic control module requires specific input signals that are not available during dynamometer testing, such as vehicle speed or transmission signals, you may simulate the signals using good engineering judgment. Keep records that describe what signals you simulate and explain why these signals are necessary for representative testing.

§ 1065.120 Fuel properties and fuel temperature and pressure.
(a) Use fuels as specified in the standard-setting part, or as specified in subpart H of this part if fuels are not specified in the standard-setting part.
(b) If the engine manufacturer specifies fuel temperature and pressure tolerances and the location where they are to be measured, then measure the fuel temperature and pressure at the specified location to show that you are within these tolerances throughout testing.
(c) If the engine manufacturer does not specify fuel temperature and pressure tolerances, use good engineering judgment to set and control fuel temperature and pressure in a way that represents typical in-use fuel temperatures and pressures.

§ 1065.122 Engine cooling and lubrication.

(a) Engine cooling. Cool the engine during testing so its intake-air, oil, coolant, block, and head temperatures are within their expected ranges for normal operation. You may use auxiliary coolers and fans.
(1) For air-cooled engines only, if you use auxiliary fans you must account for work input to the fan(s) according to § 1065.110.
(2) See § 1065.125 for more information related to intake-air cooling.
(3) See § 1065.127 for more information related to exhaust gas recirculation cooling.
(4) Measure temperatures at the manufacturer-specified locations. If the manufacturer does not specify temperature measurement locations, then use good engineering judgment to monitor intake-air, oil, coolant, block, and head temperatures to ensure that they are in their expected ranges for normal operation.
(b) Forced cooldown. You may install a forced cooldown system for an engine and an exhaust aftertreatment device according to § 1065.530(a)(1).
(c) Lubricating oil. Use lubricating oils specified in § 1065.740. For two-stroke engines that involve a specified mixture of fuel and lubricating oil, mix the lubricating oil with the fuel according to the manufacturer's specifications.
(d) Coolant. For liquid-cooled engines, use coolant as specified in § 1065.745.

§ 1065.125 Engine intake air.
(a) Use the intake-air system installed on the engine or one that represents a typical in-use configuration. This includes the charge-air cooling and exhaust gas recirculation systems.
(b) Measure temperature, humidity, and atmospheric pressure near the entrance of the furthest upstream engine or in-use intake system component. This would generally be near the engine's air filter, or near the inlet to the in-use air intake system for engines that have no air filter. For engines with multiple intakes, make measurements near the entrance of each intake.
(1) Pressure. You may use a single shared atmospheric pressure meter as long as your laboratory equipment for handling intake air maintains ambient pressure at all intakes within ±1 kPa of the shared atmospheric pressure. For engines with multiple intakes with separate atmospheric pressure measurements at each intake, use an average value for verifying compliance to § 1065.520(b)(2).
(2) Humidity. You may use a single shared humidity measurement for intake air as long as your equipment for handling intake air maintains dewpoint at all intakes to within ±0.5 °C of the shared humidity measurement. For engines with multiple intakes with separate humidity measurements at each intake, use a flow-weighted average humidity for NO_x corrections. If individual flows of each intake are not measured, use good engineering judgment to estimate a flow-weighted average humidity.
(3) Temperature. Good engineering judgment may require that you shield the temperature sensors or move them upstream of an elbow in the laboratory intake system to prevent measurement errors due to radiant heating from hot engine surfaces or in-use intake system components. You must limit the distance between the temperature sensor and the entrance to the furthest upstream engine or in-use intake system component to no more than 12 times the outer hydraulic diameter of the entrance to the furthest upstream engine or in-use intake system component. However, you may exceed this limit if you use good engineering judgment to show that the temperature at the furthest upstream engine or in-use intake system component meets the specification in paragraph (c) of this section. For engines with multiple intakes, use a flow-weighted average value to verify compliance with the specification in paragraph (c) of this

section. If individual flows of each intake are not measured, you may use good engineering judgment to estimate a flow-weighted average temperature. You may also verify that each individual intake complies with the specification in paragraph (c) of this section.
(c) Maintain the temperature of intake air to (25 ± 5) °C, except as follows:
(1) Follow the standard-setting part if it specifies different temperatures.
(2) For engines above 560 kW, you may use 35 °C as the upper bound of the tolerance. However, your system must be capable of controlling the temperature to the 25 °C setpoint for any steady-state operation at > 30% of maximum engine power.
(3) You may ask us to allow you to apply a different setpoint for intake air temperature if it is necessary to remain consistent with the provisions of § 1065.10(c)(1) for testing during which ambient temperature will be outside this range.
(d) Use an intake-air restriction that represents production engines. Make sure the intake-air restriction is between the manufacturer's specified maximum for a clean filter and the manufacturer's specified maximum allowed. Measure the static differential pressure of the restriction at the location and at the speed and torque set points specified by the manufacturer. If the manufacturer does not specify a location, measure this pressure upstream of any turbocharger or exhaust gas recirculation system connection to the intake air system. If the manufacturer does not specify speed and torque points, measure this pressure while the engine outputs maximum power. As the manufacturer, you are liable for emission compliance for all values up to the maximum restriction you specify for a particular engine.
(e) This paragraph (e) includes provisions for simulating charge-air cooling in the laboratory. This approach is described in paragraph (e)(1) of this section. Limits on using this approach are described in paragraphs (e)(2) and (3) of this section.
(1) Use a charge-air cooling system with a total intake-air capacity that represents production engines' in-use installation. Design any laboratory charge-air cooling system to minimize accumulation of condensate. Drain any accumulated condensate. Before starting a duty cycle (or preconditioning for a duty cycle), completely close all drains that would normally be closed during in-use operation. Keep those drains closed during the emission test. Maintain coolant conditions as follows:
(i) Maintain a coolant temperature of at least 20 °C at the inlet to the charge-air cooler throughout testing. We recommend maintaining a coolant temperature of 25 ±5 °C at the inlet of the charge-air cooler.
(ii) At the engine conditions specified by the manufacturer, set the coolant flow rate to achieve an air temperature within ±5 °C of the value specified by the manufacturer after the charge-air cooler's outlet. Measure the air-outlet temperature at the location specified by the manufacturer. Use this coolant flow rate set point throughout testing. If the engine manufacturer does not specify engine conditions or the corresponding charge-air cooler air outlet temperature, set the coolant flow rate at maximum engine power to achieve a charge-air cooler air outlet temperature that represents in-use operation.
(iii) If the engine manufacturer specifies pressure-drop limits across the charge-air cooling system, ensure that the pressure drop across the charge-air cooling system at engine conditions specified by the manufacturer is within the manufacturer's specified limit(s). Measure the pressure drop at the manufacturer's specified locations.
(2) Using a constant flow rate as described in paragraph (e)(1) of this section may result in unrepresentative overcooling of the intake air. The provisions of this paragraph (e)(2) apply instead of the provisions of § 1065.10(c)(1) for this simulation. Our allowance to cool intake air

as specified in this paragraph (e) does not affect your liability for field testing or for laboratory testing that is done in a way that better represents in-use operation. Where we determine that this allowance adversely affects your ability to demonstrate that your engines would comply with emission standards under in-use conditions, we may require you to use more sophisticated setpoints and controls of charge-air pressure drop, coolant temperature, and flow rate to achieve more representative results.
(3) This approach does not apply for field testing. You may not correct measured emission levels from field testing to account for any differences caused by the simulated cooling in the laboratory.

§ 1065.127 Exhaust gas recirculation.
Use the exhaust gas recirculation (EGR) system installed with the engine or one that represents a typical in-use configuration. This includes any applicable EGR cooling devices.

§ 1065.130 Engine exhaust.
(a) General. Use the exhaust system installed with the engine or one that represents a typical in-use configuration. This includes any applicable aftertreatment devices. We refer to exhaust piping as an exhaust stack; this is equivalent to a tailpipe for vehicle configurations.
(b) Aftertreatment configuration. If you do not use the exhaust system installed with the engine, configure any aftertreatment devices as follows:
(1) Position any aftertreatment device so its distance from the nearest exhaust manifold flange or turbocharger outlet is within the range specified by the engine manufacturer in the application for certification. If this distance is not specified, position aftertreatment devices to represent typical in-use vehicle configurations.
(2) You may use exhaust tubing that is not from the in-use exhaust system upstream of any aftertreatment device that is of diameter(s) typical of in-use configurations. If you use exhaust tubing that is not from the in-use exhaust system upstream of any aftertreatment device, position each aftertreatment device according to paragraph (b)(1) of this section.
(c) Sampling system connections. Connect an engine's exhaust system to any raw sampling location or dilution stage, as follows:
(1) Minimize laboratory exhaust tubing lengths and use a total length of laboratory tubing of no more than 10 m or 50 outside diameters, whichever is greater. The start of laboratory exhaust tubing should be specified as the exit of the exhaust manifold, turbocharger outlet, last aftertreatment device, or the in-use exhaust system, whichever is furthest downstream. The end of laboratory exhaust tubing should be specified as the sample point, or first point of dilution. If laboratory exhaust tubing consists of several different outside tubing diameters, count the number of diameters of length of each individual diameter, then sum all the diameters to determine the total length of exhaust tubing in diameters. Use the mean outside diameter of any converging or diverging sections of tubing. Use outside hydraulic diameters of any noncircular sections. For multiple stack configurations where all the exhaust stacks are combined, the start of the laboratory exhaust tubing may be taken at the last joint of where all the stacks are combined.
(2) You may install short sections of flexible laboratory exhaust tubing at any location in the engine or laboratory exhaust systems. You may use up to a combined total of 2 m or 10 outside diameters of flexible exhaust tubing.
(3) Insulate any laboratory exhaust tubing downstream of the first 25 outside diameters of length.

(4) Use laboratory exhaust tubing materials that are smooth-walled, electrically conductive, and not reactive with exhaust constituents. Stainless steel is an acceptable material.
(5) We recommend that you use laboratory exhaust tubing that has either a wall thickness of less than 2 mm or is air gap-insulated to minimize temperature differences between the wall and the exhaust.
(6) We recommend that you connect multiple exhaust stacks from a single engine into one stack upstream of any emission sampling. For raw or dilute partial-flow emission sampling, to ensure mixing of the multiple exhaust streams before emission sampling, we recommend a minimum Reynolds number, $Re^{\#}$, of 4000 for the combined exhaust stream, where $Re^{\#}$ is based on the inside diameter of the combined flow at the first sampling point. You may configure the exhaust system with turbulence generators, such as orifice plates or fins, to achieve good mixing; inclusion of turbulence generators may be required for $Re^{\#}$ less than 4000 to ensure mixing. $Re^{\#}$ is defined in § 1065.640. For dilute full-flow (CVS) emission sampling, you may configure the exhaust system without regard to mixing in the laboratory section of the raw exhaust. For example you may size the laboratory section to reduce its pressure drop even if the $Re^{\#}$ in the laboratory section of the raw exhaust is less than 4000.
(d) In-line instruments. You may insert instruments into the laboratory exhaust tubing, such as an in-line smoke meter. If you do this, you may leave a length of up to 5 outside diameters of laboratory exhaust tubing uninsulated on each side of each instrument, but you must leave a length of no more than 25 outside diameters of laboratory exhaust tubing uninsulated in total, including any lengths adjacent to in-line instruments.
(e) Leaks. Minimize leaks sufficiently to ensure your ability to demonstrate compliance with the applicable standards. We recommend performing a chemical balance of fuel, intake air, and exhaust according to § 1065.655 to verify exhaust system integrity.
(f) Grounding. Electrically ground the entire exhaust system.
(g) Forced cooldown. You may install a forced cooldown system for an exhaust aftertreatment device according to § 1065.530(a)(1)(i).
(h) Exhaust restriction. As the manufacturer, you are liable for emission compliance for all values up to the maximum restriction(s) you specify for a particular engine. Measure and set exhaust restriction(s) at the location(s) and at the engine speed and torque values specified by the manufacturer. Also, for variable-restriction aftertreatment devices, measure and set exhaust restriction(s) at the aftertreatment condition (degreening/aging and regeneration/loading level) specified by the manufacturer. If the manufacturer does not specify a location, measure this pressure downstream of any turbocharger. If the manufacturer does not specify speed and torque points, measure pressure while the engine produces maximum power. Use an exhaust-restriction setpoint that represents a typical in-use value, if available. If a typical in-use value for exhaust restriction is not available, set the exhaust restriction at (80 to 100) % of the maximum exhaust restriction specified by the manufacturer, or if the maximum is 5 kPa or less, the set point must be no less than 1.0 kPa from the maximum. For example, if the maximum back pressure is 4.5 kPa, do not use an exhaust restriction set point that is less than 3.5 kPa.
(i) Open crankcase emissions. If the standard-setting part requires measuring open crankcase emissions, you may either measure open crankcase emissions separately using a method that we approve in advance, or route open crankcase emissions directly into the exhaust system for emission measurement. If the engine is not already configured to route open crankcase emissions for emission measurement, route open crankcase emissions as follows:

(1) Use laboratory tubing materials that are smooth-walled, electrically conductive, and not reactive with crankcase emissions. Stainless steel is an acceptable material. Minimize tube lengths. We also recommend using heated or thin-walled or air gap-insulated tubing to minimize temperature differences between the wall and the crankcase emission constituents.
(2) Minimize the number of bends in the laboratory crankcase tubing and maximize the radius of any unavoidable bend.
(3) Use laboratory crankcase exhaust tubing that meets the engine manufacturer's specifications for crankcase back pressure.
(4) Connect the crankcase exhaust tubing into the raw exhaust downstream of any aftertreatment system, downstream of any installed exhaust restriction, and sufficiently upstream of any sample probes to ensure complete mixing with the engine's exhaust before sampling. Extend the crankcase exhaust tube into the free stream of exhaust to avoid boundary-layer effects and to promote mixing. You may orient the crankcase exhaust tube's outlet in any direction relative to the raw exhaust flow.

§ 1065.140 Dilution for gaseous and PM constituents.
(a) General. You may dilute exhaust with ambient air, purified air, or nitrogen. References in this part to "dilution air" may include any of these. For gaseous emission measurement, the dilution air must be at least 15 °C. Note that the composition of the dilution air affects some gaseous emission measurement instruments' response to emissions. We recommend diluting exhaust at a location as close as possible to the location where ambient air dilution would occur in use. Dilution may occur in a single stage or in multiple stages. For dilution in multiple stages, the first stage is considered primary dilution and later stages are considered secondary dilution.
(b) Dilution-air conditions and background concentrations. Before dilution air is mixed with exhaust, you may precondition it by increasing or decreasing its temperature or humidity. You may also remove constituents to reduce their background concentrations. The following provisions apply to removing constituents or accounting for background concentrations:
(1) You may measure constituent concentrations in the dilution air and compensate for background effects on test results. See § 1065.650 for calculations that compensate for background concentrations (40 CFR 1066.610 for vehicle testing).
(2) Measure these background concentrations the same way you measure diluted exhaust constituents, or measure them in a way that does not affect your ability to demonstrate compliance with the applicable standards. For example, you may use the following simplifications for background sampling:
(i) You may disregard any proportional sampling requirements.
(ii) You may use unheated gaseous sampling systems.
(iii) You may use unheated PM sampling systems.
(iv) You may use continuous sampling if you use batch sampling for diluted emissions.
(v) You may use batch sampling if you use continuous sampling for diluted emissions.
(3) For removing background PM, we recommend that you filter all dilution air, including primary full-flow dilution air, with high-efficiency particulate air (HEPA) filters that have an initial minimum collection efficiency specification of 99.97 % (see § 1065.1001 for procedures related to HEPA-filtration efficiencies). Ensure that HEPA filters are installed properly so that background PM does not leak past the HEPA filters. If you choose to correct for background PM without using HEPA filtration, demonstrate that the background PM in the dilution air

contributes less than 50 % to the net PM collected on the sample filter. You may correct net PM without restriction if you use HEPA filtration.

(c) Full-flow dilution; constant-volume sampling (CVS). You may dilute the full flow of raw exhaust in a dilution tunnel that maintains a nominally constant volume flow rate, molar flow rate or mass flow rate of diluted exhaust, as follows:

(1) Construction. Use a tunnel with inside surfaces of 300 series stainless steel. Electrically ground the entire dilution tunnel. We recommend a thin-walled and insulated dilution tunnel to minimize temperature differences between the wall and the exhaust gases. You may not use any flexible tubing in the dilution tunnel upstream of the PM sample probe. You may use nonconductive flexible tubing downstream of the PM sample probe and upstream of the CVS flow meter; use good engineering judgment to select a tubing material that is not prone to leaks, and configure the tubing to ensure smooth flow at the CVS flow meter.

(2) Pressure control. Maintain static pressure at the location where raw exhaust is introduced into the tunnel within ±1.2 kPa of atmospheric pressure. You may use a booster blower to control this pressure. If you test using more careful pressure control and you show by engineering analysis or by test data that you require this level of control to demonstrate compliance at the applicable standards, we will maintain the same level of static pressure control when we test.

(3) Mixing. Introduce raw exhaust into the tunnel by directing it downstream along the centerline of the tunnel. If you dilute directly from the exhaust stack, the end of the exhaust stack is considered to be the start of the dilution tunnel. You may introduce a fraction of dilution air radially from the tunnel's inner surface to minimize exhaust interaction with the tunnel walls. You may configure the system with turbulence generators such as orifice plates or fins to achieve good mixing. We recommend a minimum Reynolds number, $Re^{\#}$, of 4000 for the diluted exhaust stream, where $Re^{\#}$ is based on the inside diameter of the dilution tunnel. $Re^{\#}$ is defined in § 1065.640.

(4) Flow measurement preconditioning. You may condition the diluted exhaust before measuring its flow rate, as long as this conditioning takes place downstream of any heated HC or PM sample probes, as follows:

(i) You may use flow straighteners, pulsation dampeners, or both of these.

(ii) You may use a filter.

(iii) You may use a heat exchanger to control the temperature upstream of any flow meter, but you must take steps to prevent aqueous condensation as described in paragraph (c)(6) of this section.

(5) Flow measurement. Section 1065.240 describes measurement instruments for diluted exhaust flow.

(6) Aqueous condensation. This paragraph (c)(6) describes how you must address aqueous condensation in the CVS. As described below, you may meet these requirements by preventing or limiting aqueous condensation in the CVS from the exhaust inlet to the last emission sample probe. See that paragraph for provisions related to the CVS between the last emission sample probe and the CVS flow meter. You may heat and/or insulate the dilution tunnel walls, as well as the bulk stream tubing downstream of the tunnel to prevent or limit aqueous condensation. Where we allow aqueous condensation to occur, use good engineering judgment to ensure that the condensation does not affect your ability to demonstrate that your engines comply with the applicable standards (see § 1065.10(a)).

(i) Preventing aqueous condensation. To prevent condensation, you must keep the temperature of internal surfaces, excluding any sample probes, above the dew point of the dilute exhaust passing through the CVS tunnel. Use good engineering judgment to monitor temperatures in the CVS. For the purposes of this paragraph (c)(6), assume that aqueous condensation is pure water condensate only, even though the definition of "aqueous condensation" in § 1065.1001 includes condensation of any constituents that contain water. No specific verification check is required under this paragraph (c)(6)(i), but we may ask you to show how you comply with this requirement. You may use engineering analysis, CVS tunnel design, alarm systems, measurements of wall temperatures, and calculation of water dew point to demonstrate compliance with this requirement. For optional CVS heat exchangers, you may use the lowest water temperature at the inlet(s) and outlet(s) to determine the minimum internal surface temperature.

(ii) Limiting aqueous condensation. This paragraph (c)(6)(ii) specifies limits of allowable condensation and requires you to verify that the amount of condensation that occurs during each test interval does not exceed the specified limits.

(A) Use chemical balance equations in § 1065.655 to calculate the mole fraction of water in the dilute exhaust continuously during testing. Alternatively, you may continuously measure the mole fraction of water in the dilute exhaust prior to any condensation during testing. Use good engineering judgment to select, calibrate and verify water analyzers/detectors. The linearity verification requirements of § 1065.307 do not apply to water analyzers/detectors used to correct for the water content in exhaust samples.

(B) Use good engineering judgment to select and monitor locations on the CVS tunnel walls prior to the last emission sample probe. If you are also verifying limited condensation from the last emission sample probe to the CVS flow meter, use good engineering judgment to select and monitor locations on the CVS tunnel walls, optional CVS heat exchanger, and CVS flow meter. For optional CVS heat exchangers, you may use the lowest water temperature at the inlet(s) and outlet(s) to determine the minimum internal surface temperature. Identify the minimum surface temperature on a continuous basis.

(C) Identify the maximum potential mole fraction of dilute exhaust lost on a continuous basis during the entire test interval. This value must be less than or equal to 0.02. Calculate on a continuous basis the mole fraction of water that would be in equilibrium with liquid water at the measured minimum surface temperature. Subtract this mole fraction from the mole fraction of water that would be in the exhaust without condensation (either measured or from the chemical balance), and set any negative values to zero. This difference is the potential mole fraction of the dilute exhaust that would be lost due to water condensation on a continuous basis.

(D) Integrate the product of the molar flow rate of the dilute exhaust and the potential mole fraction of dilute exhaust lost, and divide by the totalized dilute exhaust molar flow over the test interval. This is the potential mole fraction of the dilute exhaust that would be lost due to water condensation over the entire test interval. Note that this assumes no re-evaporation. This value must be less than or equal to 0.005.

(7) Flow compensation. Maintain nominally constant molar, volumetric or mass flow of diluted exhaust. You may maintain nominally constant flow by either maintaining the temperature and pressure at the flow meter or by directly controlling the flow of diluted exhaust. You may also directly control the flow of proportional samplers to maintain proportional sampling. For an individual test, verify proportional sampling as described in § 1065.545.

(d) Partial-flow dilution (PFD). You may dilute a partial flow of raw or previously diluted exhaust before measuring emissions. Section 1065.240 describes PFD-related flow measurement instruments. PFD may consist of constant or varying dilution ratios as described in paragraphs (d)(2) and (3) of this section. An example of a constant dilution ratio PFD is a "secondary dilution PM" measurement system.

(1) Applicability. (i) You may use PFD to extract a proportional raw exhaust sample for any batch or continuous PM emission sampling over any transient duty cycle, any steady-state duty cycle, or any ramped-modal cycle.

(ii) You may use PFD to extract a proportional raw exhaust sample for any batch or continuous gaseous emission sampling over any transient duty cycle, any steady-state duty cycle, or any ramped-modal cycle.

(iii) You may use PFD to extract a proportional raw exhaust sample for any batch or continuous field-testing.

(iv)You may use PFD to extract a proportional diluted exhaust sample from a CVS for any batch or continuous emission sampling.

(v) You may use PFD to extract a constant raw or diluted exhaust sample for any continuous emission sampling.

(vi) You may use PFD to extract a constant raw or diluted exhaust sample for any steady-state emission sampling.

(2) Constant dilution-ratio PFD. Do one of the following for constant dilution-ratio PFD:

Comment [CAL1]: Underline

(i) Dilute an already proportional flow. For example, you may do this as a way of performing secondary dilution from a CVS tunnel to achieve overall dilution ratio for PM sampling.

(ii) Continuously measure constituent concentrations. For example, you might dilute to precondition a sample of raw exhaust to control its temperature, humidity, or constituent concentrations upstream of continuous analyzers. In this case, you must take into account the dilution ratio before multiplying the continuous concentration by the sampled exhaust flow rate.

(iii) Extract a proportional sample from a separate constant dilution ratio PFD system. For example, you might use a variable-flow pump to proportionally fill a gaseous storage medium such as a bag from a PFD system. In this case, the proportional sampling must meet the same specifications as varying dilution ratio PFD in paragraph (d)(3) of this section.

(iv) For each mode of a discrete-mode test (such as a locomotive notch setting or a specific setting for speed and torque), use a constant dilution ratio for any PM sampling. You must change the overall PM sampling system dilution ratio between modes so that the dilution ratio on the mode with the highest exhaust flow rate meets § 1065.140(e)(2) and the dilution ratios on all other modes is higher than this (minimum) dilution ratio by the ratio of the maximum exhaust flow rate to the exhaust flow rate of the corresponding other mode. This is the same dilution ratio requirement for RMC or field transient testing. You must account for this change in dilution ratio in your emission calculations.

(3) Varying dilution-ratio PFD. All the following provisions apply for varying dilution-ratio PFD:

Comment [CAL2]: Underline

(i) Use a control system with sensors and actuators that can maintain proportional sampling over intervals as short as 200 ms (i.e., 5 Hz control).

(ii) For control input, you may use any sensor output from one or more measurements; for example, intake-air flow, fuel flow, exhaust flow, engine speed, and intake manifold temperature and pressure.

(iii) Account for any emission transit time in the PFD system, as necessary.

(iv) You may use preprogrammed data if they have been determined for the specific test site, duty cycle, and test engine from which you dilute emissions.
(v) We recommend that you run practice cycles to meet the verification criteria in § 1065.545. Note that you must verify every emission test by meeting the verification criteria with the data from that specific test. Data from previously verified practice cycles or other tests may not be used to verify a different emission test.
(vi) You may not use a PFD system that requires preparatory tuning or calibration with a CVS or with the emission results from a CVS. Rather, you must be able to independently calibrate the PFD.
(e) Dilution air temperature, dilution ratio, residence time, and temperature control of PM samples. Dilute PM samples at least once upstream of transfer lines. You may dilute PM samples upstream of a transfer line using full-flow dilution, or partial-flow dilution immediately downstream of a PM probe. In the case of partial-flow dilution, you may have up to 26 cm of insulated length between the end of the probe and the dilution stage, but we recommend that the length be as short as practical. The intent of these specifications is to minimize heat transfer to or from the emission sample before the final stage of dilution, other than the heat you may need to add to prevent aqueous condensation. This is accomplished by initially cooling the sample through dilution. Configure dilution systems as follows:
(1) Set the dilution air temperature to (25 ±5) °C. Use good engineering judgment to select a location to measure this temperature that is as close as practical upstream of the point where dilution air mixes with raw exhaust.
(2) For any PM dilution system (i.e., CVS or PFD), add dilution air to the raw exhaust such that the minimum overall ratio of diluted exhaust to raw exhaust is within the range of (5:1 to 7:1) and is at least 2:1 for any primary dilution stage. Base this minimum value on the maximum engine exhaust flow rate for a given test interval. Either measure the maximum exhaust flow during a practice run of the test interval or estimate it based on good engineering judgment (for example, you might rely on manufacturer-published literature).
(3) Configure any PM dilution system to have an overall residence time of (1.0 to 5.5) s, as measured from the location of initial dilution air introduction to the location where PM is collected on the sample media. Also configure the system to have a residence time of at least 0.50 s, as measured from the location of final dilution air introduction to the location where PM is collected on the sample media. When determining residence times within sampling system volumes, use an assumed flow temperature of 25 °C and pressure of 101.325 kPa.
(4) Control sample temperature to a (47 ±5) °C tolerance, as measured anywhere within 20 cm upstream or downstream of the PM storage media (such as a filter). Measure this temperature with a bare-wire junction thermocouple with wires that are (0.500 ±0.025) mm diameter, or with another suitable instrument that has equivalent performance.

§ 1065.145 Gaseous and PM probes, transfer lines, and sampling system components.
(a) Continuous and batch sampling. Determine the total mass of each constituent with continuous or batch sampling. Both types of sampling systems have probes, transfer lines, and other sampling system components that are described in this section.
(b) Options for engines with multiple exhaust stacks. Measure emissions from a test engine as described in this paragraph (b) if it has multiple exhaust stacks. You may choose to use different measurement procedures for different pollutants under this paragraph (b) for a given test. For purposes of this part 1065, the test engine includes all the devices related to converting the

chemical energy in the fuel to the engine's mechanical output energy. This may or may not involve vehicle- or equipment-based devices. For example, all of an engine's cylinders are considered to be part of the test engine even if the exhaust is divided into separate exhaust stacks. As another example, all the cylinders of a diesel-electric locomotive are considered to be part of the test engine even if they transmit power through separate output shafts, such as might occur with multiple engine-generator sets working in tandem. Use one of the following procedures to measure emissions with multiple exhaust stacks:

(1) Route the exhaust flow from the multiple stacks into a single flow as described in § 1065.130(c)(6). Sample and measure emissions after the exhaust streams are mixed. Calculate the emissions as a single sample from the entire engine. We recommend this as the preferred option, since it requires only a single measurement and calculation of the exhaust molar flow for the entire engine.

(2) Sample and measure emissions from each stack and calculate emissions separately for each stack. Add the mass (or mass rate) emissions from each stack to calculate the emissions from the entire engine. Testing under this paragraph (b)(2) requires measuring or calculating the exhaust molar flow for each stack separately. If the exhaust molar flow in each stack cannot be calculated from combustion air flow(s), fuel flow(s), and measured gaseous emissions, and it is impractical to measure the exhaust molar flows directly, you may alternatively proportion the engine's calculated total exhaust molar flow rate (where the flow is calculated using combustion air mass flow(s), fuel mass flow(s), and emissions concentrations) based on exhaust molar flow measurements in each stack using a less accurate, non-traceable method. For example, you may use a total pressure probe and static pressure measurement in each stack.

(3) Sample and measure emissions from one stack and repeat the duty cycle as needed to collect emissions from each stack separately. Calculate the emissions from each stack and add the separate measurements to calculate the mass (or mass rate) emissions from the entire engine. Testing under this paragraph (b)(3) requires measuring or calculating the exhaust molar flow for each stack separately. You may alternatively proportion the engine's calculated total exhaust molar flow rate based on calculation and measurement limitations as described in paragraph (b)(2) of this section. Use the average of the engine's total power or work values from the multiple test runs to calculate brake-specific emissions. Divide the total mass (or mass rate) of each emission by the average power (or work). You may alternatively use the engine power or work associated with the corresponding stack during each test run if these values can be determined for each stack separately.

(4) Sample and measure emissions from each stack separately and calculate emissions for the entire engine based on the stack with the highest concentration. Testing under this paragraph (b)(4) requires only a single exhaust flow measurement or calculation for the entire engine. You may determine which stack has the highest concentration by performing multiple test runs, reviewing the results of earlier tests, or using good engineering judgment. Note that the highest concentration of different pollutants may occur in different stacks. Note also that the stack with the highest concentration of a pollutant during a test interval for field testing may be a different stack than the one you identified based on average concentrations over a duty cycle.

(5) Sample emissions from each stack separately and combine the wet sample streams from each stack proportionally to the exhaust molar flows in each stack. Measure the emission concentrations and calculate the emissions for the entire engine based on these weighted concentrations. Testing under this paragraph (b)(5) requires measuring or calculating the exhaust molar flow for each stack separately during the test run to proportion the sample streams

from each stack. If it is impractical to measure the exhaust molar flows directly, you may alternatively proportion the wet sample streams based on less accurate, non-traceable flow methods. For example, you may use a total pressure probe and static pressure measurement in each stack. The following restrictions apply for testing under this paragraph (b)(5):
(i) You must use an accurate, traceable measurement or calculation of the engine's total exhaust molar flow rate for calculating the mass of emissions from the entire engine.
(ii) You may dry the single, combined, proportional sample stream; you may not dry the sample streams from each stack separately.
(iii) You must measure and proportion the sample flows from each stack with active flow controls. For PM sampling, you must measure and proportion the diluted sample flows from each stack with active flow controls that use only smooth walls with no sudden change in cross-sectional area. For example, you may control the dilute exhaust PM sample flows using electrically conductive vinyl tubing and a control device that pinches the tube over a long enough transition length so no flow separation occurs.
(iv) For PM sampling, the transfer lines from each stack must be joined so the angle of the joining flows is 12.5° or less. Note that the exhaust manifold must meet the same specifications as the transfer line according to paragraph (d) of this section.
(6) Sample emissions from each stack separately and combine the wet sample streams from each stack equally. Measure the emission concentrations and calculate the emissions for the entire engine based on these measured concentrations. Testing under this paragraph (b)(6) assumes that the raw-exhaust and sample flows are the same for each stack. The following restrictions apply for testing under this paragraph (b)(6):
(i) You must measure and demonstrate that the sample flow from each stack is within 5 % of the value from the stack with the highest sample flow. You may alternatively ensure that the stacks have equal flow rates without measuring sample flows by designing a passive sampling system that meets the following requirements:
(A) The probes and transfer line branches must be symmetrical, have equal lengths and diameters, have the same number of bends, and have no filters.
(B) If probes are designed such that they are sensitive to stack velocity, the stack velocity must be similar at each probe. For example, a static pressure probe used for gaseous sampling is not sensitive to stack velocity.
(C) The stack static pressure must be the same at each probe. You can meet this requirement by placing probes at the end of stacks that are vented to atmosphere.
(D) For PM sampling, the transfer lines from each stack must be joined so the angle of the joining flows is 12.5° or less. Note that the exhaust manifold must meet the same specifications as the transfer line according to paragraph (d) of this section.
(ii) You may use the procedure in this paragraph (b)(6) only if you perform an analysis showing that the resulting error due to imbalanced stack flows and concentrations is either at or below 2 %. You may alternatively show that the resulting error does not impact your ability to demonstrate compliance with applicable standards. For example, you may use less accurate, non-traceable measurements of emission concentrations and molar flow in each stack and demonstrate that the imbalances in flows and concentrations cause 2 % or less error.
(iii) For a two-stack engine, you may use the procedure in this paragraph (b)(6) only if you can show that the stack with the higher flow has the lower average concentration for each pollutant over the duty cycle.

(iv) You must use an accurate, traceable measurement or calculation of the engine's total exhaust molar flow rate for calculating the mass of emissions from the entire engine.
(v) You may dry the single, equally combined, sample stream; you may not dry the sample streams from each stack separately.
(vi) You may determine your exhaust flow rates with a chemical balance of exhaust gas concentrations and either intake air flow or fuel flow.
(c) Gaseous and PM sample probes. A probe is the first fitting in a sampling system. It protrudes into a raw or diluted exhaust stream to extract a sample, such that its inside and outside surfaces are in contact with the exhaust. A sample is transported out of a probe into a transfer line, as described in paragraph (d) of this section. The following provisions apply to sample probes:
(1) Probe design and construction. Use sample probes with inside surfaces of 300 series stainless steel or, for raw exhaust sampling, use any nonreactive material capable of withstanding raw exhaust temperatures. Locate sample probes where constituents are mixed to their mean sample concentration. Take into account the mixing of any crankcase emissions that may be routed into the raw exhaust. Locate each probe to minimize interference with the flow to other probes. We recommend that all probes remain free from influences of boundary layers, wakes, and eddies—especially near the outlet of a raw-exhaust stack where unintended dilution might occur. Make sure that purging or back-flushing of a probe does not influence another probe during testing. You may use a single probe to extract a sample of more than one constituent as long as the probe meets all the specifications for each constituent.
(2) Gaseous sample probes. Use either single-port or multi-port probes for sampling gaseous emissions. You may orient these probes in any direction relative to the raw or diluted exhaust flow. For some probes, you must control sample temperatures, as follows:
(i) For probes that extract NO_x from diluted exhaust, control the probe's wall temperature to prevent aqueous condensation.
(ii) For probes that extract hydrocarbons for THC or NMHC analysis from the diluted exhaust of compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW, we recommend heating the probe to minimize hydrocarbon contamination consistent with good engineering judgment. If you routinely fail the contamination check in the 1065.520 pretest check, we recommend heating the probe section to approximately 190 °C to minimize contamination.
(3) PM sample probes. Use PM probes with a single opening at the end. Orient PM probes to face directly upstream. If you shield a PM probe's opening with a PM pre-classifier such as a hat, you may not use the preclassifier we specify in paragraph (f)(1) of this section. We recommend sizing the inside diameter of PM probes to approximate isokinetic sampling at the expected mean flow rate.
(d) Transfer lines. You may use transfer lines to transport an extracted sample from a probe to an analyzer, storage medium, or dilution system, noting certain restrictions for PM sampling in § 1065.140(e). Minimize the length of all transfer lines by locating analyzers, storage media, and dilution systems as close to probes as practical. We recommend that you minimize the number of bends in transfer lines and that you maximize the radius of any unavoidable bend. Avoid using 90° elbows, tees, and cross-fittings in transfer lines. Where such connections and fittings are necessary, take steps, using good engineering judgment, to ensure that you meet the temperature tolerances in this paragraph (d). This may involve measuring temperature at various locations within transfer lines and fittings. You may use a single transfer line to transport a

sample of more than one constituent, as long as the transfer line meets all the specifications for each constituent. The following construction and temperature tolerances apply to transfer lines:
(1) Gaseous samples. Use transfer lines with inside surfaces of 300 series stainless steel, PTFE, Viton™, or any other material that you demonstrate has better properties for emission sampling. For raw exhaust sampling, use a non-reactive material capable of withstanding raw exhaust temperatures. You may use in-line filters if they do not react with exhaust constituents and if the filter and its housing meet the same temperature requirements as the transfer lines, as follows:
(i) For NO_x transfer lines upstream of either an NO_2-to-NO converter that meets the specifications of § 1065.378 or a chiller that meets the specifications of § 1065.376, maintain a sample temperature that prevents aqueous condensation.
(ii) For THC transfer lines for testing compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW, maintain a wall temperature tolerance throughout the entire line of (191 ±11) °C. If you sample from raw exhaust, you may connect an unheated, insulated transfer line directly to a probe. Design the length and insulation of the transfer line to cool the highest expected raw exhaust temperature to no lower than 191 °C, as measured at the transfer line's outlet. For dilute sampling, you may use a transition zone between the probe and transfer line of up to 92 cm to allow your wall temperature to transition to (191 ±11) °C.
(2) PM samples. We recommend heated transfer lines or a heated enclosure to minimize temperature differences between transfer lines and exhaust constituents. Use transfer lines that are inert with respect to PM and are electrically conductive on the inside surfaces. We recommend using PM transfer lines made of 300 series stainless steel. Electrically ground the inside surface of PM transfer lines.
(e) Optional sample-conditioning components for gaseous sampling. You may use the following sample-conditioning components to prepare gaseous samples for analysis, as long as you do not install or use them in a way that adversely affects your ability to show that your engines comply with all applicable gaseous emission standards.
(1) NO_2-to-NO converter. You may use an NO_2-to-NO converter that meets the converter conversion verification specified in § 1065.378 at any point upstream of a NO_x analyzer, sample bag, or other storage medium.
(2) Sample dryer. You may use either type of sample dryer described in this paragraph (e)(2) to decrease the effects of water on gaseous emission measurements. You may not use a chemical dryer, or use dryers upstream of PM sample filters.
(i) Osmotic-membrane. You may use an osmotic-membrane dryer upstream of any gaseous analyzer or storage medium, as long as it meets the temperature specifications in paragraph (d)(1) of this section. Because osmotic-membrane dryers may deteriorate after prolonged exposure to certain exhaust constituents, consult with the membrane manufacturer regarding your application before incorporating an osmotic-membrane dryer. Monitor the dewpoint, T_{dew}, and absolute pressure, p_{total}, downstream of an osmotic-membrane dryer. You may use continuously recorded values of T_{dew} and p_{total} in the amount of water calculations specified in § 1065.645. For our testing we may use average temperature and pressure values over the test interval or a nominal pressure value that we estimate as the dryer's average pressure expected during testing as constant values in the amount of water calculations specified in § 1065.645. For your testing, you may use the maximum temperature or minimum pressure values observed during a test interval or duty cycle or the high alarm temperature setpoint or low alarm pressure setpoint as constant values in the calculations specified in § 1065.645. For your testing, you may

also use a nominal p_{total}, which you may estimate as the dryer's lowest absolute pressure expected during testing.

(ii) Thermal chiller. You may use a thermal chiller upstream of some gas analyzers and storage media. You may not use a thermal chiller upstream of a THC measurement system for compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW. If you use a thermal chiller upstream of an NO_2-to-NO converter or in a sampling system without an NO_2-to-NO converter, the chiller must meet the NO_2 loss-performance check specified in § 1065.376. Monitor the dewpoint, T_{dew}, and absolute pressure, p_{total}, downstream of a thermal chiller. You may use continuously recorded values of T_{dew} and p_{total} in the amount of water calculations specified in § 1065.645. If it is valid to assume the degree of saturation in the thermal chiller, you may calculate T_{dew} based on the known chiller performance and continuous monitoring of chiller temperature, $T_{chiller}$. If it is valid to assume a constant temperature offset between $T_{chiller}$ and T_{dew}, due to a known and fixed amount of sample reheat between the chiller outlet and the temperature measurement location, you may factor in this assumed temperature offset value into emission calculations. If we ask for it, you must show by engineering analysis or by data the validity of any assumptions allowed by this paragraph (e)(2)(ii). For our testing we may use average temperature and pressure values over the test interval or a nominal pressure value that we estimate as the dryer's average pressure expected during testing as constant values in the calculations specified in § 1065.645. For your testing you may use the maximum temperature and minimum pressure values observed during a test interval or duty cycle or the high alarm temperature setpoint and the low alarm pressure setpoint as constant values in the amount of water calculations specified in § 1065.645. For your testing you may also use a nominal p_{total}, which you may estimate as the dryer's lowest absolute pressure expected during testing.

(3) Sample pumps. You may use sample pumps upstream of an analyzer or storage medium for any gas. Use sample pumps with inside surfaces of 300 series stainless steel, PTFE, or any other material that you demonstrate has better properties for emission sampling. For some sample pumps, you must control temperatures, as follows:

(i) If you use a NO_x sample pump upstream of either an NO_2-to-NO converter that meets § 1065.378 or a chiller that meets § 1065.376, it must be heated to prevent aqueous condensation.

(ii) For testing compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW, if you use a THC sample pump upstream of a THC analyzer or storage medium, its inner surfaces must be heated to a tolerance of (191 ±11) °C.

(4) Ammonia Scrubber. You may use ammonia scrubbers for any or all gaseous sampling systems to prevent interference with NH_3, poisoning of the NO_2-to-NO converter, and deposits in the sampling system or analyzers. Follow the ammonia scrubber manufacturer's recommendations or use good engineering judgment in applying ammonia scrubbers.

(f) Optional sample-conditioning components for PM sampling. You may use the following sample-conditioning components to prepare PM samples for analysis, as long as you do not install or use them in a way that adversely affects your ability to show that your engines comply with the applicable PM emission standards. You may condition PM samples to minimize positive and negative biases to PM results, as follows:

(1) PM preclassifier. You may use a PM preclassifier to remove large-diameter particles. The PM preclassifier may be either an inertial impactor or a cyclonic separator. It must be constructed of 300 series stainless steel. The preclassifier must be rated to remove at least 50 % of PM at an aerodynamic diameter of 10 μm and no more than 1 % of PM at an aerodynamic

diameter of 1 μm over the range of flow rates for which you use it. Follow the preclassifier manufacturer's instructions for any periodic servicing that may be necessary to prevent a buildup of PM. Install the preclassifier in the dilution system downstream of the last dilution stage. Configure the preclassifier outlet with a means of bypassing any PM sample media so the preclassifier flow may be stabilized before starting a test. Locate PM sample media within 75 cm downstream of the preclassifier's exit. You may not use this preclassifier if you use a PM probe that already has a preclassifier. For example, if you use a hat-shaped preclassifier that is located immediately upstream of the probe in such a way that it forces the sample flow to change direction before entering the probe, you may not use any other preclassifier in your PM sampling system.
(2) Other components. You may request to use other PM conditioning components upstream of a PM preclassifier, such as components that condition humidity or remove gaseous-phase hydrocarbons from the diluted exhaust stream. You may use such components only if we approve them under § 1065.10.

§ 1065.150 Continuous sampling.
You may use continuous sampling techniques for measurements that involve raw or dilute sampling. Make sure continuous sampling systems meet the specifications in § 1065.145. Make sure continuous analyzers meet the specifications in subparts C and D of this part.

§ 1065.170 Batch sampling for gaseous and PM constituents.
Batch sampling involves collecting and storing emissions for later analysis. Examples of batch sampling include collecting and storing gaseous emissions in a bag or collecting and storing PM on a filter. You may use batch sampling to store emissions that have been diluted at least once in some way, such as with CVS, PFD, or BMD. You may use batch-sampling to store undiluted emissions.
(a) Sampling methods. If you extract from a constant-volume flow rate, sample at a constant-volume flow rate as follows:
(1) Verify proportional sampling after an emission test as described in § 1065.545. Use good engineering judgment to select storage media that will not significantly change measured emission levels (either up or down). For example, do not use sample bags for storing emissions if the bags are permeable with respect to emissions or if they off gas emissions to the extent that it affects your ability to demonstrate compliance with the applicable gaseous emission standards. As another example, do not use PM filters that irreversibly absorb or adsorb gases to the extent that it affects your ability to demonstrate compliance with the applicable PM emission standard.
(2) You must follow the requirements in § 1065.140(e)(2) related to PM dilution ratios. For each filter, if you expect the net PM mass on the filter to exceed 400 μg, assuming a 38 mm diameter filter stain area, you may take the following actions in sequence:
(i) For discrete-mode testing only, you may reduce sample time as needed to target a filter loading of 400 μg, but not below the minimum sample time specified in the standard-setting part.
(ii) Reduce filter face velocity as needed to target a filter loading of 400 μg, down to 50 cm/s or less.
(iii) Increase overall dilution ratio above the values specified in § 1065.140(e)(2) to target a filter loading of 400 μg.
(b) Gaseous sample storage media. Store gas volumes in sufficiently clean containers that minimally off-gas or allow permeation of gases. Use good engineering judgment to determine

acceptable thresholds of storage media cleanliness and permeation. To clean a container, you may repeatedly purge and evacuate a container and you may heat it. Use a flexible container (such as a bag) within a temperature-controlled environment, or use a temperature controlled rigid container that is initially evacuated or has a volume that can be displaced, such as a piston and cylinder arrangement. Use containers meeting the specifications in the Table1 of this section, noting that you may request to use other container materials under § 1065.10. Sample temperatures must stay within the following ranges for each container material:
(1) Up to 40 °C for Tedlar™ and Kynar™.
(2) (191 ±11) °C for Teflon™ and 300 series stainless steel used with measuring THC or NMHC from compression-ignition engines, two-stroke spark-ignition engines, and four-stroke spark-ignition engines at or below 19 kW. For all other engines and pollutants, these materials may be used for sample temperatures up to 202 °C.

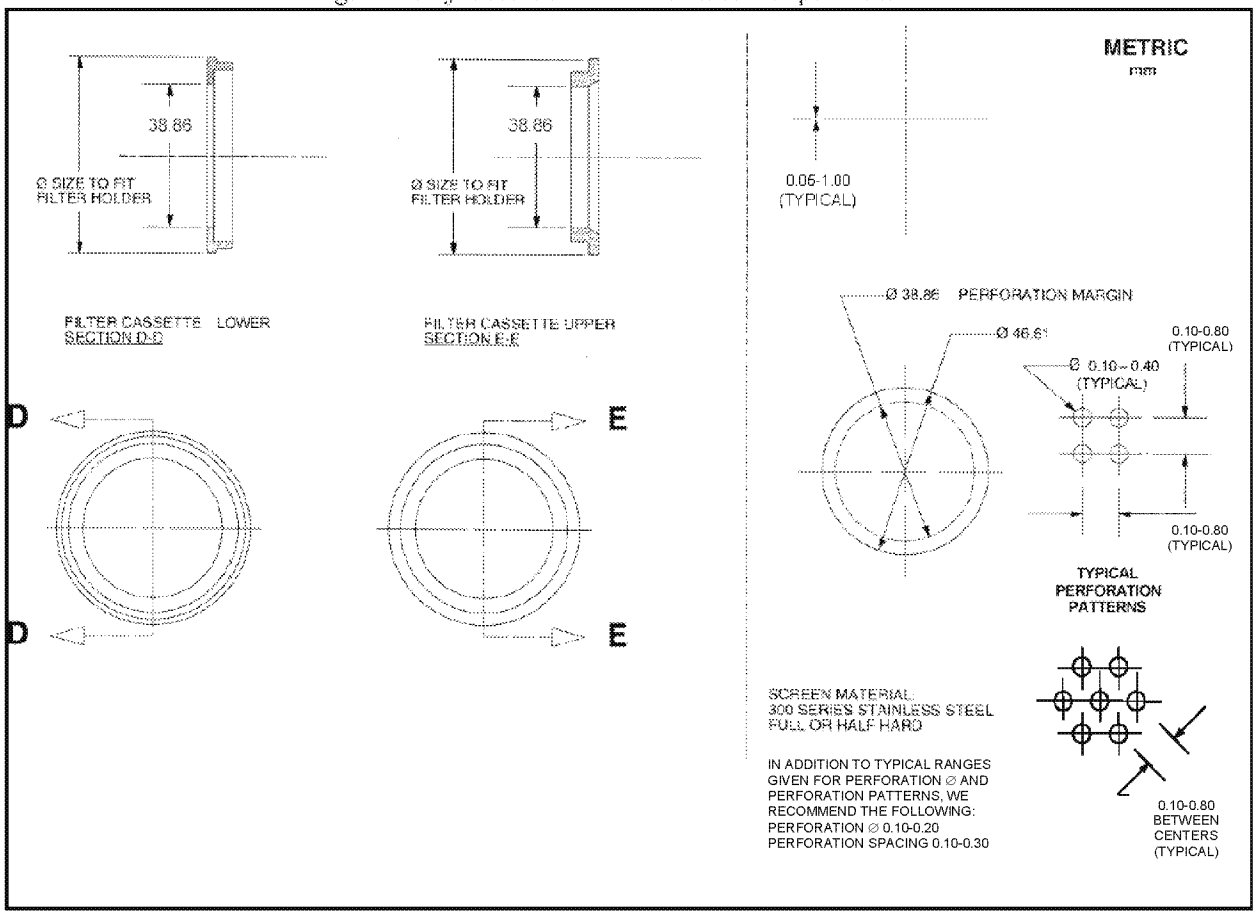
TABLE 1 OF § 1065.170– CONTAINER MATERIALS FOR GASEOUS BATCH SAMPLING

Emissions	Engine type	
	Compression-ignition Two-stroke spark-ignition Four-stroke spark-ignition at or below 19 kW	All other engines
CO, CO_2, O_2, CH_4, C_2H_6, C_3H_8, NO, NO_2, N_2O	Tedlar™, Kynar™, Teflon™, or 300 series stainless steel	Tedlar™, Kynar™, Teflon™, or 300 series stainless steel
THC, NMHC	Teflon™ or 300 series stainless steel	Tedlar™, Kynar™, Teflon™, or 300 series stainless steel

(c) PM sample media. Apply the following methods for sampling particulate emissions:
(1) If you use filter-based sampling media to extract and store PM for measurement, your procedure must meet the following specifications:
(i) If you expect that a filter's total surface concentration of PM will exceed 400 μg, assuming a 38 mm diameter filter stain area, for a given test interval, you may use filter media with a minimum initial collection efficiency of 98 %; otherwise you must use a filter media with a minimum initial collection efficiency of 99.7 %. Collection efficiency must be measured as described in ASTM D2986 (incorporated by reference in § 1065.1010), though you may rely on the sample-media manufacturer's measurements reflected in their product ratings to show that you meet this requirement.
(ii) The filter must be circular, with an overall diameter of 46.50 ±0.6 mm and an exposed diameter of at least 38 mm. See the cassette specifications in paragraph (c)(1)(vii) of this section.
(iii) We highly recommend that you use a pure PTFE filter material that does not have any flow-through support bonded to the back and has an overall thickness of 40 ±20 μm. An inert polymer ring may be bonded to the periphery of the filter material for support and for sealing between the filter cassette parts. We consider Polymethylpentene (PMP) and PTFE inert materials for a support ring, but other inert materials may be used. See the cassette specifications in paragraph (c)(1)(vii) of this section. We allow the use of PTFE-coated glass fiber filter material, as long as this filter media selection does not affect your ability to demonstrate compliance with the applicable standards, which we base on a pure PTFE filter material. Note that we will use pure PTFE filter material for compliance testing, and we may require you to use

pure PTFE filter material for any compliance testing we require, such as for selective enforcement audits.
(iv) You may request to use other filter materials or sizes under the provisions of § 1065.10.
(v) To minimize turbulent deposition and to deposit PM evenly on a filter, use a filter holder with a 12.5° (from center) divergent cone angle to transition from the transfer-line inside diameter to the exposed diameter of the filter face. Use 300 series stainless steel for this transition.
(vi) Maintain a filter face velocity near 100 cm/s with less than 5% of the recorded flow values exceeding 100 cm/s, unless you expect the net PM mass on the filter to exceed 400 µg, assuming a 38 mm diameter filter stain area. Measure face velocity as the volumetric flow rate of the sample at the pressure upstream of the filter and temperature of the filter face as measured in § 1065.140(e), divided by the filter's exposed area. You may use the exhaust stack or CVS tunnel pressure for the upstream pressure if the pressure drop through the PM sampler up to the filter is less than 2 kPa.
(vii) Use a clean cassette designed to the specifications of Figure 1 of § 1065.170. In auto changer configurations, you may use cassettes of similar design. Cassettes must be made of one of the following materials: Delrin™, 300 series stainless steel, polycarbonate, acrylonitrile-butadiene-styrene (ABS) resin, or conductive polypropylene. We recommend that you keep filter cassettes clean by periodically washing or wiping them with a compatible solvent applied using a lint-free cloth. Depending upon your cassette material, ethanol (C_2H_5OH) might be an acceptable solvent. Your cleaning frequency will depend on your engine's PM and HC emissions.
(viii) If you keep the cassette in the filter holder after sampling, prevent flow through the filter until either the holder or cassette is removed from the PM sampler. If you remove the cassettes from filter holders after sampling, transfer the cassette to an individual container that is covered or sealed to prevent communication of semi-volatile matter from one filter to another. If you remove the filter holder, cap the inlet and outlet. Keep them covered or sealed until they return to the stabilization or weighing environments.
(ix) The filters should not be handled outside of the PM stabilization and weighing environments and should be loaded into cassettes, filter holders, or auto changer apparatus before removal from these environments.
(2) You may use other PM sample media that we approve under § 1065.10, including non-filtering techniques. For example, you might deposit PM on an inert substrate that collects PM using electrostatic, thermophoresis, inertia, diffusion, or some other deposition mechanism, as approved.

Figure 1 of §1065.170—PM filter cassette specifications.



§ 1065.190 PM-stabilization and weighing environments for gravimetric analysis.
(a) This section describes the two environments required to stabilize and weigh PM for gravimetric analysis: the PM stabilization environment, where filters are stored before weighing; and the weighing environment, where the balance is located. The two environments may share a common space. These volumes may be one or more rooms, or they may be much smaller, such as a glove box or an automated weighing system consisting of one or more countertop-sized environments.
(b) We recommend that you keep both the stabilization and the weighing environments free of ambient contaminants, such as dust, aerosols, or semi-volatile material that could contaminate PM samples. We recommend that these environments conform with an "as-built" Class Six clean room specification according to ISO 14644-1 (incorporated by reference in § 1065.1010); however, we also recommend that you deviate from ISO 14644-1 as necessary to minimize air motion that might affect weighing. We recommend maximum air-supply and air-return velocities of 0.05 m/s in the weighing environment.
(c) Verify the cleanliness of the PM-stabilization environment using reference filters, as described in § 1065.390(d).
(d) Maintain the following ambient conditions within the two environments during all stabilization and weighing:
(1) Ambient temperature and tolerances. Maintain the weighing environment at a tolerance of (22 ±1) °C. If the two environments share a common space, maintain both environments at a tolerance of (22 ±1) °C. If they are separate, maintain the stabilization environment at a tolerance of (22 ±3) °C.
(2) Dewpoint. Maintain a dewpoint of 9.5 °C in both environments. This dewpoint will control the amount of water associated with sulfuric acid (H_2SO_4) PM, such that 1.2216 grams of water will be associated with each gram of H_2SO_4.
(3) Dewpoint tolerances. If the expected fraction of sulfuric acid in PM is unknown, we recommend controlling dewpoint at within ±1 °C tolerance. This would limit any dewpoint-related change in PM to less than ±2 %, even for PM that is 50 % sulfuric acid. If you know your expected fraction of sulfuric acid in PM, we recommend that you select an appropriate dewpoint tolerance for showing compliance with emission standards using the following table as a guide:

TABLE 1 OF § 1065.190—DEWPOINT TOLERANCE AS A FUNCTION OF % PM CHANGE AND % SULFURIC ACID PM

Expected sulfuric acid fraction of PM	±0.5 % PM mass change	±1 % PM mass change	±2 % PM mass change
5 %	±3 °C	±6 °C	±12 °C
50 %	±0.3 °C	±0.6 °C	±1.2 °C
100 %	±0.15 °C	±0.3 °C	±0.6 °C

(e) Verify the following ambient conditions using measurement instruments that meet the specifications in subpart C of this part:
(1) Continuously measure dewpoint and ambient temperature. Use these values to determine if the stabilization and weighing environments have remained within the tolerances specified in paragraph (d) of this section for at least 60 min before weighing sample media (e.g., filters). We recommend that you use an interlock that automatically prevents the balance from reporting

values if either of the environments have not been within the applicable tolerances for the past 60 min.
(2) Continuously measure atmospheric pressure within the weighing environment. An acceptable alternative is to use a barometer that measures atmospheric pressure outside the weighing environment, as long as you can ensure that atmospheric pressure at the balance is always within ±100 Pa of that outside environment during weighing operations. Record atmospheric pressure as you weigh filters, and use these pressure values to perform the buoyancy correction in § 1065.690.
(f) We recommend that you install a balance as follows:
(1) Install the balance on a vibration-isolation platform to isolate it from external noise and vibration.
(2) Shield the balance from convective airflow with a static-dissipating draft shield that is electrically grounded.
(3) Follow the balance manufacturer's specifications for all preventive maintenance.
(4) Operate the balance manually or as part of an automated weighing system.
(g) Minimize static electric charge in the balance environment, as follows:
(1) Electrically ground the balance.
(2) Use 300 series stainless steel tweezers if PM sample media (e.g., filters) must be handled manually.
(3) Ground tweezers with a grounding strap, or provide a grounding strap for the operator such that the grounding strap shares a common ground with the balance. Make sure grounding straps have an appropriate resistor to protect operators from accidental shock.
(4) Provide a static-electricity neutralizer that is electrically grounded in common with the balance to remove static charge from PM sample media (e.g., filters), as follows:
(i) You may use radioactive neutralizers such as a Polonium (^{210}Po) source. Replace radioactive sources at the intervals recommended by the neutralizer manufacturer.
(ii) You may use other neutralizers, such as corona-discharge ionizers. If you use a corona-discharge ionizer, we recommend that you monitor it for neutral net charge according to the ionizer manufacturer's recommendations.
(5) We recommend that you use a device to monitor the static charge of PM sample media (e.g., filter) surface.
(6) We recommend that you neutralize PM sample media (e.g., filters) to within ±2.0 V of neutral. Measure static voltages as follows:
(i) Measure static voltage of PM sample media (e.g., filters) according to the electrostatic voltmeter manufacturer's instructions.
(ii) Measure static voltage of PM sample media (e.g., filters) while the media is at least 15 cm away from any grounded surfaces to avoid mirror image charge interference.

§ 1065.195 PM-stabilization environment for in-situ analyzers.
(a) This section describes the environment required to determine PM in-situ. For in-situ analyzers, such as an inertial balance, this is the environment within a PM sampling system that surrounds the PM sample media (e.g., filters). This is typically a very small volume.
(b) Maintain the environment free of ambient contaminants, such as dust, aerosols, or semi-volatile material that could contaminate PM samples. Filter all air used for stabilization with HEPA filters. Ensure that HEPA filters are installed properly so that background PM does not leak past the HEPA filters.

(c) Maintain the following thermodynamic conditions within the environment before measuring PM:
(1) Ambient temperature. Select a nominal ambient temperature, T_{amb}, between (42 and 52) °C. Maintain the ambient temperature within ±1.0 °C of the selected nominal value.
(2) Dewpoint. Select a dewpoint, T_{dew}, that corresponds to T_{amb} such that $T_{dew} = (0.95 \cdot T_{amb} - 11.40)$ °C. The resulting dewpoint will control the amount of water associated with sulfuric acid (H_2SO_4) PM, such that 1.1368 grams of water will be associated with each gram of H_2SO_4. For example, if you select a nominal ambient temperature of 47 °C, set a dewpoint of 33.3 °C.
(3) Dewpoint tolerance. If the expected fraction of sulfuric acid in PM is unknown, we recommend controlling dewpoint within ±1.0 °C. This would limit any dewpoint-related change in PM to less than ±2 %, even for PM that is 50 % sulfuric acid. If you know your expected fraction of sulfuric acid in PM, we recommend that you select an appropriate dewpoint tolerance for showing compliance with emission standards using Table 1 of § 1065.190 as a guide:
(4) Absolute pressure. Use good engineering judgment to maintain a tolerance of absolute pressure if your PM measurement instrument requires it.
(d) Continuously measure dewpoint, temperature, and pressure using measurement instruments that meet the PM-stabilization environment specifications in subpart C of this part. Use these values to determine if the in-situ stabilization environment is within the tolerances specified in paragraph (c) of this section. Do not use any PM quantities that are recorded when any of these parameters exceed the applicable tolerances.
(e) If you use an inertial PM balance, we recommend that you install it as follows:
(1) Isolate the balance from any external noise and vibration that is within a frequency range that could affect the balance.
(2) Follow the balance manufacturer's specifications.
(f) If static electricity affects an inertial balance, you may use a static neutralizer, as follows:
(1) You may use a radioactive neutralizer such as a Polonium (^{210}Po) source or a Krypton (^{85}Kr) source. Replace radioactive sources at the intervals recommended by the neutralizer manufacturer.
(2) You may use other neutralizers, such as a corona-discharge ionizer. If you use a corona-discharge ionizer, we recommend that you monitor it for neutral net charge according to the ionizer manufacturer's recommendations.

Subpart C—MEASUREMENT INSTRUMENTS

§ 1065.201 Overview and general provisions.

(a) Scope. This subpart specifies measurement instruments and associated system requirements related to emission testing in a laboratory or similar environment and in the field. This includes laboratory instruments and portable emission measurement systems (PEMS) for measuring engine parameters, ambient conditions, flow-related parameters, and emission concentrations.

(b) Instrument types. You may use any of the specified instruments as described in this subpart to perform emission tests. If you want to use one of these instruments in a way that is not specified in this subpart, or if you want to use a different instrument, you must first get us to approve your alternate procedure under § 1065.10. Where we specify more than one instrument for a particular measurement, we may identify which instrument serves as the reference for comparing with an alternate procedure. You may generally use instruments with compensation algorithms that are functions of other gaseous measurements and the known or assumed fuel properties for the test fuel. The target value for any compensation algorithm is 0 % (that is, no bias high and no bias low), regardless of the uncompensated signal's bias.

(c) Measurement systems. Assemble a system of measurement instruments that allows you to show that your engines comply with the applicable emission standards, using good engineering judgment. When selecting instruments, consider how conditions such as vibration, temperature, pressure, humidity, viscosity, specific heat, and exhaust composition (including trace concentrations) may affect instrument compatibility and performance.

(d) Redundant systems. For all measurement instruments described in this subpart, you may use data from multiple instruments to calculate test results for a single test. If you use redundant systems, use good engineering judgment to use multiple measured values in calculations or to disregard individual measurements. Note that you must keep your results from all measurements. This requirement applies whether or not you actually use the measurements in your calculations.

(e) Range. You may use an instrument's response above 100 % of its operating range if this does not affect your ability to show that your engines comply with the applicable emission standards. Note that we require additional testing and reporting if an analyzer responds above 100 % of its range. Auto-ranging analyzers do not require additional testing or reporting.

(f) Related subparts for laboratory testing. Subpart D of this part describes how to evaluate the performance of the measurement instruments in this subpart. In general, if an instrument is specified in a specific section of this subpart, its calibration and verifications are typically specified in a similarly numbered section in subpart D of this part. For example, § 1065.290 gives instrument specifications for PM balances and § 1065.390 describes the corresponding calibrations and verifications. Note that some instruments also have other requirements in other sections of subpart D of this part. Subpart B of this part identifies specifications for other types of equipment, and subpart H of this part specifies engine fluids and analytical gases.

(g) Field testing and testing with PEMS. Subpart J of this part describes how to use these and other measurement instruments for field testing and other PEMS testing.

(h) Recommended practices. This subpart identifies a variety of recommended but not required practices for proper measurements. We believe in most cases it is necessary to follow these recommended practices for accurate and repeatable measurements. However, we do not specifically require you to follow these recommended practices to perform a valid test, as long as you meet the required calibrations and verifications of measurement systems specified in subpart

D of this part. Similarly, we are not required to follow all recommended practices, as long as we meet the required calibrations and verifications. Our decision to follow or not follow a given recommendation when we perform a test does not depend on whether you followed it during your testing.

§ 1065.202 Data updating, recording, and control.
Your test system must be able to update data, record data and control systems related to operator demand, the dynamometer, sampling equipment, and measurement instruments. Use data acquisition and control systems that can record at the specified minimum frequencies, as follows:

TABLE 1 OF § 1065.202–DATA RECORDING AND CONTROL MINIMUM FREQUENCIES

Applicable Test Protocol Section	Measured Values	Minimum Command and Control Frequency[a]	Minimum Recording Frequency[b,c]
§ 1065.510	Speed and torque during an engine step-map	1 Hz	1 mean value per step
§ 1065.510	Speed and torque during an engine sweep-map	5 Hz	1 Hz means
§ 1065.514 § 1065.530	Transient duty cycle reference and feedback speeds and torques	5 Hz	1 Hz means
§ 1065.514 § 1065.530	Steady-state and ramped-modal duty cycle reference and feedback speeds and torques	1 Hz	1 Hz
§ 1065.520 § 1065.530 § 1065.550	Continuous concentrations of raw or dilute analyzers	—	1 Hz
§ 1065.520 § 1065.530 § 1065.550	Batch concentrations of raw or dilute analyzers	—	1 mean value per test interval
§ 1065.530 § 1065.545	Diluted exhaust flow rate from a CVS with a heat exchanger upstream of the flow measurement	—	1 Hz
§ 1065.530 § 1065.545	Diluted exhaust flow rate from a CVS without a heat exchanger upstream of the flow measurement	5 Hz	1 Hz means
§ 1065.530 § 1065.545	Intake-air or raw-exhaust flow rate	—	1 Hz means
§ 1065.530 § 1065.545	Dilution air flow if actively controlled (for example, a partial-flow PM sampling system)[d]	5 Hz	1 Hz means
§ 1065.530 § 1065.545	Sample flow from a CVS that has a heat exchanger	1 Hz	1 Hz
§ 1065.530 § 1065.545	Sample flow from a CVS that does not have a heat exchanger	5 Hz	1 Hz means

[a]The specifications for minimum command and control frequency do not apply for CFVs that are not using active control.
[b]1 Hz means are data reported from the instrument at a higher frequency, but recorded as a series of 1 s mean values at a rate of 1 Hz.
[c]For CFVs in a CVS, the minimum recording frequency is 1 Hz. The minimum recording frequency does not apply for CFVs used to control sampling from a CVS utilizing CFVs.
[d]Dilution air flow specifications do not apply for CVS dilution air.

§ 1065.205 Performance specifications for measurement instruments.
Your test system as a whole must meet all the calibrations, verifications, and test-validation criteria specified outside this section for laboratory testing or field testing, as applicable. We recommend that your instruments meet the specifications in Table 1 of this section for all ranges

you use for testing. We also recommend that you keep any documentation you receive from instrument manufacturers showing that your instruments meet the specifications in Table 1 of this section.

TABLE 1 OF § 1065.205–RECOMMENDED PERFORMANCE SPECIFICATIONS FOR MEASUREMENT INSTRUMENTS

Measurement Instrument	Measured quantity symbol	Complete System Rise time ($t_{10\text{-}90}$) and Fall time ($t_{90\text{-}10}$)[a]	Recording update frequency	Accuracy[b]	Repeatability[b]	Noise[b]
Engine speed transducer	f_n	1 s	1 Hz means	2 % of pt. or 0.5 % of max.	1 % of pt. or 0.25 % of max.	0.05 % of max
Engine torque transducer	T	1 s	1 Hz means	2 % of pt. or 1 % of max.	1 % of pt. or 0.5 % of max	0.05 % of max.
Electrical work (active-power meter)	W	1 s	1 Hz means	2 % of pt. or 0.5 % of max.	1 % of pt. or 0.25 % of max.	0.05 % of max
General pressure transducer (not a part of another instrument)	p	5 s	1 Hz	2 % of pt. or 1 % of max.	1 % of pt. or 0.5 % of max.	0.1 % of max
Atmospheric pressure meter for PM-stabilization and balance environments	p_{atmos}	50 s	5 times per hour	50 Pa	25 Pa	5 Pa
General purpose atmospheric pressure meter	p_{atmos}	50 s	5 times per hour	250 Pa	100Pa	50 Pa
Temperature sensor for PM-stabilization and balance environments	T	50 s	0.1 Hz	0.25 K	0.1 K	0.1 K
Other temperature sensor (not a part of another instrument)	T	10 s	0.5 Hz	0.4 % of pt. K or 0.2 % of max. K	0.2 % of pt. K or 0.1 % of max. K	0.1 % of max
Dewpoint sensor for intake air, PM-stabilization and balance environments	T_{dew}	50 s	0.1 Hz	0.25 K	0.1 K	0.02 K
Other dewpoint sensor	T_{dew}	50 s	0.1 Hz	1 K	0.5 K	0.1 K
Fuel flow meter[c] (Fuel totalizer)	$\dot{m}$	5 s (—)	1 Hz (—)	2 % of pt. or 1.5 % of max.	1 % of pt. or 0.75 % of max.	0.5 % of max.
Total diluted exhaust meter (CVS)[c] (With heat exchanger before meter)	$\dot{n}$	1 s (5 s)	1 Hz means (1 Hz)	2 % of pt. or 1.5 % of max.	1 % of pt. or 0.75 % of max.	1 % of max.
Dilution air, inlet air, exhaust, and sample flow meters[c]	$\dot{n}$	1 s	1 Hz means of 5 Hz samples	2.5 % of pt. or 1.5 % of max.	1.25 % of pt. or 0.75 % of max.	1 % of max.
Continuous gas analyzer	x	5 s	1 Hz	2 % of pt. or 2 % of meas.	1 % of pt. or 1 % of meas.	1 % of max.
Batch gas analyzer	x	—	—	2 % of pt. or 2 % of meas.	1 % of pt. or 1 % of meas.	1 % of max.
Gravimetric PM balance	m_{PM}	-----	-----	See § 1065.790	0.5 µg	-----
Inertial PM balance	m_{PM}	5 s	1 Hz	2 % of pt. or 2 % of meas.	1 % of pt. or 1 % of meas.	0.2 % of max.

[a] The performance specifications identified in the table apply separately for rise time and fall time.

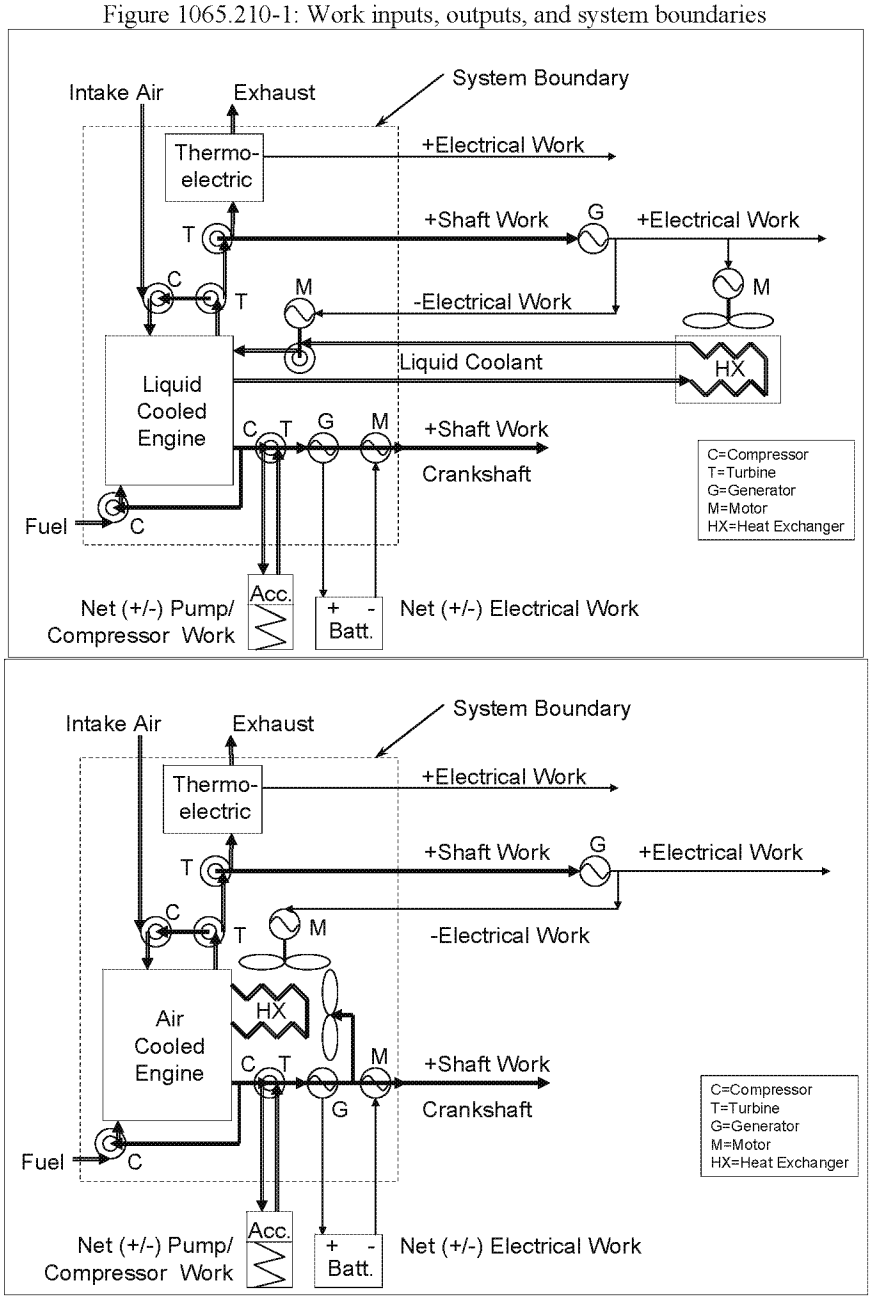
[b] Accuracy, repeatability, and noise are all determined with the same collected data, as described in § 1065.305, and based on absolute values. "pt." refers to the overall flow-weighted mean value expected at the standard; "max." refers to the peak value expected at the standard over any test interval, not the maximum of the instrument's range; "meas" refers to the actual flow-weighted mean measured over any test interval.

[c] The procedure for accuracy, repeatability and noise measurement described in § 1065.305 may be modified for flow meters to allow noise to be measured at the lowest calibrated value instead of zero flow rate.

§ 1065.210 Work input and output sensors.

(a) Application. Use instruments as specified in this section to measure work inputs and outputs during engine operation. We recommend that you use sensors, transducers, and meters that meet the specifications in Table 1 of § 1065.205. Note that your overall systems for measuring work inputs and outputs must meet the linearity verifications in § 1065.307. We recommend that you measure work inputs and outputs where they cross the system boundary as shown in Figure 1 of § 1065.210. The system boundary is different for air-cooled engines than for liquid-cooled engines. If you choose to measure work before or after a work conversion, relative to the system boundary, use good engineering judgment to estimate any work-conversion losses in a way that avoids overestimation of total work. For example, if it is impractical to instrument the shaft of an exhaust turbine generating electrical work, you may decide to measure its converted electrical work. As another example, you may decide to measure the tractive (i.e., electrical output) power of a locomotive, rather than the brake power of the locomotive engine. In these cases, divide the electrical work by accurate values of electrical generator efficiency ($\eta < 1$), or assume an efficiency of 1 ($\eta = 1$), which would over-estimate brake-specific emissions. For the example of using locomotive tractive power with a generator efficiency of 1 ($\eta = 1$), this means using the tractive power as the brake power in emission calculations. Do not underestimate any work conversion efficiencies for any components outside the system boundary that do not return work into the system boundary. And do not overestimate any work conversion efficiencies for components outside the system boundary that do return work into the system boundary. In all cases, ensure that you are able to accurately demonstrate compliance with the applicable standards.

Figure 1065.210-1: Work inputs, outputs, and system boundaries



(b) Shaft work. Use speed and torque transducer outputs to calculate total work according to § 1065.650.
(1) Speed. Use a magnetic or optical shaft-position detector with a resolution of at least 60 counts per revolution, in combination with a frequency counter that rejects common-mode noise.
(2) Torque. You may use a variety of methods to determine engine torque. As needed, and based on good engineering judgment, compensate for torque induced by the inertia of accelerating and decelerating components connected to the flywheel, such as the drive shaft and dynamometer rotor. Use any of the following methods to determine engine torque:
(i) Measure torque by mounting a strain gage or similar instrument in-line between the engine and dynamometer.
(ii) Measure torque by mounting a strain gage or similar instrument on a lever arm connected to the dynamometer housing.
(iii) Calculate torque from internal dynamometer signals, such as armature current, as long as you calibrate this measurement as described in § 1065.310.
(c) Electrical work. Use a watt-hour meter output to calculate total work according to § 1065.650. Use a watt-hour meter that outputs active power. Watt-hour meters typically combine a Wheatstone bridge voltmeter and a Hall-effect clamp-on ammeter into a single microprocessor-based instrument that analyzes and outputs several parameters, such as alternating or direct current voltage, current, power factor, apparent power, reactive power, and active power.
(d) Pump, compressor or turbine work. Use pressure transducer and flow-meter outputs to calculate total work according to § 1065.650. For flow meters, see § 1065.220 through § 1065.248.

§ 1065.215 Pressure transducers, temperature sensors, and dewpoint sensors.
(a) Application. Use instruments as specified in this section to measure pressure, temperature, and dewpoint.
(b) Component requirements. We recommend that you use pressure transducers, temperature sensors, and dewpoint sensors that meet the specifications in Table 1 of § 1065.205. Note that your overall systems for measuring pressure, temperature, and dewpoint must meet the calibration and verifications in § 1065.315.
(c) Temperature. For PM-balance environments or other precision temperature measurements over a narrow temperature range, we recommend thermistors. For other applications we recommend thermocouples that are not grounded to the thermocouple sheath. You may use other temperature sensors, such as resistive temperature detectors (RTDs).
(d) Pressure. Pressure transducers must be located in a temperature-controlled environment, or they must compensate for temperature changes over their expected operating range. Transducer materials must be compatible with the fluid being measured. For atmospheric pressure or other precision pressure measurements, we recommend either capacitance-type, quartz crystal, or laser-interferometer transducers. For other applications, we recommend either strain gage or capacitance-type pressure transducers. You may use other pressure-measurement instruments, such as manometers, where appropriate.
(e) Dewpoint. For PM-stabilization environments, we recommend chilled-surface hygrometers, which include chilled mirror detectors and chilled surface acoustic wave (SAW) detectors. For

other applications, we recommend thin-film capacitance sensors. You may use other dewpoint sensors, such as a wet-bulb/dry-bulb psychrometer, where appropriate.

FLOW-RELATED MEASUREMENTS

§ 1065.220 Fuel flow meter.
(a) Application. You may use fuel flow in combination with a chemical balance of fuel, inlet air, and raw exhaust to calculate raw exhaust flow as described in § 1065.655(e), as follows:
(1) Use the actual value of calculated raw exhaust flow rate in the following cases:
(i) For multiplying raw exhaust flow rate with continuously sampled concentrations.
(ii) For multiplying total raw exhaust flow with batch-sampled concentrations.
(iii) For calculating the dilution air flow for background correction as described in § 1065.667.
(2) In the following cases, you may use a fuel flow meter signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust molar flow rate's actual calculated value:
(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.
(ii) For multiplying with continuously sampled gas concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.
(b) Component requirements. We recommend that you use a fuel flow meter that meets the specifications in Table 1 of § 1065.205. We recommend a fuel flow meter that measures mass directly, such as one that relies on gravimetric or inertial measurement principles. This may involve using a meter with one or more scales for weighing fuel or using a Coriolis meter. Note that your overall system for measuring fuel flow must meet the linearity verification in § 1065.307 and the calibration and verifications in § 1065.320.
(c) Recirculating fuel. In any fuel-flow measurement, account for any fuel that bypasses the engine or returns from the engine to the fuel storage tank.
(d) Flow conditioning. For any type of fuel flow meter, condition the flow as needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a length equal to at least 10 pipe diameters) or by using specially designed tubing bends, straightening fins, or pneumatic pulsation dampeners to establish a steady and predictable velocity profile upstream of the meter. Condition the flow as needed to prevent any gas bubbles in the fuel from affecting the fuel meter.

§ 1065.225 Intake-air flow meter.
(a) Application. You may use an intake-air flow meter in combination with a chemical balance of fuel, inlet air, and exhaust to calculate raw exhaust flow as described in § 1065.655(e) and (f), as follows:
(1) Use the actual value of calculated raw exhaust in the following cases:
(i) For multiplying raw exhaust flow rate with continuously sampled concentrations.
(ii) For multiplying total raw exhaust flow with batch-sampled concentrations.
(iii) For verifying minimum dilution ratio for PM batch sampling as described in § 1065.546.

(iv) For calculating the dilution air flow for background correction as described in § 1065.667.
(2) In the following cases, you may use an intake-air flow meter signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust flow rate's actual calculated value:
(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.
(ii) For multiplying with continuously sampled gas concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.
(b) Component requirements. We recommend that you use an intake-air flow meter that meets the specifications in Table 1 of § 1065.205. This may include a laminar flow element, an ultrasonic flow meter, a subsonic venturi, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer. Note that your overall system for measuring intake-air flow must meet the linearity verification in § 1065.307 and the calibration in § 1065.325.
(c) Flow conditioning. For any type of intake-air flow meter, condition the flow as needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a length equal to at least 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

§ 1065.230 Raw exhaust flow meter.
(a) Application. You may use measured raw exhaust flow, as follows:
(1) Use the actual value of calculated raw exhaust in the following cases:
(i) Multiply raw exhaust flow rate with continuously sampled concentrations.
(ii) Multiply total raw exhaust with batch sampled concentrations.
(2) In the following cases, you may use a raw exhaust flow meter signal that does not give the actual value of raw exhaust, as long as it is linearly proportional to the exhaust flow rate's actual calculated value:
(i) For feedback control of a proportional sampling system, such as a partial-flow dilution system.
(ii) For multiplying with continuously sampled gas concentrations, if the same signal is used in a chemical-balance calculation to determine work from brake-specific fuel consumption and fuel consumed.
(b) Component requirements. We recommend that you use a raw-exhaust flow meter that meets the specifications in Table 1 of § 1065.205. This may involve using an ultrasonic flow meter, a subsonic venturi, an averaging Pitot tube, a hot-wire anemometer, or other measurement principle. This would generally not involve a laminar flow element or a thermal-mass meter. Note that your overall system for measuring raw exhaust flow must meet the linearity verification in § 1065.307 and the calibration and verifications in § 1065.330. Any raw-exhaust meter must be designed to appropriately compensate for changes in the raw exhaust's thermodynamic, fluid, and compositional states.
(c) Flow conditioning. For any type of raw exhaust flow meter, condition the flow as needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or

repeatability of the meter. You may accomplish this by using a sufficient length of straight tubing (such as a length equal to at least 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.
(d) Exhaust cooling. You may cool raw exhaust upstream of a raw-exhaust flow meter, as long as you observe all the following provisions:
(1) Do not sample PM downstream of the cooling.
(2) If cooling causes exhaust temperatures above 202 °C to decrease to below 180 °C, do not sample NMHC downstream of the cooling for compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW.
(3) The cooling must not cause aqueous condensation.

§ 1065.240 Dilution air and diluted exhaust flow meters.
(a) Application. Use a diluted exhaust flow meter to determine instantaneous diluted exhaust flow rates or total diluted exhaust flow over a test interval. You may use the difference between a diluted exhaust flow meter and a dilution air meter to calculate raw exhaust flow rates or total raw exhaust flow over a test interval.
(b) Component requirements. We recommend that you use a diluted exhaust flow meter that meets the specifications in Table 1 of § 1065.205. Note that your overall system for measuring diluted exhaust flow must meet the linearity verification in § 1065.307 and the calibration and verifications in § 1065.340 and § 1065.341. You may use the following meters:
(1) For constant-volume sampling (CVS) of the total flow of diluted exhaust, you may use a critical-flow venturi (CFV) or multiple critical-flow venturis arranged in parallel, a positive-displacement pump (PDP), a subsonic venturi (SSV), or an ultrasonic flow meter (UFM). Combined with an upstream heat exchanger, either a CFV or a PDP will also function as a passive flow controller in a CVS system. However, you may also combine any flow meter with any active flow control system to maintain proportional sampling of exhaust constituents. You may control the total flow of diluted exhaust, or one or more sample flows, or a combination of these flow controls to maintain proportional sampling.
(2) For any other dilution system, you may use a laminar flow element, an ultrasonic flow meter, a subsonic venturi, a critical-flow venturi or multiple critical-flow venturis arranged in parallel, a positive-displacement meter, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer.
(c) Flow conditioning. For any type of diluted exhaust flow meter, condition the flow as needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. For some meters, you may accomplish this by using a sufficient length of straight tubing (such as a length equal to at least 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.
(d) Exhaust cooling. You may cool diluted exhaust upstream of a dilute-exhaust flow meter, as long as you observe all the following provisions:
(1) Do not sample PM downstream of the cooling.

(2) If cooling causes exhaust temperatures above 202 °C to decrease to below 180 °C, do not sample NMHC downstream of the cooling for compression-ignition engines, two-stroke spark-ignition engines, or four-stroke spark-ignition engines at or below 19 kW.
(3) The cooling must not cause aqueous condensation as described in § 1065.140(c)(6).

§ 1065.245 Sample flow meter for batch sampling.
(a) Application. Use a sample flow meter to determine sample flow rates or total flow sampled into a batch sampling system over a test interval. You may use the difference between a diluted exhaust sample flow meter and a dilution air meter to calculate raw exhaust flow rates or total raw exhaust flow over a test interval.
(b) Component requirements. We recommend that you use a sample flow meter that meets the specifications in Table 1 of § 1065.205. This may involve a laminar flow element, an ultrasonic flow meter, a subsonic venturi, a critical-flow venturi or multiple critical-flow venturis arranged in parallel, a positive-displacement meter, a thermal-mass meter, an averaging Pitot tube, or a hot-wire anemometer. Note that your overall system for measuring sample flow must meet the linearity verification in § 1065.307. For the special case where CFVs are used for both the diluted exhaust and sample-flow measurements and their upstream pressures and temperatures remain similar during testing, you do not have to quantify the flow rate of the sample-flow CFV. In this special case, the sample-flow CFV inherently flow-weights the batch sample relative to the diluted exhaust CFV.
(c) Flow conditioning. For any type of sample flow meter, condition the flow as needed to prevent wakes, eddies, circulating flows, or flow pulsations from affecting the accuracy or repeatability of the meter. For some meters, you may accomplish this by using a sufficient length of straight tubing (such as a length equal to at least 10 pipe diameters) or by using specially designed tubing bends, orifice plates or straightening fins to establish a predictable velocity profile upstream of the meter.

§ 1065.248 Gas divider.
(a) Application. You may use a gas divider to blend calibration gases.
(b) Component requirements. Use a gas divider that blends gases to the specifications of § 1065.750 and to the flow-weighted concentrations expected during testing. You may use critical-flow gas dividers, capillary-tube gas dividers, or thermal-mass-meter gas dividers. Note that your overall gas-divider system must meet the linearity verification in § 1065.307.

CO AND CO_2 MEASUREMENTS

§ 1065.250 Nondispersive infrared analyzer.
(a) Application. Use a nondispersive infrared (NDIR) analyzer to measure CO and CO_2 concentrations in raw or diluted exhaust for either batch or continuous sampling.
(b) Component requirements. We recommend that you use an NDIR analyzer that meets the specifications in Table 1 of § 1065.205. Note that your NDIR-based system must meet the calibration and verifications in § § 1065.350 and 1065.355 and it must also meet the linearity verification in § 1065.307.

HYDROCARBON MEASUREMENTS

§ 1065.260 Flame-ionization detector.
(a) Application. Use a flame-ionization detector (FID) analyzer to measure hydrocarbon concentrations in raw or diluted exhaust for either batch or continuous sampling. Determine hydrocarbon concentrations on a carbon number basis of one, C_1. For measuring THC or THCE you must use a FID analyzer. For measuring CH_4 you must meet the requirements of paragraph (f) of this section. See subpart I of this part for special provisions that apply to measuring hydrocarbons when testing with oxygenated fuels.
(b) Component requirements. We recommend that you use a FID analyzer that meets the specifications in Table 1 of § 1065.205. Note that your FID-based system for measuring THC, THCE, or CH_4 must meet all the verifications for hydrocarbon measurement in subpart D of this part, and it must also meet the linearity verification in § 1065.307.
(c) Heated FID analyzers. For measuring THC or THCE from compression-ignition engines, two-stroke spark-ignition engines, and four-stroke spark-ignition engines at or below 19 kW, you must use heated FID analyzers that maintain all surfaces that are exposed to emissions at a temperature of (191 ±11) °C.
(d) FID fuel and burner air. Use FID fuel and burner air that meet the specifications of § 1065.750. Do not allow the FID fuel and burner air to mix before entering the FID analyzer to ensure that the FID analyzer operates with a diffusion flame and not a premixed flame.
(e) NMHC and NMOG. For demonstrating compliance with NMHC standards, you may either measure THC and CH_4 and determine NMHC as described in § 1065.660(b)(2) or (3), or you may measure THC and determine NMHC mass as described in § 1065.660(b)(1). See 40 CFR 1066.635 for methods to demonstrate compliance with NMOG standards for vehicle testing.
(f) CH_4. For reporting CH_4 or for demonstrating compliance with CH_4 standards, you may use a FID analyzer with a nonmethane cutter as described in § 1065.265 or you may use a GC-FID as described in § 1065.267. Determine CH_4 as described in § 1065.660(c).

§ 1065.265 Nonmethane cutter.
(a) Application. You may use a nonmethane cutter to measure CH_4 with a FID analyzer. A nonmethane cutter oxidizes all nonmethane hydrocarbons to CO_2 and H_2O. You may use a nonmethane cutter for raw or diluted exhaust for batch or continuous sampling.
(b) System performance. Determine nonmethane-cutter performance as described in § 1065.365 and use the results to calculate CH_4 or NMHC emissions in § 1065.660.
(c) Configuration. Configure the nonmethane cutter with a bypass line if it is needed for the verification described in § 1065.365.
(d) Optimization. You may optimize a nonmethane cutter to maximize the penetration of CH_4 and the oxidation of all other hydrocarbons. You may humidify a sample and you may dilute a sample with purified air or oxygen (O_2) upstream of the nonmethane cutter to optimize its performance. You must account for any sample humidification and dilution in emission calculations.

§ 1065.267 Gas chromatograph with a flame ionization detector.

(a) Application. You may use a gas chromatograph with a flame ionization detector (GC-FID) to measure CH_4 concentrations of diluted exhaust for batch sampling. While you may also use a nonmethane cutter to measure CH_4, as described in § 1065.265, use a reference procedure based on a gas chromatograph for comparison with any proposed alternate measurement procedure under § 1065.10.
(b) Component requirements. We recommend that you use a GC-FID that meets the specifications in Table 1 of § 1065.205 and that the measurement be done according to SAE J1151 (incorporated by reference in § 1065.1010). The GC-FID must meet the linearity verification in § 1065.307.

§ 1065.269 Photoacoustic analyzer for ethanol and methanol.
(a) Application. You may use a photoacoustic analyzer to measure ethanol and/or methanol concentrations in diluted exhaust for batch sampling.
(b) Component requirements. We recommend that you use a photoacoustic analyzer that meets the specifications in Table 1 of § 1065.205. Note that your photoacoustic system must meet the verification in § 1065.369 and it must also meet the linearity verification in § 1065.307. Use an optical wheel configuration that gives analytical priority to measurement of the least stable components in the sample. Select a sample integration time of at least 5 seconds. Take into account sample chamber and sample line volumes when determining flush times for your instrument.

NO_x AND N_2O MEASUREMENTS

§ 1065.270 Chemiluminescent detector.
(a) Application. You may use a chemiluminescent detector (CLD) to measure NO_x concentration in raw or diluted exhaust for batch or continuous sampling. We generally accept a CLD for NO_x measurement, even though it measures only NO and NO_2, when coupled with an NO_2-to-NO converter, since conventional engines and aftertreatment systems do not emit significant amounts of NO_x species other than NO and NO_2. Measure other NO_x species if required by the standard-setting part. While you may also use other instruments to measure NO_x, as described in § 1065.272, use a reference procedure based on a chemiluminescent detector for comparison with any proposed alternate measurement procedure under § 1065.10.
(b) Component requirements. We recommend that you use a CLD that meets the specifications in Table 1 of § 1065.205. Note that your CLD-based system must meet the quench verification in § 1065.370 and it must also meet the linearity verification in § 1065.307. You may use a heated or unheated CLD, and you may use a CLD that operates at atmospheric pressure or under a vacuum.
(c) NO_2-to-NO converter. Place upstream of the CLD an internal or external NO_2-to-NO converter that meets the verification in § 1065.378. Configure the converter with a bypass line if it is needed to facilitate this verification.
(d) Humidity effects. You must maintain all CLD temperatures to prevent aqueous condensation. If you remove humidity from a sample upstream of a CLD, use one of the following configurations:

(1) Connect a CLD downstream of any dryer or chiller that is downstream of an NO_2-to-NO converter that meets the verification in § 1065.378.
(2) Connect a CLD downstream of any dryer or thermal chiller that meets the verification in § 1065.376.
(e) Response time. You may use a heated CLD to improve CLD response time.

§ 1065.272 Nondispersive ultraviolet analyzer.
(a) Application. You may use a nondispersive ultraviolet (NDUV) analyzer to measure NO_x concentration in raw or diluted exhaust for batch or continuous sampling. We generally accept an NDUV for NO_x measurement, even though it measures only NO and NO_2, since conventional engines and aftertreatment systems do not emit significant amounts of other NO_x species. Measure other NO_x species if required by the standard-setting part. Note that good engineering judgment may preclude you from using an NDUV analyzer if sampled exhaust from test engines contains oil (or other contaminants) in sufficiently high concentrations to interfere with proper operation.
(b) Component requirements. We recommend that you use an NDUV analyzer that meets the specifications in Table 1 of § 1065.205. Note that your NDUV-based system must meet the verifications in § 1065.372 and it must also meet the linearity verification in § 1065.307.
(c) NO_2-to-NO converter. If your NDUV analyzer measures only NO, place upstream of the NDUV analyzer an internal or external NO_2-to-NO converter that meets the verification in § 1065.378. Configure the converter with a bypass to facilitate this verification.
(d) Humidity effects. You must maintain NDUV temperature to prevent aqueous condensation, unless you use one of the following configurations:
(1) Connect an NDUV downstream of any dryer or chiller that is downstream of an NO_2-to-NO converter that meets the verification in § 1065.378.
(2) Connect an NDUV downstream of any dryer or thermal chiller that meets the verification in § 1065.376.

§ 1065.275 N_2O measurement devices.
(a) General component requirements. We recommend that you use an analyzer that meets the specifications in Table 1 of § 1065.205. Note that your system must meet the linearity verification in § 1065.307.
(b) Instrument types. You may use any of the following analyzers to measure N_2O:
(1) Nondispersive infrared (NDIR) analyzer.
(2) Fourier transform infrared (FTIR) analyzer. Use appropriate analytical procedures for interpretation of infrared spectra. For example, EPA Test Method 320 is considered a valid method for spectral interpretation (see http://www.epa.gov/ttn/emc/methods/method320.html).
(3) Laser infrared analyzer. Examples of laser infrared analyzers are pulsed-mode high-resolution narrow band mid-infrared analyzers, and modulated continuous wave high-resolution narrow band mid-infrared analyzers.
(4) Photoacoustic analyzer. Use an optical wheel configuration that gives analytical priority to measurement of the least stable components in the sample. Select a sample integration time of at least 5 seconds. Take into account sample chamber and sample line volumes when determining flush times for your instrument.

(5) Gas chromatograph analyzer. You may use a gas chromatograph with an electron-capture detector (GC-ECD) to measure N_2O concentrations of diluted exhaust for batch sampling.
(i)You may use a packed or porous layer open tubular (PLOT) column phase of suitable polarity and length to achieve adequate resolution of the N_2O peak for analysis. Examples of acceptable columns are a PLOT column consisting of bonded polystyrene-divinylbenzene or a Porapack Q packed column. Take the column temperature profile and carrier gas selection into consideration when setting up your method to achieve adequate N_2O peak resolution.
(ii) Use good engineering judgment to zero your instrument and correct for drift. You do not need to follow the specific procedures in § § 1065.530 and 1065.550(b) that would otherwise apply. For example, you may perform a span gas measurement before and after sample analysis without zeroing and use the average area counts of the pre-span and post-span measurements to generate a response factor (area counts/span gas concentration), which you then multiply by the area counts from your sample to generate the sample concentration.
(c) Interference verification. Perform interference verification for NDIR, FTIR, laser infrared analyzers, and photoacoustic analyzers using the procedures of § 1065.375. Interference verification is not required for GC-ECD. Certain interference gases can positively interfere with NDIR, FTIR, and photoacoustic analyzers by causing a response similar to N_2O. When running the interference verification for these analyzers, use interference gases as follows:
(1) The interference gases for NDIR analyzers are CO, CO_2, H_2O, CH_4, and SO_2. Note that interference species, with the exception of H_2O, are dependent on the N_2O infrared absorption band chosen by the instrument manufacturer. For each analyzer determine the N_2O infrared absorption band. For each N_2O infrared absorption band, use good engineering judgment to determine which interference gases to use in the verification.
(2) Use good engineering judgment to determine interference gases for FTIR, and laser infrared analyzers. Note that interference species, with the exception of H_2O, are dependent on the N_2O infrared absorption band chosen by the instrument manufacturer. For each analyzer determine the N_2O infrared absorption band. For each N_2O infrared absorption band, use good engineering judgment to determine interference gases to use in the verification.
(3) The interference gases for photoacoustic analyzers are CO, CO_2, and H_2O.

O_2 Measurements

§ 1065.280 Paramagnetic and magnetopneumatic O_2 detection analyzers.
(a) Application. You may use a paramagnetic detection (PMD) or magnetopneumatic detection (MPD) analyzer to measure O_2 concentration in raw or diluted exhaust for batch or continuous sampling. You may use O_2 measurements with intake air or fuel flow measurements to calculate exhaust flow rate according to § 1065.650.
(b) Component requirements. We recommend that you use a PMD or MPD analyzer that meets the specifications in Table 1 of § 1065.205. Note that it must meet the linearity verification in § 1065.307.

Air-to-Fuel Ratio Measurements

§ 1065.284 Zirconia (ZrO_2) analyzer.

(a) Application. You may use a zirconia (ZrO_2) analyzer to measure air-to-fuel ratio in raw exhaust for continuous sampling. You may use O_2 measurements with intake air or fuel flow measurements to calculate exhaust flow rate according to § 1065.650.
(b) Component requirements. We recommend that you use a ZrO_2 analyzer that meets the specifications in Table 1 of § 1065.205. Note that your ZrO_2-based system must meet the linearity verification in § 1065.307.

PM MEASUREMENTS

§ 1065.290 PM gravimetric balance.
(a) Application. Use a balance to weigh net PM on a sample medium for laboratory testing.
(b) Component requirements. We recommend that you use a balance that meets the specifications in Table 1 of § 1065.205. Note that your balance-based system must meet the linearity verification in § 1065.307. If the balance uses internal calibration weights for routine spanning and the weights do not meet the specifications in § 1065.790, the weights must be verified independently with external calibration weights meeting the requirements of § 1065.790. While you may also use an inertial balance to measure PM, as described in § 1065.295, use a reference procedure based on a gravimetric balance for comparison with any proposed alternate measurement procedure under § 1065.10.
(c) Pan design. We recommend that you use a balance pan designed to minimize corner loading of the balance, as follows:
(1) Use a pan that centers the PM sample media (such as a filter) on the weighing pan. For example, use a pan in the shape of a cross that has upswept tips that center the PM sample media on the pan.
(2) Use a pan that positions the PM sample as low as possible.
(d) Balance configuration. Configure the balance for optimum settling time and stability at your location.

§ 1065.295 PM inertial balance for field-testing analysis.
(a) Application. You may use an inertial balance to quantify net PM on a sample medium for field testing.
(b) Component requirements. We recommend that you use a balance that meets the specifications in Table 1 of § 1065.205. Note that your balance-based system must meet the linearity verification in § 1065.307. If the balance uses an internal calibration process for routine spanning and linearity verifications, the process must be NIST-traceable.
(c) Loss correction. You may use PM loss corrections to account for PM loss in the inertial balance, including the sample handling system.
(d) Deposition. You may use electrostatic deposition to collect PM, as long as its collection efficiency is at least 95%.

Subpart D—CALIBRATIONS AND VERIFICATIONS

§ 1065.301 Overview and general provisions.

(a) This subpart describes required and recommended calibrations and verifications of measurement systems. See subpart C of this part for specifications that apply to individual instruments.

(b) You must generally use complete measurement systems when performing calibrations or verifications in this subpart. For example, this would generally involve evaluating instruments based on values recorded with the complete system you use for recording test data, including analog-to-digital converters. For some calibrations and verifications, we may specify that you disconnect part of the measurement system to introduce a simulated signal.

(c) If we do not specify a calibration or verification for a portion of a measurement system, calibrate that portion of your system and verify its performance at a frequency consistent with any recommendations from the measurement-system manufacturer, consistent with good engineering judgment.

(d) Use NIST-traceable standards to the tolerances we specify for calibrations and verifications. Where we specify the need to use NIST-traceable standards, you may alternatively ask for our approval to use international standards that are not NIST-traceable.

§ 1065.303 Summary of required calibration and verifications.

The following table summarizes the required and recommended calibrations and verifications described in this subpart and indicates when these have to be performed:

TABLE 1 OF § 1065.303–SUMMARY OF REQUIRED CALIBRATION AND VERIFICATIONS

Type of calibration or verification	Minimum frequency[1]
§ 1065.305: Accuracy, repeatability and noise	Accuracy: Not required, but recommended for initial installation. Repeatability: Not required, but recommended for initial installation. Noise: Not required, but recommended for initial installation.

§ 1065.307: Linearity verification	Speed: Upon initial installation, within 370 days before testing and after major maintenance. Torque: Upon initial installation, within 370 days before testing and after major maintenance. Electrical power, current, and voltage: Upon initial installation, within 370 days before testing and after major maintenance.[2] Fuel flow rate: Upon initial installation, within 370 days before testing, and after major maintenance. Intake-air, dilution air, diluted exhaust, and batch sampler flow rates: Upon initial installation, within 370 days before testing and after major maintenance, unless flow is verified by propane check or by carbon or oxygen balance. Raw exhaust flow rate: Upon initial installation, within 185 days before testing and after major maintenance, unless flow is verified by propane check or by carbon or oxygen balance. Gas dividers: Upon initial installation, within 370 days before testing, and after major maintenance. Gas analyzers (unless otherwise noted): Upon initial installation, within 35 days before testing and after major maintenance. FTIR and photoacoustic analyzers: Upon initial installation, within 370 days before testing and after major maintenance. GC-ECD: Upon initial installation and after major maintenance. PM balance: Upon initial installation, within 370 days before testing and after major maintenance. Pressure, temperature, and dewpoint: Upon initial installation, within 370 days before testing and after major maintenance.
§ 1065.308: Continuous gas analyzer system response and updating-recording verification—for gas analyzers not continuously compensated for other gas species	Upon initial installation or after system modification that would affect response.
§ 1065.309: Continuous gas analyzer system-response and updating-recording verification—for gas analyzers continuously compensated for other gas species	Upon initial installation or after system modification that would affect response.
§ 1065.310: Torque	Upon initial installation and after major maintenance.
§ 1065.315: Pressure, temperature, dewpoint	Upon initial installation and after major maintenance.
§ 1065.320: Fuel flow	Upon initial installation and after major maintenance.
§ 1065.325: Intake flow	Upon initial installation and after major maintenance.
§ 1065.330: Exhaust flow	Upon initial installation and after major maintenance.
§ 1065.340: Diluted exhaust flow (CVS)	Upon initial installation and after major maintenance.
§ 1065.341: CVS and batch sampler verification[3]	Upon initial installation, within 35 days before testing, and after major maintenance.
§ 1065.342 Sample dryer verification	For thermal chillers: upon installation and after major maintenance. For osmotic membranes; upon installation, within 35 days of testing, and after major maintenance.
§ 1065.345: Vacuum leak	For laboratory testing: upon initial installation of the sampling system, within 8 hours before the start of the first test interval of each duty-cycle sequence, and after maintenance such as pre-filter changes. For field testing: after each installation of the sampling system on the vehicle, prior to the start of the field test, and after maintenance such as pre-filter changes.
§ 1065.350: CO_2 NDIR H_2O interference	Upon initial installation and after major maintenance.
§ 1065.355: CO NDIR CO_2 and H_2O interference	Upon initial installation and after major maintenance.
§ 1065.360: FID calibration THC FID optimization, and THC FID verification	Calibrate all FID analyzers: upon initial installation and after major maintenance. Optimize and determine CH_4 response for THC FID analyzers: upon initial installation and after major maintenance. Verify CH_4 response for THC FID analyzers: upon initial installation, within 185 days before testing, and after major maintenance.

§ 1065.362: Raw exhaust FID O_2 interference	For all FID analyzers: upon initial installation, and after major maintenance. For THC FID analyzers: upon initial installation, after major maintenance, and after FID optimization according to § 1065.360.
§ 1065.365: Nonmethane cutter penetration	Upon initial installation, within 185 days before testing, and after major maintenance.
§ 1065.369: H_2O, CO, and CO_2 interference verification for ethanol photoacoustic analyzers	Upon initial installation and after major maintenance.
§ 1065.370: CLD CO_2 and H_2O quench	Upon initial installation and after major maintenance.
§ 1065.372: NDUV HC and H_2O interference	Upon initial installation and after major maintenance.
§ 1065.375: N_2O analyzer interference	Upon initial installation and after major maintenance.
§ 1065.376: Chiller NO_2 penetration	Upon initial installation and after major maintenance.
§ 1065.378: NO_2-to-NO converter conversion	Upon initial installation, within 35 days before testing, and after major maintenance.
§ 1065.390: PM balance and weighing	Independent verification: upon initial installation, within 370 days before testing, and after major maintenance. Zero, span, and reference sample verifications: within 12 hours of weighing, and after major maintenance.
§ 1065.395: Inertial PM balance and weighing	Independent verification: upon initial installation, within 370 days before testing, and after major maintenance. Other verifications: upon initial installation and after major maintenance.

[1]Perform calibrations and verifications more frequently than we specify, according to measurement system manufacturer instructions and good engineering judgment.
[2]Perform linearity verification either for electrical power or for current and voltage.
[3]The CVS verification described in § 1065.341 is not required for systems that agree within ±2 % based on a chemical balance of carbon or oxygen of the intake air, fuel, and diluted exhaust.

§ 1065.305 Verifications for accuracy, repeatability, and noise.

(a) This section describes how to determine the accuracy, repeatability, and noise of an instrument. Table 1 of § 1065.205 specifies recommended values for individual instruments.

(b) We do not require you to verify instrument accuracy, repeatability, or noise. However, it may be useful to consider these verifications to define a specification for a new instrument, to verify the performance of a new instrument upon delivery, or to troubleshoot an existing instrument.

(c) In this section we use the letter "y" to denote a generic measured quantity, the superscript over-bar to denote an arithmetic mean (such as $\overline{y}$), and the subscript "$_{ref}$" to denote the reference quantity being measured.

(d) Conduct these verifications as follows:

(1) Prepare an instrument so it operates at its specified temperatures, pressures, and flows. Perform any instrument linearization or calibration procedures prescribed by the instrument manufacturer.

(2) Zero the instrument as you would before an emission test by introducing a zero signal. Depending on the instrument, this may be a zero-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gas analyzers, use a zero gas that meets the specifications of § 1065.750.

(3) Span the instrument as you would before an emission test by introducing a span signal. Depending on the instrument, this may be a span-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gas analyzers, use a span gas that meets the specifications of § 1065.750.

(4) Use the instrument to quantify a NIST-traceable reference quantity, y_{ref}. For gas analyzers the reference gas must meet the specifications of § 1065.750. Select a reference quantity near the mean value expected during testing. For all gas analyzers, use a quantity near the flow-weighted mean concentration expected at the standard or expected during testing, whichever is greater. For noise verification, use the same zero gas from paragraph (d)(2) of this section as the reference quantity. In all cases, allow time for the instrument to stabilize while it measures the reference quantity. Stabilization time may include time to purge an instrument and time to account for its response.

(5) Sample and record values for 30 seconds (you may select a longer sampling period if the recording update frequency is less than 0.5 Hz), record the arithmetic mean, $\overline{y}_i$ and record the standard deviation, σ_i of the recorded values. Refer to § 1065.602 for an example of calculating arithmetic mean and standard deviation.

(6) Also, if the reference quantity is not absolutely constant, which might be the case with a reference flow, sample and record values of y_{refi} for 30 seconds and record the arithmetic mean of the values, $\overline{y}_{ref}$. Refer to § 1065.602 for an example of calculating arithmetic mean.

(7) Subtract the reference value, y_{ref} (or $\overline{y}_{refi}$), from the arithmetic mean, $\overline{y}_i$. Record this value as the error, ε_i.

(8) Repeat the steps specified in paragraphs (d)(2) through (7) of this section until you have ten arithmetic means ($\overline{y}_1$, $\overline{y}_2$, $\overline{y}_i$,... $\overline{y}_{10}$), ten standard deviations, (σ_1, σ_2, σ_i,...σ_{10}), and ten errors (ε_1, ε_2, ε_i,...ε_{10}).

(9) Use the following values to quantify your measurements:

(i) Accuracy. Instrument accuracy is the absolute difference between the reference quantity, y_{ref} (or $\overline{y}_{ref}$), and the arithmetic mean of the ten $\overline{y}_i$ values, $\overline{y}$. Refer to the example of an accuracy calculation in § 1065.602. We recommend that instrument accuracy be within the specifications in Table 1 of § 1065.205.

(ii) Repeatability. Repeatability is two times the standard deviation of the ten errors (that is, repeatability = $2\sigma_\varepsilon$). Refer to the example of a standard-deviation calculation in § 1065.602. We recommend that instrument repeatability be within the specifications in Table 1 of § 1065.205.

(iii) Noise. Noise is two times the root-mean-square of the ten standard deviations (that is, noise = $2 \cdot rms_\sigma$) when the reference signal is a zero-quantity signal. Refer to the example of a root-mean-square calculation in § 1065.602. We recommend that instrument noise be within the specifications in Table 1 of § 1065.205.

(10) You may use a measurement instrument that does not meet the accuracy, repeatability, or noise specifications in Table 1 of § 1065.205, as long as you meet the following criteria:

(i) Your measurement systems meet all the other required calibration, verification, and validation specifications that apply as specified in the regulations.

(ii) The measurement deficiency does not adversely affect your ability to demonstrate compliance with the applicable standards.

§ 1065.307 Linearity verification.

(a) Scope and frequency. Perform linearity verification on each measurement system listed in Table 1 of this section at least as frequently as indicated in Table 1 of § 1065.303, consistent with measurement system manufacturer's recommendations and good engineering judgment. The intent of linearity verification is to determine that a measurement system responds accurately and proportionally over the measurement range of interest. Linearity verification generally consists of introducing a series of at least 10 reference values to a measurement system. The measurement system quantifies each reference value. The measured values are then collectively compared to the reference values by using a least-squares linear regression and the linearity criteria specified in Table 1 of this section.

(b) Performance requirements. If a measurement system does not meet the applicable linearity criteria referenced in Table 1 of this section, correct the deficiency by re-calibrating, servicing, or replacing components as needed. Repeat the linearity verification after correcting the deficiency to ensure that the measurement system meets the linearity criteria. Before you may use a measurement system that does not meet linearity criteria, you must demonstrate to us that the deficiency does not adversely affect your ability to demonstrate compliance with the applicable standards.

(c) Procedure. Use the following linearity verification protocol, or use good engineering judgment to develop a different protocol that satisfies the intent of this section, as described in paragraph (a) of this section:

(1) In this paragraph (c), the letter "y" denotes a generic measured quantity, the superscript over-bar denotes an arithmetic mean (such as $\bar{y}$), and the subscript "$_{ref}$" denotes the known or reference quantity being measured.

(2) Use good engineering judgment to operate a measurement system at normal operating conditions. This may include any specified adjustment or periodic calibration of the measurement system.

(3) If applicable, zero the instrument as you would before an emission test by introducing a zero signal. Depending on the instrument, this may be a zero-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gas analyzers, use a zero gas that meets the specifications of § 1065.750 and introduce it directly at the analyzer port.

(4) If applicable, span the instrument as you would before an emission test by introducing a span signal. Depending on the instrument, this may be a span-concentration gas, a reference signal, a set of reference thermodynamic conditions, or some combination of these. For gas analyzers, use a span gas that meets the specifications of § 1065.750 and introduce it directly at the analyzer port.

(5) If applicable, after spanning the instrument, check zero with the same signal you used in paragraph (c)(3) of this section. Based on the zero reading, use good engineering judgment to determine whether or not to rezero and or re-span the instrument before continuing.

(6) For all measured quantities, use the instrument manufacturer's recommendations and good engineering judgment to select reference values, y_{refi}, that cover a range of values that you expect would prevent extrapolation beyond these values during emission testing. We recommend selecting a zero reference signal as one of the reference values for the linearity verification. For pressure, temperature, dewpoint, power, current, voltage, photoacoustic analyzers, and GC-ECD

linearity verifications, we recommend at least three reference values. For all other linearity verifications select at least ten reference values.
(7) Use the instrument manufacturer's recommendations and good engineering judgment to select the order in which you will introduce the series of reference values. For example, you may select the reference values randomly to avoid correlation with previous measurements and to avoid hysteresis; you may select reference values in ascending or descending order to avoid long settling times of reference signals; or you may select values to ascend and then descend to incorporate the effects of any instrument hysteresis into the linearity verification.
(8) Generate reference quantities as described in paragraph (d) of this section. For gas analyzers, use gas concentrations known to be within the specifications of § 1065.750 and introduce them directly at the analyzer port.
(9) Introduce a reference signal to the measurement instrument.
(10) Allow time for the instrument to stabilize while it measures the value at the reference condition. Stabilization time may include time to purge an instrument and time to account for its response.
(11) At a recording frequency of at least f Hz, specified in Table 1 of § 1065.205, measure the value at the reference condition for 30 seconds (you may select a longer sampling period if the recording update frequency is less than 0.5 Hz) and record the arithmetic mean of the recorded values, $\overline{y}_i$. Refer to § 1065.602 for an example of calculating an arithmetic mean.
(12) Repeat the steps in paragraphs (c)(9) though (11) of this section until measurements are complete at each of the reference conditions.
(13) Use the arithmetic means, $\overline{y}_i$, and reference values, y_{refi}, to calculate least-squares linear regression parameters and statistical values to compare to the minimum performance criteria specified in Table 1 of this section. Use the calculations described in § 1065.602. Using good engineering judgment, you may weight the results of individual data pairs (i.e. (y_{refi}, $\overline{y}_i$)), in the linear regression calculations.
(d) Reference signals. This paragraph (d) describes recommended methods for generating reference values for the linearity-verification protocol in paragraph (c) of this section. Use reference values that simulate actual values, or introduce an actual value and measure it with a reference-measurement system. In the latter case, the reference value is the value reported by the reference-measurement system. Reference values and reference-measurement systems must be NIST-traceable. We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty, if not specified elsewhere in this part 1065. Use the following recommended methods to generate reference values or use good engineering judgment to select a different reference:
(1) Speed. Run the engine or dynamometer at a series of steady-state speeds and use a strobe, photo tachometer, or laser tachometer to record reference speeds.
(2) Torque. Use a series of calibration weights and a calibration lever arm to simulate engine torque. You may instead use the engine or dynamometer itself to generate a nominal torque that is measured by a reference load cell or proving ring in series with the torque-measurement system. In this case, use the reference load cell measurement as the reference value. Refer to § 1065.310 for a torque-calibration procedure similar to the linearity verification in this section.
(3) Electrical power, current, and voltage. You must perform linearity verification for either electrical power meters, or for current and voltage meters. Perform linearity verifications using a

reference meter and controlled sources of current and voltage. We recommend using a complete calibration system that is suitable for the electrical power distribution industry.

(4) Fuel rate. Operate the engine at a series of constant fuel-flow rates or re-circulate fuel back to a tank through the fuel flow meter at different flow rates. Use a gravimetric reference measurement (such as a scale, balance, or mass comparator) at the inlet to the fuel-measurement system. Use a stopwatch or timer to measure the time intervals over which reference masses of fuel are introduced to the fuel measurement system. The reference fuel mass divided by the time interval is the reference fuel flow rate.

(5) Flow rates—inlet air, dilution air, diluted exhaust, raw exhaust, or sample flow. Use a reference flow meter with a blower or pump to simulate flow rates. Use a restrictor, diverter valve, a variable-speed blower or a variable-speed pump to control the range of flow rates. Use the reference meter's response as the reference values.

(i) Reference flow meters. Because the flow range requirements for these various flows are large, we allow a variety of reference meters. For example, for diluted exhaust flow for a full-flow dilution system, we recommend a reference subsonic venturi flow meter with a restrictor valve and a blower to simulate flow rates. For inlet air, dilution air, diluted exhaust for partial-flow dilution, raw exhaust, or sample flow, we allow reference meters such as critical flow orifices, critical flow venturis, laminar flow elements, master mass flow standards, or Roots meters. Make sure the reference meter is calibrated and its calibration is NIST-traceable. If you use the difference of two flow measurements to determine a net flow rate, you may use one of the measurements as a reference for the other.

(ii) Reference flow values. Because the reference flow is not absolutely constant, sample and record values of $\dot{n}_{\mathrm{refi}}$ for 30 seconds and use the arithmetic mean of the values, $\overline{\dot{n}}_{\mathrm{ref}}$, as the reference value. Refer to § 1065.602 for an example of calculating arithmetic mean.

(6) Gas division. Use one of the two reference signals:

(i) At the outlet of the gas-division system, connect a gas analyzer that meets the linearity verification described in this section and has not been linearized with the gas divider being verified. For example, verify the linearity of an analyzer using a series of reference analytical gases directly from compressed gas cylinders that meet the specifications of § 1065.750. We recommend using a FID analyzer or a PMD or MPD O_2 analyzer because of their inherent linearity. Operate this analyzer consistent with how you would operate it during an emission test. Connect a span gas to the gas-divider inlet. Use the gas-division system to divide the span gas with purified air or nitrogen. Select gas divisions that you typically use. Use a selected gas division as the measured value. Use the analyzer response divided by the span gas concentration as the reference gas-division value. Because the instrument response is not absolutely constant, sample and record values of x_{refi} for 30 seconds and use the arithmetic mean of the values, $\overline{x}_{\mathrm{ref}}$, as the reference value. Refer to § 1065.602 for an example of calculating arithmetic mean.

(ii) Using good engineering judgment and the gas divider manufacturer's recommendations, use one or more reference flow meters to measure the flow rates of the gas divider and verify the gas-division value.

(7) Continuous constituent concentration. For reference values, use a series of gas cylinders of known gas concentration or use a gas-division system that is known to be linear with a span gas. Gas cylinders, gas-division systems, and span gases that you use for reference values must meet the specifications of § 1065.750.

(8) Temperature. You may perform the linearity verification for temperature measurement systems with thermocouples, RTDs, and thermistors by removing the sensor from the system and using a simulator in its place. Use a NIST-traceable simulator that is independently calibrated and, as appropriate, cold-junction-compensated. The simulator uncertainty scaled to absolute temperature must be less than 0.5 % of T_{max}. If you use this option, you must use sensors that the supplier states are accurate to better than 0.5 % of T_{max} compared with their standard calibration curve.
(9) Mass. For linearity verification for gravimetric PM balances, use external calibration weights that meet the requirements in § 1065.790.
(e) Measurement systems that require linearity verification. Table 1 of this section indicates measurement systems that require linearity verification, subject to the following provisions:
(1) Perform linearity verification more frequently based on the instrument manufacturer's recommendation or good engineering judgment.
(2) The expression "x_{min}" refers to the reference value used during linearity verification that is closest to zero. This is the value used to calculate the first tolerance in Table 1 of this section using the intercept, a_0. Note that this value may be zero, positive, or negative depending on the reference values. For example, if the reference values chosen to validate a pressure transducer vary from -10 to -1 kPa, x_{min} is -1 kPa. If the reference values used to validate a temperature device vary from 290 to 390 K, x_{min} is 290 K.
(3) The expression "max" generally refers to the absolute value of the reference value used during linearity verification that is furthest from zero. This is the value used to scale the first and third tolerances in Table 1 of this section using a_0 and *SEE*. For example, if the reference values chosen to validate a pressure transducer vary from -10 to -1 kPa, then p_{max} is +10 kPa. If the reference values used to validate a temperature device vary from 290 to 390 K, then T_{max} is 390 K. For gas dividers where "max" is expressed as, x_{max}/x_{span}; x_{max} is the maximum gas concentration used during the verification, x_{span} is the undivided, undiluted, span gas concentration, and the resulting ratio is the maximum divider point reference value used during the verification (typically 1). The following are special cases where "max" refers to a different value:
(i) For linearity verification with a PM balance, m_{max} refers to the typical mass of a PM filter.
(ii) For linearity verification of torque on the engine's primary output shaft, T_{max} refers to the manufacturer's specified engine torque peak value of the lowest torque engine to be tested.
(4) The specified ranges are inclusive. For example, a specified range of 0.98-1.02 for a_1 means $0.98 \leq a_1 \leq 1.02$.
(5) Linearity verification is optional for systems that pass the flow-rate verification for diluted exhaust as described in § 1065.341 (the propane check) or for systems that agree within ±2 % based on a chemical balance of carbon or oxygen of the intake air, fuel, and exhaust.
(6) You must meet the a_1 criteria for these quantities only if the absolute value of the quantity is required, as opposed to a signal that is only linearly proportional to the actual value.
(7) Linearity verification is required for the following temperature measurements:
(i) The following temperature measurements always require linearity verification:
(A) Air intake.
(B) Aftertreatment bed(s), for engines tested with aftertreatment devices subject to cold-start testing.

(C) Dilution air for gaseous and PM sampling, including CVS, double-dilution, and partial-flow systems.
(D) PM sample.
(E) Chiller sample, for gaseous sampling systems that use thermal chillers to dry samples and use chiller temperature to calculate the dewpoint at the outlet of the chiller. For your testing, if you choose to use a high alarm temperature setpoint for the chiller temperature as a constant value in determining the amount of water removed from the emission sample, you may use good engineering judgment to verify the accuracy of the high alarm temperature setpoint instead of linearity verification on the chiller temperature. To verify that the alarm trip point value is no less than 2.0 °C below the reference value at the trip point, we recommend that you input a reference simulated temperature signal below the alarm trip point and increase this signal until the high alarm trips.
(ii) Linearity verification is required for the following temperature measurements if these temperature measurements are specified by the engine manufacturer:
(A) Fuel inlet.
(B) Air outlet to the test cell's charge air cooler air outlet, for engines tested with a laboratory heat exchanger that simulates an installed charge air cooler.
(C) Coolant inlet to the test cell's charge air cooler, for engines tested with a laboratory heat exchanger that simulates an installed charge air cooler.
(D) Oil in the sump/pan.
(E) Coolant before the thermostat, for liquid-cooled engines.
(8) Linearity verification is required for the following pressure measurements:
(i) The following pressure measurements always require linearity verification:
(A) Air intake restriction.
(B) Exhaust back pressure as required in § 1065.130(h).
(C) Barometer.
(D) CVS inlet gage pressure where the raw exhaust enters the tunnel.
(E) Sample dryer, for gaseous sampling systems that use either osmotic-membrane or thermal chillers to dry samples. For your testing, if you choose to use a low alarm pressure setpoint for the sample dryer pressure as a constant value in determining the amount of water removed from the emission sample, you may use good engineering judgment to verify the accuracy of the low alarm pressure setpoint instead of linearity verification on the sample dryer pressure. To verify that the trip point value is no more than 4.0 kPa above the reference value at the trip point, we recommend that you input a reference pressure signal above the alarm trip point and decrease this signal until the low alarm trips.
(ii) Linearity verification is required for the following pressure measurements if these pressure measurements are specified by the engine manufacturer:
(A) The test cell's charge air cooler and interconnecting pipe pressure drop, for turbo-charged engines tested with a laboratory heat exchanger that simulates an installed charge air cooler.
(B) Fuel outlet.

TABLE 1 OF § 1065.307–MEASUREMENT SYSTEMS THAT REQUIRE LINEARITY VERIFICATION

Measurement system	Quantity	Linearity criteria			
		$\lvert x_{min}(a_1-1)+a_0 \rvert$	a_1	SEE	r^2
Speed	f_n	$\leq 0.05\ \% \cdot f_{nmax}$	0.98-1.02	$\leq 2\ \% \cdot f_{nmax}$	≥ 0.990
Torque	T	$\leq 1\ \% \cdot T_{max}$	0.98-1.02	$\leq 2\ \% \cdot T_{max}$	≥ 0.990
Electrical power	P	$\leq 1\ \% \cdot P_{max}$	0.98-1.02	$\leq 2\ \% \cdot P_{max}$	≥ 0.990
Current	I	$\leq 1\ \% \cdot I_{max}$	0.98-1.02	$\leq 2\ \% \cdot I_{max}$	≥ 0.990
Voltage	U	$\leq 1\ \% \cdot U_{max}$	0.98-1.02	$\leq 2\ \% \cdot U_{max}$	≥ 0.990
Fuel flow rate	$\dot{m}$	$\leq 1\ \% \cdot \dot{m}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{m}_{max}$	≥ 0.990
Intake-air flow rate[1]	$\dot{n}$	$\leq 1\ \% \cdot \dot{n}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{n}_{max}$	≥ 0.990
Dilution air flow rate[1]	$\dot{n}$	$\leq 1\ \% \cdot \dot{n}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{n}_{max}$	≥ 0.990
Diluted exhaust flow rate[1]	$\dot{n}$	$\leq 1\ \% \cdot \dot{n}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{n}_{max}$	≥ 0.990
Raw exhaust flow rate[1]	$\dot{n}$	$\leq 1\ \% \cdot \dot{n}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{n}_{max}$	≥ 0.990
Batch sampler flow rates[1]	$\dot{n}$	$\leq 1\ \% \cdot \dot{n}_{max}$	0.98-1.02	$\leq 2\ \% \cdot \dot{n}_{max}$	≥ 0.990
Gas dividers	x/x_{span}	$\leq 0.5\ \% \cdot x_{max}/x_{span}$	0.98-1.02	$\leq 2\ \% \cdot x_{max}/x_{span}$	≥ 0.990
Gas analyzers for laboratory testing	x	$\leq 0.5\ \% \cdot x_{max}$	0.99-1.01	$\leq 1\ \% \cdot x_{max}$	≥ 0.998
Gas analyzers for field testing	x	$\leq 1\ \% \cdot x_{max}$	0.99-1.01	$\leq 1\ \% \cdot x_{max}$	≥ 0.998
PM balance	m	$\leq 1\ \% \cdot m_{max}$	0.99-1.01	$\leq 1\ \% \cdot m_{max}$	≥ 0.998
Pressures	p	$\leq 1\ \% \cdot p_{max}$	0.99-1.01	$\leq 1\ \% \cdot p_{max}$	≥ 0.998
Dewpoint for intake air, PM-stabilization and balance environments	T_{dew}	$\leq 0.5\ \% \cdot T_{dewmax}$	0.99-1.01	$\leq 0.5\ \% \cdot T_{dewmax}$	≥ 0.998
Other dewpoint measurements	T_{dew}	$\leq 1\ \% \cdot T_{dewmax}$	0.99-1.01	$\leq 1\ \% \cdot T_{dewmax}$	≥ 0.998
Analog-to-digital conversion of temperature signals	T	$\leq 1\ \% \cdot T_{max}$	0.99-1.01	$\leq 1\ \% \cdot T_{max}$	≥ 0.998

[1]For flow meters that determine volumetric flow rate, $\dot{V}_{std}$, you may substitute $\dot{V}_{std}$ for $\dot{n}$ as the quantity and substitute $\dot{V}_{stdmax}$ for $\dot{n}_{max}$.

§ 1065.308 Continuous gas analyzer system-response and updating-recording verification—for gas analyzers not continuously compensated for other gas species.

(a) Scope and frequency. This section describes a verification procedure for system response and updating-recording frequency for continuous gas analyzers that output a gas species mole fraction (i.e., concentration) using a single gas detector, i.e., gas analyzers not continuously compensated for other gas species measured with multiple gas detectors. See § 1065.309 for verification procedures that apply to continuous gas analyzers that are continuously compensated for other gas species measured with multiple gas detectors. Perform this verification to determine the system response of the continuous gas analyzer and its sampling system. This

verification is required for continuous gas analyzers used for transient or ramped-modal testing. You need not perform this verification for batch gas analyzer systems or for continuous gas analyzer systems that are used only for discrete-mode testing. Perform this verification after initial installation (i.e., test cell commissioning) and after any modifications to the system that would change system response. For example, perform this verification if you add a significant volume to the transfer lines by increasing their length or adding a filter; or if you reduce the frequency at which the gas analyzer updates its output or the frequency at which you sample and record gas-analyzer concentrations.

(b) Measurement principles. This test verifies that the updating and recording frequencies match the overall system response to a rapid change in the value of concentrations at the sample probe. Gas analyzers and their sampling systems must be optimized such that their overall response to a rapid change in concentration is updated and recorded at an appropriate frequency to prevent loss of information. This test also verifies that the measurement system meets a minimum response time. You may use the results of this test to determine transformation time, t_{50}, for the purposes of time alignment of continuous data in accordance with § 1065.650(c)(2)(i). You may also use an alternate procedure to determine t_{50} in accordance with good engineering judgment. Note that any such procedure for determining t_{50} must account for both transport delay and analyzer response time.

(c) System requirements. Demonstrate that each continuous analyzer has adequate update and recording frequencies and has a minimum rise time and a minimum fall time during a rapid change in gas concentration. You must meet one of the following criteria:

(1) The product of the mean rise time, $t_{10\text{-}90}$, and the frequency at which the system records an updated concentration must be at least 5, and the product of the mean fall time, $t_{90\text{-}10}$, and the frequency at which the system records an updated concentration must be at least 5. If the recording frequency is different than the analyzer's output update frequency, you must use the lower of these two frequencies for this verification, which is referred to as the updating-recording frequency. This verification applies to the nominal updating and recording frequencies. This criterion makes no assumption regarding the frequency content of changes in emission concentrations during emission testing; therefore, it is valid for any testing. Also, the mean rise time must be at or below 10 seconds and the mean fall time must be at or below 10 seconds.

(2) The frequency at which the system records an updated concentration must be at least 5 Hz. This criterion assumes that the frequency content of significant changes in emission concentrations during emission testing do not exceed 1 Hz. Also, the mean rise time must be at or below 10 seconds and the mean fall time must be at or below 10 seconds.

(3) You may use other criteria if we approve the criteria in advance.

(4) You may meet the overall PEMS verification in § 1065.920 instead of the verification in this section for field testing with PEMS.

(d) Procedure. Use the following procedure to verify the response of each continuous gas analyzer:

(1) Instrument setup. Follow the analyzer manufacturer's start-up and operating instructions. Adjust the measurement system as needed to optimize performance. Run this verification with the analyzer operating in the same manner you will use for emission testing. If the analyzer shares its sampling system with other analyzers, and if gas flow to the other analyzers will affect

the system response time, then start up and operate the other analyzers while running this verification test. You may run this verification test on multiple analyzers sharing the same sampling system at the same time. If you use any analog or real-time digital filters during emission testing, you must operate those filters in the same manner during this verification.
(2) Equipment setup. We recommend using minimal lengths of gas transfer lines between all connections and fast-acting three-way valves (2 inlets, 1 outlet) to control the flow of zero and blended span gases to the sample system's probe inlet or a tee near the outlet of the probe. If you inject the gas at a tee near the outlet of the probe, you may correct the transformation time, t_{50}, for an estimate of the transport time from the probe inlet to the tee. Normally the gas flow rate is higher than the sample flow rate and the excess is overflowed out the inlet of the probe. If the gas flow rate is lower than the sample flow rate, the gas concentrations must be adjusted to account for the dilution from ambient air drawn into the probe. We recommend you use the final, stabilized analyzer reading as the final gas concentration. Select span gases for the species being measured. You may use binary or multi-gas span gases. You may use a gas blending or mixing device to blend span gases. A gas blending or mixing device is recommended when blending span gases diluted in N_2 with span gases diluted in air. You may use a multi-gas span gas, such as NO-CO-CO_2-C_3H_8-CH_4, to verify multiple analyzers at the same time. If you use standard binary span gases, you must run separate response tests for each analyzer. In designing your experimental setup, avoid pressure pulsations due to stopping the flow through the gas-blending device. The change in gas concentration must be at least 20 % of the analyzer's range.
(3) Data collection. (i) Start the flow of zero gas.
(ii) Allow for stabilization, accounting for transport delays and the slowest analyzer's full response.
(iii) Start recording data. For this verification you must record data at a frequency greater than or equal to that of the updating-recording frequency used during emission testing. You may not use interpolation or filtering to alter the recorded values.
(iv) Switch the flow to allow the blended span gases to flow to the analyzer. If you intend to use the data from this test to determine t_{50} for time alignment, record this time as t_0.
(v) Allow for transport delays and the slowest analyzer's full response.
(vi) Switch the flow to allow zero gas to flow to the analyzer. If you intend to use the data from this test to determine t_{50} for time alignment, record this time as t_{100}.
(vii) Allow for transport delays and the slowest analyzer's full response.
(viii) Repeat the steps in paragraphs (d)(3)(iv) through (vii) of this section to record seven full cycles, ending with zero gas flowing to the analyzers.
(ix) Stop recording.
(e) Performance evaluation. (1) If you choose to demonstrate compliance with paragraph (c)(1) of this section, use the data from paragraph (d)(3) of this section to calculate the mean rise time, $t_{10\text{-}90}$, and mean fall time, $t_{90\text{-}10}$, for each of the analyzers being verified. You may use interpolation between recorded values to determine rise and fall times. If the recording frequency used during emission testing is different from the analyzer's output update frequency, you must use the lower of these two frequencies for this verification. Multiply these times (in seconds) by their respective updating-recording frequencies in Hertz (1/second). The resulting product must be at least 5 for both rise time and fall time. If either value is less than 5, increase the updating-recording frequency, or adjust the flows or design of the sampling system to

increase the rise time and fall time as needed. You may also configure analog or digital filters before recording to increase rise and fall times. In no case may the mean rise time or mean fall time be greater than 10 seconds.
(2) If a measurement system fails the criterion in paragraph (e)(1) of this section, ensure that signals from the system are updated and recorded at a frequency of at least 5 Hz. In no case may the mean rise time or mean fall time be greater than 10 seconds.
(3) If a measurement system fails the criteria in paragraphs (e)(1) and (2) of this section, you may use the measurement system only if the deficiency does not adversely affect your ability to show compliance with the applicable standards.
(f) Transformation time, t_{50}, determination. If you choose to determine t_{50} for purposes of time alignment using data generated in paragraph (d)(3) of this section, calculate the mean $t_{0\text{-}50}$ and the mean $t_{100\text{-}50}$ from the recorded data. Average these two values to determine the final t_{50} for the purposes of time alignment in accordance with § 1065.650(c)(2)(i).
(g) Optional procedure. Instead of using a three-way valve to switch between zero and span gases, you may use a fast-acting two-way valve to switch sampling between ambient air and span gas at the probe inlet. For this alternate procedure, the following provisions apply:
(1) If your probe is sampling from a continuously flowing gas stream (e.g., a CVS tunnel), you may adjust the span gas flow rate to be different than the sample flow rate.
(2) If your probe is sampling from a gas stream that is not continuously flowing (e.g., a raw exhaust stack), you must adjust the span gas flow rate to be less than the sample flow rate so ambient air is always being drawn into the probe inlet. This avoids errors associated with overflowing span gas out of the probe inlet and drawing it back in when sampling ambient air.
(3) When sampling ambient air or ambient air mixed with span gas, all the analyzer readings must be stable within ±0.5 % of the target gas concentration step size. If any analyzer reading is outside the specified range, you must resolve the problem and verify that all the analyzer readings meet this specification.
(4) For oxygen analyzers, you may use purified N_2 as the zero gas and ambient air (plus purified N_2 if needed) as the reference gas. Perform the verification with seven repeat measurements that each consist of stabilizing with purified N_2, switching to ambient air and observing the analyzer's rise and stabilized reading, followed by switching back to purified N_2 and observing the analyzer's fall and stabilized reading.

§ 1065.309 Continuous gas analyzer system-response and updating-recording verification—for gas analyzers continuously compensated for other gas species.
(a) Scope and frequency. This section describes a verification procedure for system response and updating-recording frequency for continuous gas analyzers that output a single gas species mole fraction (i.e., concentration) based on a continuous combination of multiple gas species measured with multiple detectors (i.e., gas analyzers continuously compensated for other gas species). See § 1065.308 for verification procedures that apply to continuous gas analyzers that are not continuously compensated for other gas species or that use only one detector for gaseous species. Perform this verification to determine the system response of the continuous gas analyzer and its sampling system. This verification is required for continuous gas analyzers used for transient or ramped-modal testing. You need not perform this verification for batch gas analyzers or for continuous gas analyzers that are used only for discrete-mode testing. For this

check we consider water vapor a gaseous constituent. This verification does not apply to any processing of individual analyzer signals that are time-aligned to their t_{50} times and were verified according to § 1065.308. For example, this verification does not apply to correction for water removed from the sample done in post-processing according to § 1065.659 (40 CFR 1066.620 for vehicle testing) and it does not apply to NMHC determination from THC and CH_4 according to § 1065.660. Perform this verification after initial installation (i.e., test cell commissioning) and after any modifications to the system that would change the system response.

(b) Measurement principles. This procedure verifies that the updating and recording frequencies match the overall system response to a rapid change in the value of concentrations at the sample probe. It indirectly verifies the time-alignment and uniform response of all the continuous gas detectors used to generate a continuously combined/compensated concentration measurement signal. Gas analyzer systems must be optimized such that their overall response to rapid change in concentration is updated and recorded at an appropriate frequency to prevent loss of information. This test also verifies that the measurement system meets a minimum response time. For this procedure, ensure that all compensation algorithms and humidity corrections are turned on. You may use the results of this test to determine transformation time, t_{50}, for the purposes of time alignment of continuous data in accordance with § 1065.650(c)(2)(i). You may also use an alternate procedure to determine t_{50} consistent with good engineering judgment. Note that any such procedure for determining t_{50} must account for both transport delay and analyzer response time.

(c) System requirements. Demonstrate that each continuously combined/compensated concentration measurement has adequate updating and recording frequencies and has a minimum rise time and a minimum fall time during a system response to a rapid change in multiple gas concentrations, including H_2O concentration if H_2O compensation is applied. You must meet one of the following criteria:

(1) The product of the mean rise time, $t_{10\text{-}90}$, and the frequency at which the system records an updated concentration must be at least 5, and the product of the mean fall time, $t_{90\text{-}10}$, and the frequency at which the system records an updated concentration must be at least 5. If the recording frequency is different than the update frequency of the continuously combined/compensated signal, you must use the lower of these two frequencies for this verification. This criterion makes no assumption regarding the frequency content of changes in emission concentrations during emission testing; therefore, it is valid for any testing. Also, the mean rise time must be at or below 10 seconds and the mean fall time must be at or below 10 seconds.

(2) The frequency at which the system records an updated concentration must be at least 5 Hz. This criterion assumes that the frequency content of significant changes in emission concentrations during emission testing do not exceed 1 Hz. Also, the mean rise time must be at or below 10 seconds and the mean fall time must be at or below 10 seconds.

(3) You may use other criteria if we approve them in advance.

(4) You may meet the overall PEMS verification in § 1065.920 instead of the verification in this section for field testing with PEMS.

(d) Procedure. Use the following procedure to verify the response of each continuously compensated analyzer (verify the combined signal, not each individual continuously combined concentration signal):

(1) Instrument setup. Follow the analyzer manufacturer's start-up and operating instructions. Adjust the measurement system as needed to optimize performance. Run this verification with the analyzer operating in the same manner you will use for emission testing. If the analyzer shares its sampling system with other analyzers, and if gas flow to the other analyzers will affect the system response time, then start up and operate the other analyzers while running this verification test. You may run this verification test on multiple analyzers sharing the same sampling system at the same time. If you use any analog or real-time digital filters during emission testing, you must operate those filters in the same manner during this verification.
(2) Equipment setup. We recommend using minimal lengths of gas transfer lines between all connections and fast-acting three-way valves (2 inlets, 1 outlet) to control the flow of zero and blended span gases to the sample system's probe inlet or a tee near the outlet of the probe. If you inject the gas at a tee near the outlet of the probe, you may correct the transformation time, t_{50}, for an estimate of the transport time from the probe inlet to the tee. Normally the gas flow rate is higher than the sample flow rate and the excess is overflowed out the inlet of the probe. If the gas flow rate is lower than the sample flow rate, the gas concentrations must be adjusted to account for the dilution from ambient air drawn into the probe. We recommend you use the final, stabilized analyzer reading as the final gas concentration. Select span gases for the species being continuously combined, other than H_2O. Select concentrations of compensating species that will yield concentrations of these species at the analyzer inlet that covers the range of concentrations expected during testing. You may use binary or multi-gas span gases. You may use a gas blending or mixing device to blend span gases. A gas blending or mixing device is recommended when blending span gases diluted in N_2 with span gases diluted in air. You may use a multi-gas span gas, such as NO-CO-CO_2-C_3H_8-CH_4, to verify multiple analyzers at the same time. In designing your experimental setup, avoid pressure pulsations due to stopping the flow through the gas blending device. The change in gas concentration must be at least 20 % of the analyzer's range. If H_2O correction is applicable, then span gases must be humidified before entering the analyzer; however, you may not humidify NO_2 span gas by passing it through a sealed humidification vessel that contains water. You must humidify NO_2 span gas with another moist gas stream. We recommend humidifying your NO-CO-CO_2-C_3H_8-CH_4, balance N_2 blended gas by flowing the gas mixture through a sealed vessel that humidifies the gas by bubbling it through distilled water and then mixing the gas with dry NO_2 gas, balance purified air. If your system does not use a sample dryer to remove water from the sample gas, you must humidify your span gas to the highest sample H_2O content that you estimate during emission sampling. If your system uses a sample dryer during testing, it must pass the sample dryer verification check in § 1065.342, and you must humidify your span gas to an H_2O content greater than or equal to the level determined in § 1065.145(e)(2). If you are humidifying span gases without NO_2, use good engineering judgment to ensure that the wall temperatures in the transfer lines, fittings, and valves from the humidifying system to the probe are above the dewpoint required for the target H_2O content. If you are humidifying span gases with NO_2, use good engineering judgment to ensure that there is no condensation in the transfer lines, fittings, or valves from the point where humidified gas is mixed with NO_2 span gas to the probe. We recommend that you design your setup so that the wall temperatures in the transfer lines, fittings, and valves from the humidifying system to the probe are at least 5 °C above the local sample gas dewpoint. Operate the measurement and sample handling system as you do for emission testing.

Make no modifications to the sample handling system to reduce the risk of condensation. Flow humidified gas through the sampling system before this check to allow stabilization of the measurement system's sampling handling system to occur, as it would for an emission test.
(3) Data collection. (i) Start the flow of zero gas.
(ii) Allow for stabilization, accounting for transport delays and the slowest analyzer's full response.
(iii) Start recording data. For this verification you must record data at a frequency greater than or equal to that of the updating-recording frequency used during emission testing. You may not use interpolation or filtering to alter the recorded values.
(iv) Switch the flow to allow the blended span gases to flow to the analyzer. If you intend to use the data from this test to determine t_{50} for time alignment, record this time as t_0.
(v) Allow for transport delays and the slowest analyzer's full response.
(vi) Switch the flow to allow zero gas to flow to the analyzer. If you intend to use the data from this test to determine t_{50} for time alignment, record this time as t_{100}.
(vii) Allow for transport delays and the slowest analyzer's full response.
(viii) Repeat the steps in paragraphs (d)(3)(iv) through (vii) of this section to record seven full cycles, ending with zero gas flowing to the analyzers.
(ix) Stop recording.
(e) Performance evaluations. (1) If you choose to demonstrate compliance with paragraph (c)(1) of this section, use the data from paragraph (d)(3) of this section to calculate the mean rise time, $t_{10\text{-}90}$, and mean fall time, $t_{90\text{-}10}$, for the continuously combined signal from each analyzer being verified. You may use interpolation between recorded values to determine rise and fall times. If the recording frequency used during emission testing is different from the analyzer's output update frequency, you must use the lower of these two frequencies for this verification. Multiply these times (in seconds) by their respective updating-recording frequencies in Hz (1/second). The resulting product must be at least 5 for both rise time and fall time. If either value is less than 5, increase the updating-recording frequency or adjust the flows or design of the sampling system to increase the rise time and fall time as needed. You may also configure analog or digital filters before recording to increase rise and fall times. In no case may the mean rise time or mean fall time be greater than 10 seconds.
(2) If a measurement system fails the criterion in paragraph (e)(1) of this section, ensure that signals from the system are updated and recorded at a frequency of at least 5 Hz. In no case may the mean rise time or mean fall time be greater than 10 seconds.
(3) If a measurement system fails the criteria in paragraphs (e)(1) and (2) of this section, you may use the measurement system only if the deficiency does not adversely affect your ability to show compliance with the applicable standards.
(f) Transformation time, t_{50}, determination. If you choose to determine t_{50} for purposes of time alignment using data generated in paragraph (d)(3) of this section, calculate the mean $t_{0\text{-}50}$ and the mean $t_{100\text{-}50}$ from the recorded data. Average these two values to determine the final t_{50} for the purposes of time alignment in accordance with § 1065.650(c)(2)(i).
(g) Optional procedure. Follow the optional procedures in § 1065.308(g), noting that you may use compensating gases mixed with ambient air for oxygen analyzers.
(h) Analyzers with H_2O compensation sampling downstream of a sample dryer. You may omit humidifying the span gas as described in this paragraph (h). If an analyzer compensates only for

H_2O, you may apply the requirements of § 1065.308 instead of the requirements of this section. You may omit humidifying the span gas if you meet the following conditions:
(1) The analyzer is located downstream of a sample dryer.
(2) The maximum value for H_2O mole fraction downstream of the dryer must be less than or equal to 0.010. Verify this during each sample dryer verification according to § 1065.342.

MEASUREMENT OF ENGINE PARAMETERS AND AMBIENT CONDITIONS

§ 1065.310 Torque calibration.
(a) Scope and frequency. Calibrate all torque-measurement systems including dynamometer torque measurement transducers and systems upon initial installation and after major maintenance. Use good engineering judgment to repeat the calibration. Follow the torque transducer manufacturer's instructions for linearizing your torque sensor's output. We recommend that you calibrate the torque-measurement system with a reference force and a lever arm.
(b) Recommended procedure to quantify lever-arm length. Quantify the lever-arm length, NIST-traceable within ±0.5 % uncertainty. The lever arm's length must be measured from the centerline of the dynamometer to the point at which the reference force is measured. The lever arm must be perpendicular to gravity (i.e., horizontal), and it must be perpendicular to the dynamometer's rotational axis. Balance the lever arm's torque or quantify its net hanging torque, NIST-traceable within ±1 % uncertainty, and account for it as part of the reference torque.
(c) Recommended procedure to quantify reference force. We recommend dead-weight calibration, but you may use either of the following procedures to quantify the reference force, NIST-traceable within ±0.5 % uncertainty.
(1) Dead-weight calibration. This technique applies a known force by hanging known weights at a known distance along a lever arm. Make sure the weights' lever arm is perpendicular to gravity (i.e., horizontal) and perpendicular to the dynamometer's rotational axis. Apply at least six calibration-weight combinations for each applicable torque-measuring range, spacing the weight quantities about equally over the range. Oscillate or rotate the dynamometer during calibration to reduce frictional static hysteresis. Determine each weight's reference force by multiplying its NIST-traceable mass by the local acceleration of Earth's gravity, as described in § 1065.630. Calculate the reference torque as the weights' reference force multiplied by the lever arm reference length.
(2) Strain gage, load transducer, or proving ring calibration. This technique applies force either by hanging weights on a lever arm (these weights and their lever arm length are not used as part of the reference torque determination) or by operating the dynamometer at different torques. Apply at least six force combinations for each applicable torque-measuring range, spacing the force quantities about equally over the range. Oscillate or rotate the dynamometer during calibration to reduce frictional static hysteresis. In this case, the reference torque is determined by multiplying the force output from the reference meter (such as a strain gage, load transducer, or proving ring) by its effective lever-arm length, which you measure from the point where the force measurement is made to the dynamometer's rotational axis. Make sure you measure this

length perpendicular to the reference meter's measurement axis and perpendicular to the dynamometer's rotational axis.

§ 1065.315 Pressure, temperature, and dewpoint calibration.
(a) Calibrate instruments for measuring pressure, temperature, and dewpoint upon initial installation. Follow the instrument manufacturer's instructions and use good engineering judgment to repeat the calibration, as follows:
(1) Pressure. We recommend temperature-compensated, digital-pneumatic, or deadweight pressure calibrators, with data-logging capabilities to minimize transcription errors. We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(2) Temperature. We recommend digital dry-block or stirred-liquid temperature calibrators, with data logging capabilities to minimize transcription errors. We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty. You may perform linearity verification for temperature measurement systems with thermocouples, RTDs, and thermistors by removing the sensor from the system and using a simulator in its place. Use a NIST-traceable simulator that is independently calibrated and, as appropriate, cold-junction compensated. The simulator uncertainty scaled to absolute temperature must be less than 0.5 % of T_{max}. If you use this option, you must use sensors that the supplier states are accurate to better than 0.5 % of T_{max} compared with their standard calibration curve.
(3) Dewpoint. We recommend a minimum of three different temperature-equilibrated and temperature-monitored calibration salt solutions in containers that seal completely around the dewpoint sensor. We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(b) You may remove system components for off-site calibration. We recommend specifying calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.

FLOW-RELATED MEASUREMENTS

§ 1065.320 Fuel-flow calibration.
(a) Calibrate fuel-flow meters upon initial installation. Follow the instrument manufacturer's instructions and use good engineering judgment to repeat the calibration.
(b) You may also develop a procedure based on a chemical balance of carbon or oxygen in engine exhaust.
(c) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of the tubing configuration upstream and downstream of the flow meter. We recommend specifying calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.

§ 1065.325 Intake-flow calibration.
(a) Calibrate intake-air flow meters upon initial installation. Follow the instrument manufacturer's instructions and use good engineering judgment to repeat the calibration. We recommend using a calibration subsonic venturi, ultrasonic flow meter or laminar flow element.

We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(b) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of the tubing configuration upstream and downstream of the flow meter. We recommend specifying calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(c) If you use a subsonic venturi or ultrasonic flow meter for intake flow measurement, we recommend that you calibrate it as described in § 1065.340.

§ 1065.330 Exhaust-flow calibration.
(a) Calibrate exhaust-flow meters upon initial installation. Follow the instrument manufacturer's instructions and use good engineering judgment to repeat the calibration. We recommend that you use a calibration subsonic venturi or ultrasonic flow meter and simulate exhaust temperatures by incorporating a heat exchanger between the calibration meter and the exhaust-flow meter. If you can demonstrate that the flow meter to be calibrated is insensitive to exhaust temperatures, you may use other reference meters such as laminar flow elements, which are not commonly designed to withstand typical raw exhaust temperatures. We recommend using calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(b) You may remove system components for off-site calibration. When installing a flow meter with an off-site calibration, we recommend that you consider the effects of the tubing configuration upstream and downstream of the flow meter. We recommend specifying calibration reference quantities that are NIST-traceable within 0.5 % uncertainty.
(c) If you use a subsonic venturi or ultrasonic flow meter for raw exhaust flow measurement, we recommend that you calibrate it as described in § 1065.340.

§ 1065.340 Diluted exhaust flow (CVS) calibration.
(a) Overview. This section describes how to calibrate flow meters for diluted exhaust constant-volume sampling (CVS) systems.
(b) Scope and frequency. Perform this calibration while the flow meter is installed in its permanent position, except as allowed in paragraph (c) of this section. Perform this calibration after you change any part of the flow configuration upstream or downstream of the flow meter that may affect the flow-meter calibration. Perform this calibration upon initial CVS installation and whenever corrective action does not resolve a failure to meet the diluted exhaust flow verification (i.e., propane check) in § 1065.341.
(c) Ex-situ CFV and SSV calibration. You may remove a CFV or SSV from its permanent position for calibration as long as it meets the following requirements when installed in the CVS:
(1) Upon installation of the CFV or SSV into the CVS, use good engineering judgment to verify that you have not introduced any leaks between the CVS inlet and the venturi.
(2) After ex-situ venturi calibration, you must verify all venturi flow combinations for CFVs or at minimum of 10 flow points for an SSV using the propane check as described in § 1065.341. Your propane check result for each venturi flow point may not exceed the tolerance in § 1065.341(f)(5).

(3) To verify your ex-situ calibration for a CVS with more than a single CFV, perform the following check to verify that there are no flow meter entrance effects that can prevent you from passing this verification.
(i) Use a constant flow device like a CFO kit to deliver a constant flow of propane to the dilution tunnel.
(ii) Measure hydrocarbon concentrations at a minimum of 10 separate flow rates for an SSV flow meter, or at all possible flow combinations for a CFV flow meter, while keeping the flow of propane constant. We recommend selecting CVS flow rates in a random order.
(iii) Measure the concentration of hydrocarbon background in the dilution air at the beginning and end of this test. Subtract the average background concentration from each measurement at each flow point before performing the regression analysis in paragraph (c)(3)(iv) of this section.
(iv) Perform a power regression using all the paired values of flow rate and corrected concentration to obtain a relationship in the form of $y = a \cdot x^b$. Use concentration as the independent variable and flow rate as the dependent variable. For each data point, calculate the difference between the measured flow rate and the value represented by the curve fit. The difference at each point must be less than ±1 % of the appropriate regression value. The value of b must be between –1.005 and –0.995. If your results do not meet these limits, take corrective action consistent with § 1065.341(a).
(v) If your results do not meet the limits set in paragraph (iv) of this section, determine the source of error, which are described in § 1065.341(a), and take corrective action as necessary.
(d) Reference flow meter. Calibrate a CVS flow meter using a reference flow meter such as a subsonic venturi flow meter, a long-radius ASME/NIST flow nozzle, a smooth approach orifice, a laminar flow element, a set of critical flow venturis, or an ultrasonic flow meter. Use a reference flow meter that reports quantities that are NIST-traceable within ±1 % uncertainty. Use this reference flow meter's response to flow as the reference value for CVS flow-meter calibration.
(e) Configuration. Do not use an upstream screen or other restriction that could affect the flow ahead of the reference flow meter, unless the flow meter has been calibrated with such a restriction.
(f) PDP calibration. Calibrate a positive-displacement pump (PDP) to determine a flow-versus-PDP speed equation that accounts for flow leakage across sealing surfaces in the PDP as a function of PDP inlet pressure. Determine unique equation coefficients for each speed at which you operate the PDP. Calibrate a PDP flow meter as follows:
(1) Connect the system as shown in Figure 1 of this section.
(2) Leaks between the calibration flow meter and the PDP must be less than 0.3 % of the total flow at the lowest calibrated flow point; for example, at the highest restriction and lowest PDP-speed point.
(3) While the PDP operates, maintain a constant temperature at the PDP inlet within ±2 % of the mean absolute inlet temperature, $\overline{T}_{in}$.
(4) Set the PDP speed to the first speed point at which you intend to calibrate.
(5) Set the variable restrictor to its wide-open position.
(6) Operate the PDP for at least 3 min to stabilize the system. Continue operating the PDP and record the mean values of at least 30 seconds of sampled data of each of the following quantities:

(i) The mean flow rate of the reference flow meter, $\overline{n}_{ref}$. This may include several measurements of different quantities, such as reference meter pressures and temperatures, for calculating $\overline{n}_{ref}$.

(ii) The mean temperature at the PDP inlet, $\overline{T}_{in}$.

(iii) The mean static absolute pressure at the PDP inlet, $\overline{p}_{in}$.

(iv) The mean static absolute pressure at the PDP outlet, $\overline{p}_{out}$.

(v) The mean PDP speed, $\overline{f}_{nPDP}$.

(7) Incrementally close the restrictor valve to decrease the absolute pressure at the inlet to the PDP, p_{in}.

(8) Repeat the steps in paragraphs (e)(6) and (7) of this section to record data at a minimum of six restrictor positions ranging from the wide open restrictor position to the minimum expected pressure at the PDP inlet.

(9) Calibrate the PDP by using the collected data and the equations in § 1065.640.

(10) Repeat the steps in paragraphs (e)(6) through (9) of this section for each speed at which you operate the PDP.

(11) Use the equations in § 1065.642 to determine the PDP flow equation for emission testing.

(12) Verify the calibration by performing a CVS verification (i.e., propane check) as described in § 1065.341.

(13) Do not use the PDP below the lowest inlet pressure tested during calibration.

(g) CFV calibration. Calibrate a critical-flow venturi (CFV) to verify its discharge coefficient, C_d, at the lowest expected static differential pressure between the CFV inlet and outlet. Calibrate a CFV flow meter as follows:

(1) Connect the system as shown in Figure 1 of this section.

(2) Verify that any leaks between the calibration flow meter and the CFV are less than 0.3 % of the total flow at the highest restriction.

(3) Start the blower downstream of the CFV.

(4) While the CFV operates, maintain a constant temperature at the CFV inlet within ±2 % of the mean absolute inlet temperature, $\overline{T}_{in}$.

(5) Set the variable restrictor to its wide-open position. Instead of a variable restrictor, you may alternately vary the pressure downstream of the CFV by varying blower speed or by introducing a controlled leak. Note that some blowers have limitations on nonloaded conditions.

(6) Operate the CFV for at least 3 min to stabilize the system. Continue operating the CFV and record the mean values of at least 30 seconds of sampled data of each of the following quantities:

(i) The mean flow rate of the reference flow meter, $\overline{n}_{ref}$. This may include several measurements of different quantities, such as reference meter pressures and temperatures, for calculating $\overline{n}_{ref}$.

(ii) The mean dewpoint of the calibration air, $\overline{T}_{dew}$. See § 1065.640 for permissible assumptions during emission measurements.

(iii) The mean temperature at the venturi inlet, $\overline{T}_{in}$.

(iv) The mean static absolute pressure at the venturi inlet, $\overline{p}_{in}$.

(v) The mean static differential pressure between the CFV inlet and the CFV outlet, $\Delta\overline{p}_{CFV}$.

(7) Incrementally close the restrictor valve or decrease the downstream pressure to decrease the differential pressure across the CFV, $\Delta\overline{p}_{CFV}$.

(8) Repeat the steps in paragraphs (f)(6) and (7) of this section to record mean data at a minimum of ten restrictor positions, such that you test the fullest practical range of $\Delta\overline{p}_{CFV}$ expected during testing. We do not require that you remove calibration components or CVS components to calibrate at the lowest possible restrictions.

(9) Determine C_d and the lowest allowable pressure ratio, r, according to § 1065.640.

(10) Use C_d to determine CFV flow during an emission test. Do not use the CFV below the lowest allowed r, as determined in § 1065.640.

(11) Verify the calibration by performing a CVS verification (i.e., propane check) as described in § 1065.341.

(12) If your CVS is configured to operate more than one CFV at a time in parallel, calibrate your CVS by one of the following:

(i) Calibrate every combination of CFVs according to this section and § 1065.640. Refer to § 1065.642 for instructions on calculating flow rates for this option.

(ii) Calibrate each CFV according to this section and § 1065.640. Refer to § 1065.642 for instructions on calculating flow rates for this option.

(h) SSV calibration. Calibrate a subsonic venturi (SSV) to determine its calibration coefficient, C_d, for the expected range of inlet pressures. Calibrate an SSV flow meter as follows:

(1) Connect the system as shown in Figure 1 of this section.

(2) Verify that any leaks between the calibration flow meter and the SSV are less than 0.3 % of the total flow at the highest restriction.

(3) Start the blower downstream of the SSV.

(4) While the SSV operates, maintain a constant temperature at the SSV inlet within ±2 % of the mean absolute inlet temperature, $\overline{T}_{in}$.

(5) Set the variable restrictor or variable-speed blower to a flow rate greater than the greatest flow rate expected during testing. You may not extrapolate flow rates beyond calibrated values, so we recommend that you make sure the Reynolds number, $Re^{\#}$, at the SSV throat at the greatest calibrated flow rate is greater than the maximum $Re^{\#}$ expected during testing.

(6) Operate the SSV for at least 3 min to stabilize the system. Continue operating the SSV and record the mean of at least 30 seconds of sampled data of each of the following quantities:

(i) The mean flow rate of the reference flow meter $\overline{\dot{n}}_{ref}$. This may include several measurements of different quantities, such as reference meter pressures and temperatures, for calculating $\overline{\dot{n}}_{ref}$.

(ii) Optionally, the mean dewpoint of the calibration air, $\overline{T}_{dew}$. See § 1065.640 for permissible assumptions.

(iii) The mean temperature at the venturi inlet, $\overline{T}_{in}$.

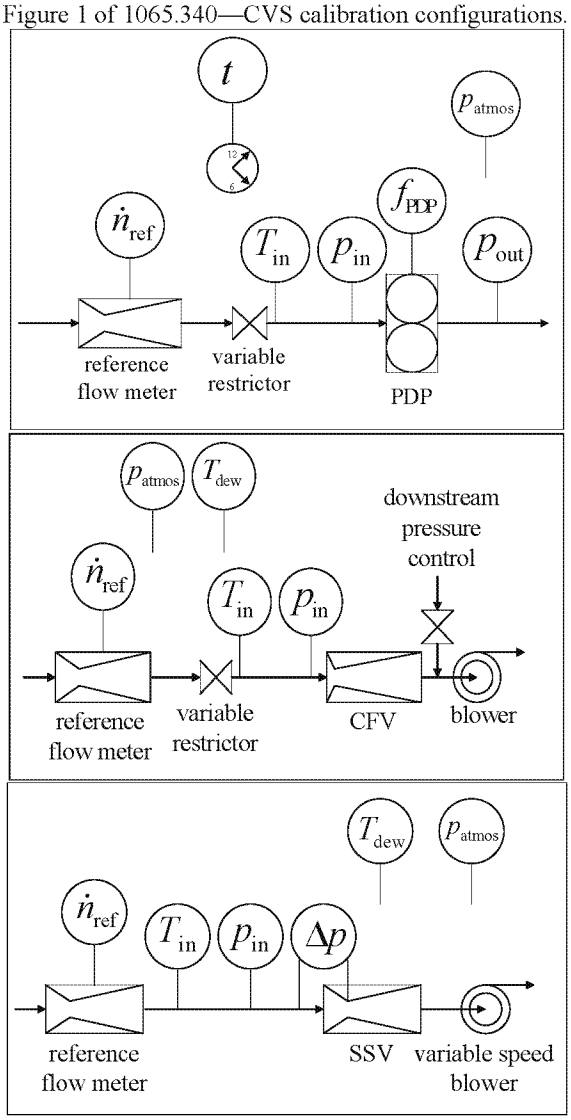
(iv) The mean static absolute pressure at the venturi inlet, $\overline{p}_{in}$.

(v) Static differential pressure between the static pressure at the venturi inlet and the static pressure at the venturi throat, $\Delta\overline{p}_{SSV}$.

(7) Incrementally close the restrictor valve or decrease the blower speed to decrease the flow rate.

(8) Repeat the steps in paragraphs (g)(6) and (7) of this section to record data at a minimum of ten flow rates.
(9) Determine a functional form of C_d versus $Re^{\#}$ by using the collected data and the equations in § 1065.640.
(10) Verify the calibration by performing a CVS verification (i.e., propane check) as described in § 1065.341 using the new C_d versus $Re^{\#}$ equation.
(11) Use the SSV only between the minimum and maximum calibrated flow rates.
(12) Use the equations in § 1065.642 to determine SSV flow during a test.
(i) Ultrasonic flow meter calibration. [Reserved]

Figure 1 of 1065.340—CVS calibration configurations.



§ 1065.341 CVS, PFD, and batch sampler verification (propane check).

(a) A propane check serves as a CVS verification to determine if there is a discrepancy in measured values of diluted exhaust flow. You may use the same procedure to verify PFDs and batch samplers. For purposes of PFD and batch sampler verification, read the term CVS to mean PFD or batch sampler as appropriate. A propane check also serves as a batch-sampler verification to determine if there is a discrepancy in a batch sampling system that extracts a sample from a CVS, as described in paragraph (g) of this section. Using good engineering judgment and safe practices, this check may be performed using a gas other than propane, such as CO_2 or CO. A failed propane check might indicate one or more problems that may require corrective action, as follows:

(1) Incorrect analyzer calibration. Re-calibrate, repair, or replace the FID analyzer.

(2) Leaks. Inspect CVS tunnel, connections, fasteners, and HC sampling system, and repair or replace components.

(3) Poor mixing. Perform the verification as described in this section while traversing a sampling probe across the tunnel's diameter, vertically and horizontally. If the analyzer response indicates any deviation exceeding ±2 % of the mean measured concentration, consider operating the CVS at a higher flow rate or installing a mixing plate or orifice to improve mixing.

(4) Hydrocarbon contamination in the sample system. Perform the hydrocarbon-contamination verification as described in § 1065.520.

(5) Change in CVS calibration. Perform a calibration of the CVS flow meter as described in § 1065.340.

(6) Flow meter entrance effects. Inspect the CVS tunnel to determine whether the entrance effects from the piping configuration upstream of the flow meter adversely affect the flow measurement.

(7) Other problems with the CVS or sampling verification hardware or software. Inspect the CVS system, CVS verification hardware, and software for discrepancies.

(b) A propane check uses either a reference mass or a reference flow rate of C_3H_8 as a tracer gas in a CVS. Note that if you use a reference flow rate, account for any non-ideal gas behavior of C_3H_8 in the reference flow meter. Refer to § 1065.640 and § 1065.642, which describe how to calibrate and use certain flow meters. Do not use any ideal gas assumptions in § 1065.640 and § 1065.642. The propane check compares the calculated mass of injected C_3H_8 using HC measurements and CVS flow rate measurements with the reference value.

(c) Prepare for the propane check as follows:

(1) If you use a reference mass of C_3H_8 instead of a reference flow rate, obtain a cylinder charged with C_3H_8. Determine the reference cylinder's mass of C_3H_8 within ±0.5 % of the amount of C_3H_8 that you expect to use.

(2) Select appropriate flow rates for the CVS and C_3H_8.

(3) Select a C_3H_8 injection port in the CVS. Select the port location to be as close as practical to the location where you introduce engine exhaust into the CVS. Connect the C_3H_8 cylinder to the injection system.

(4) Operate and stabilize the CVS.

(5) Preheat or pre-cool any heat exchangers in the sampling system.

(6) Allow heated and cooled components such as sample lines, filters, chillers, and pumps to stabilize at operating temperature.

(7) You may purge the HC sampling system during stabilization.

(8) If applicable, perform a vacuum side leak verification of the HC sampling system as described in § 1065.345.
(9) You may also conduct any other calibrations or verifications on equipment or analyzers.
(d) If you performed the vacuum-side leak verification of the HC sampling system as described in paragraph (c)(8) of this section, you may use the HC contamination procedure in § 1065.520(f) to verify HC contamination. Otherwise, zero, span, and verify contamination of the HC sampling system, as follows:
(1) Select the lowest HC analyzer range that can measure the C_3H_8 concentration expected for the CVS and C_3H_8 flow rates.
(2) Zero the HC analyzer using zero air introduced at the analyzer port.
(3) Span the HC analyzer using C_3H_8 span gas introduced at the analyzer port.
(4) Overflow zero air at the HC probe inlet or into a tee near the outlet of the probe.
(5) Measure the stable HC concentration of the HC sampling system as overflow zero air flows. For batch HC measurement, fill the batch container (such as a bag) and measure the HC overflow concentration.
(6) If the overflow HC concentration exceeds 2 μmol/mol, do not proceed until contamination is eliminated. Determine the source of the contamination and take corrective action, such as cleaning the system or replacing contaminated portions.
(7) When the overflow HC concentration does not exceed 2 μmol/mol, record this value as $x_{THCinit}$ and use it to correct for HC contamination as described in § 1065.660.
(e) Perform the propane check as follows:
(1) For batch HC sampling, connect clean storage media, such as evacuated bags.
(2) Operate HC measurement instruments according to the instrument manufacturer's instructions.
(3) If you will correct for dilution air background concentrations of HC, measure and record background HC in the dilution air.
(4) Zero any integrating devices.
(5) Begin sampling, and start any flow integrators.
(6) Release the contents of the C_3H_8 reference cylinder at the rate you selected. If you use a reference flow rate of C_3H_8, start integrating this flow rate.
(7) Continue to release the cylinder's contents until at least enough C_3H_8 has been released to ensure accurate quantification of the reference C_3H_8 and the measured C_3H_8.
(8) Shut off the C_3H_8 reference cylinder and continue sampling until you have accounted for time delays due to sample transport and analyzer response.
(9) Stop sampling and stop any integrators.
(f) Perform post-test procedure as follows:
(1) If you used batch sampling, analyze batch samples as soon as practical.
(2) After analyzing HC, correct for contamination and background.
(3) Calculate total C_3H_8 mass based on your CVS and HC data as described in § 1065.650 (40 CFR 1066.605 for vehicle testing) and § 1065.660, using the molar mass of C_3H_8, M_{C3H8}, instead the effective molar mass of HC, M_{HC}.
(4) If you use a reference mass, determine the cylinder's propane mass within ±0.5 % and determine the C_3H_8 reference mass by subtracting the empty cylinder propane mass from the full cylinder propane mass.

(5) Subtract the reference C_3H_8 mass from the calculated mass. If this difference is within ±2 % of the reference mass, the CVS passes this verification. If not, take corrective action as described in paragraph (a) of this section.
(g) You may repeat the propane check to verify a batch sampler, such as a PM secondary dilution system.
(1) Configure the HC sampling system to extract a sample near the location of the batch sampler's storage media (such as a PM filter). If the absolute pressure at this location is too low to extract an HC sample, you may sample HC from the batch sampler pump's exhaust. Use caution when sampling from pump exhaust because an otherwise acceptable pump leak downstream of a batch sampler flow meter will cause a false failure of the propane check.
(2) Repeat the propane check described in this section, but sample HC from the batch sampler.
(3) Calculate C_3H_8 mass, taking into account any secondary dilution from the batch sampler.
(4) Subtract the reference C_3H_8 mass from the calculated mass. If this difference is within ±5 % of the reference mass, the batch sampler passes this verification. If not, take corrective action as described in paragraph (a) of this section.

§ 1065.342 Sample dryer verification.
(a) Scope and frequency. If you use a sample dryer as allowed in § 1065.145(e)(2) to remove water from the sample gas, verify the performance upon installation, after major maintenance, for thermal chiller. For osmotic membrane dryers, verify the performance upon installation, after major maintenance, and within 35 days of testing.
(b) Measurement principles. Water can inhibit an analyzer's ability to properly measure the exhaust component of interest and thus is sometimes removed before the sample gas reaches the analyzer. For example water can negatively interfere with a CLD's NO_x response through collisional quenching and can positively interfere with an NDIR analyzer by causing a response similar to CO.
(c) System requirements. The sample dryer must meet the specifications as determined in § 1065.145(e)(2) for dewpoint, T_{dew}, and absolute pressure, p_{total}, downstream of the osmotic-membrane dryer or thermal chiller.
(d) Sample dryer verification procedure. Use the following method to determine sample dryer performance. Run this verification with the dryer and associated sampling system operating in the same manner you will use for emission testing (including operation of sample pumps). You may run this verification test on multiple sample dryers sharing the same sampling system at the same time. You may run this verification on the sample dryer alone, but you must use the maximum gas flow rate expected during testing. You may use good engineering judgment to develop a different protocol.
(1) Use PTFE or stainless steel tubing to make necessary connections.
(2) Humidify room air, N_2, or purified air by bubbling it through distilled water in a sealed vessel that humidifies the gas to the highest sample water content that you estimate during emission sampling.
(3) Introduce the humidified gas upstream of the sample dryer. You may disconnect the transfer line from the probe and introduce the humidified gas at the inlet of the transfer line of the sample system used during testing. You may use the sample pumps in the sample system to draw gas through the vessel.
(4) Maintain the sample lines, fittings, and valves from the location where the humidified gas water content is measured to the inlet of the sampling system at a temperature at least 5 °C above

the local humidified gas dewpoint. For dryers used in NO_x sample systems, verify the sample system components used in this verification prevent aqueous condensation as required in § 1065.145(d)(1)(i). We recommend that the sample system components be maintained at least 5 °C above the local humidified gas dewpoint to prevent aqueous condensation.
(5) Measure the humidified gas dewpoint, T_{dew}, and absolute pressure, p_{total}, as close as possible to the inlet of the sample dryer or inlet of the sample system to verify the water content is at least as high as the highest value that you estimated during emission sampling. You may verify the water content based on any humidity parameter (e.g. mole fraction water, local dewpoint, or absolute humidity).
(6) Measure the humidified gas dewpoint, T_{dew}, and absolute pressure, p_{total}, as close as possible to the outlet of the sample dryer. Note that the dewpoint changes with absolute pressure. If the dewpoint at the sample dryer outlet is measured at a different pressure, then this reading must be corrected to the dewpoint at the sample dryer absolute pressure, p_{total}.
(7) The sample dryer meets the verification if the dewpoint at the sample dryer pressure as measured in paragraph (d)(6) of this section is less than the dewpoint corresponding to the sample dryer specifications as determined in § 1065.145(e)(2) plus 2 °C or if the mole fraction of water as measured in (d)(6) is less than the corresponding sample dryer specifications plus 0.002 mol/mol.
(e) Alternate sample dryer verification procedure. The following method may be used in place of the sample dryer verification procedure in (d) of this section. If you use a humidity sensor for continuous monitoring of dewpoint at the sample dryer outlet you may skip the performance check in § 1065.342(d), but you must make sure that the dryer outlet humidity is at or below the minimum value used for quench, interference, and compensation checks.

§ 1065.345 Vacuum-side leak verification.
(a) Scope and frequency. Verify that there are no significant vacuum-side leaks using one of the leak tests described in this section. For laboratory testing, perform the vacuum-side leak verification upon initial sampling system installation, within 8 hours before the start of the first test interval of each duty-cycle sequence, and after maintenance such as pre-filter changes. For field testing, perform the vacuum-side leak verification after each installation of the sampling system on the vehicle, prior to the start of the field test, and after maintenance such as pre-filter changes. This verification does not apply to any full-flow portion of a CVS dilution system.
(b) Measurement principles. A leak may be detected either by measuring a small amount of flow when there should be zero flow, or by detecting the dilution of a known concentration of span gas when it flows through the vacuum side of a sampling system.
(c) Low-flow leak test. Test a sampling system for low-flow leaks as follows:
(1) Seal the probe end of the system by taking one of the following steps:
(i) Cap or plug the end of the sample probe.
(ii) Disconnect the transfer line at the probe and cap or plug the transfer line.
(iii) Close a leak-tight valve located in the sample transfer line within 92 cm of the probe.
(2) Operate all vacuum pumps. After stabilizing, verify that the flow through the vacuum-side of the sampling system is less than 0.5 % of the system's normal in-use flow rate. You may estimate typical analyzer and bypass flows as an approximation of the system's normal in-use flow rate.
(d) Dilution-of-span-gas leak test. You may use any gas analyzer for this test. If you use a FID for this test, correct for any HC contamination in the sampling system according to § 1065.660.

To avoid misleading results from this test, we recommend using only analyzers that have a repeatability of 0.5% or better at the span gas concentration used for this test. Perform a vacuum-side leak test as follows:
(1) Prepare a gas analyzer as you would for emission testing.
(2) Supply span gas to the analyzer port and verify that it measures the span gas concentration within its expected measurement accuracy and repeatability.
(3) Route overflow span gas to the inlet of the sample probe or at a tee fitting in the transfer line near the exit of the probe. You may use a valve upstream of the overflow fitting to prevent overflow of span gas out of the inlet of the probe, but you must then provide an overflow vent in the overflow supply line.
(4) Verify that the measured overflow span gas concentration is within ±0.5% of the span gas concentration. A measured value lower than expected indicates a leak, but a value higher than expected may indicate a problem with the span gas or the analyzer itself. A measured value higher than expected does not indicate a leak.
(e) Vacuum-decay leak test. To perform this test you must apply a vacuum to the vacuum-side volume of your sampling system and then observe the leak rate of your system as a decay in the applied vacuum. To perform this test you must know the vacuum-side volume of your sampling system to within ±10% of its true volume. For this test you must also use measurement instruments that meet the specifications of subpart C of this part and of this subpart D. Perform a vacuum-decay leak test as follows:
(1) Seal the probe end of the system as close to the probe opening as possible by taking one of the following steps:
(i) Cap or plug the end of the sample probe.
(ii) Disconnect the transfer line at the probe and cap or plug the transfer line.
(iii) Close a leak-tight valve located in the sample transfer line within 92 cm of the probe.
(2) Operate all vacuum pumps. Draw a vacuum that is representative of normal operating conditions. In the case of sample bags, we recommend that you repeat your normal sample bag pump-down procedure twice to minimize any trapped volumes.
(3) Turn off the sample pumps and seal the system. Measure and record the absolute pressure of the trapped gas and optionally the system absolute temperature. Wait long enough for any transients to settle and long enough for a leak at 0.5% to have caused a pressure change of at least 10 times the resolution of the pressure transducer, then again record the pressure and optionally temperature.
(4) Calculate the leak flow rate based on an assumed value of zero for pumped-down bag volumes and based on known values for the sample system volume, the initial and final pressures, optional temperatures, and elapsed time. Using the calculations specified in 1065.644, verify that the vacuum-decay leak flow rate is less than 0.5 % of the system's normal in-use flow rate.

CO AND CO_2 MEASUREMENTS

§ 1065.350 H_2O interference verification for CO_2 NDIR analyzers.
(a) Scope and frequency. If you measure CO_2 using an NDIR analyzer, verify the amount of H_2O interference after initial analyzer installation and after major maintenance.
(b) Measurement principles. H_2O can interfere with an NDIR analyzer's response to CO_2. If the NDIR analyzer uses compensation algorithms that utilize measurements of other gases to meet

this interference verification, simultaneously conduct these other measurements to test the compensation algorithms during the analyzer interference verification.

(c) System requirements. A CO_2 NDIR analyzer must have an H_2O interference that is within (0.0 ±0.4) mmol/mol, though we strongly recommend a lower interference that is within (0.0 ±0.2) mmol/mol.

(d) Procedure. Perform the interference verification as follows:

(1) Start, operate, zero, and span the CO_2 NDIR analyzer as you would before an emission test. If the sample is passed through a dryer during emission testing, you may run this verification test with the dryer if it meets the requirements of § 1065.342. Operate the dryer at the same conditions as you will for an emission test. You may also run this verification test without the sample dryer.

(2) Create a humidified test gas by bubbling zero gas that meets the specifications in § 1065.750 through distilled H_2O in a sealed vessel. If the sample is not passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the maximum expected during emission testing. If the sample is passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the level determined in § 1065.145(e)(2) for that dryer.

(3) Introduce the humidified test gas into the sample system. You may introduce it downstream of any sample dryer, if one is used during testing.

(4) If the sample is not passed through a dryer during this verification test, measure the H_2O mole fraction, x_{H2O}, of the humidified test gas, as close as possible to the inlet of the analyzer. For example, measure dewpoint, T_{dew}, and absolute pressure, p_{total}, to calculate x_{H2O}. Verify that the H_2O content meets the requirement in paragraph (d)(2) of this section. If the sample is passed through a dryer during this verification test, you must verify that the H_2O content of the humidified test gas downstream of the vessel meets the requirement in paragraph (d)(2) of this section based on either direct measurement of the H_2O content (e.g., dewpoint and pressure) or an estimate based on the vessel pressure and temperature. Use good engineering judgment to estimate the H_2O content. For example, you may use previous direct measurements of H_2O content to verify the vessel's level of saturation.

(5) If a sample dryer is not used in this verification test, use good engineering judgment to prevent condensation in the transfer lines, fittings, or valves from the point where x_{H2O} is measured to the analyzer. We recommend that you design your system so the wall temperatures in the transfer lines, fittings, and valves from the point where x_{H2O} is measured to the analyzer are at least 5 °C above the local sample gas dewpoint.

(6) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.

(7) While the analyzer measures the sample's concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of this data. The analyzer meets the interference verification if this value is within (0.0 ±0.4) mmol/mol.

(e) Exceptions. The following exceptions apply:

(1) You may omit this verification if you can show by engineering analysis that for your CO_2 sampling system and your emission-calculation procedures, the H_2O interference for your CO_2 NDIR analyzer always affects your brake-specific emission results within ±0.5 % of each of the applicable standards. This specification also applies for vehicle testing, except that it relates to emission results in g/mile or g/kilometer.

(2) You may use a CO_2 NDIR analyzer that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

§ 1065.355 H_2O and CO_2 interference verification for CO NDIR analyzers.

(a) Scope and frequency. If you measure CO using an NDIR analyzer, verify the amount of H_2O and CO_2 interference after initial analyzer installation and after major maintenance.

(b) Measurement principles. H_2O and CO_2 can positively interfere with an NDIR analyzer by causing a response similar to CO. If the NDIR analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference verification, simultaneously conduct these other measurements to test the compensation algorithms during the analyzer interference verification.

(c) System requirements. A CO NDIR analyzer must have combined H_2O and CO_2 interference that is within ±2 % of the flow-weighted mean concentration of CO expected at the standard, though we strongly recommend a lower interference that is within ±1 %.

(d) Procedure. Perform the interference verification as follows:

(1) Start, operate, zero, and span the CO NDIR analyzer as you would before an emission test. If the sample is passed through a dryer during emission testing, you may run this verification test with the dryer if it meets the requirements of § 1065.342. Operate the dryer at the same conditions as you will for an emission test. You may also run this verification test without the sample dryer.

(2) Create a humidified CO_2 test gas by bubbling a CO_2 span gas that meets the specifications in § 1065.750 through distilled H_2O in a sealed vessel. If the sample is not passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the maximum expected during emission testing. If the sample is passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the level determined in § 1065.145(e)(2) for that dryer. Use a CO_2 span gas concentration at least as high as the maximum expected during testing.

(3) Introduce the humidified CO_2 test gas into the sample system. You may introduce it downstream of any sample dryer, if one is used during testing.

(4) If the sample is not passed through a dryer during this verification test, measure the H_2O mole fraction, x_{H2O}, of the humidified CO_2 test gas as close as possible to the inlet of the analyzer. For example, measure dewpoint, T_{dew}, and absolute pressure, p_{total}, to calculate x_{H2O}. Verify that the H_2O content meets the requirement in paragraph (d)(2) of this section. If the sample is passed through a dryer during this verification test, you must verify that the H_2O content of the humidified test gas downstream of the vessel meets the requirement in paragraph (d)(2) of this section based on either direct measurement of the H_2O content (e.g., dewpoint and pressure) or an estimate based on the vessel pressure and temperature. Use good engineering judgment to estimate the H_2O content. For example, you may use previous direct measurements of H_2O content to verify the vessel's level of saturation.

(5) If a sample dryer is not used in this verification test, use good engineering judgment to prevent condensation in the transfer lines, fittings, or valves from the point where x_{H2O} is measured to the analyzer. We recommend that you design your system so that the wall temperatures in the transfer lines, fittings, and valves from the point where x_{H2O} is measured to the analyzer are at least 5 °C above the local sample gas dewpoint.

(6) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.
(7) While the analyzer measures the sample's concentration, record its output for 30 seconds. Calculate the arithmetic mean of this data.
(8) The analyzer meets the interference verification if the result of paragraph (d)(7) of this section meets the tolerance in paragraph (c) of this section.
(9) You may also run interference procedures for CO_2 and H_2O separately. If the CO_2 and H_2O levels used are higher than the maximum levels expected during testing, you may scale down each observed interference value by multiplying the observed interference by the ratio of the maximum expected concentration value to the actual value used during this procedure. You may run separate interference concentrations of H_2O (down to 0.025 mol/mol H_2O content) that are lower than the maximum levels expected during testing, but you must scale up the observed H_2O interference by multiplying the observed interference by the ratio of the maximum expected H_2O concentration value to the actual value used during this procedure. The sum of the two scaled interference values must meet the tolerance in paragraph (c) of this section.
(e) Exceptions. The following exceptions apply:
(1) You may omit this verification if you can show by engineering analysis that for your CO sampling system and your emission-calculation procedures, the combined CO_2 and H_2O interference for your CO NDIR analyzer always affects your brake-specific CO emission results within ±0.5 % of the applicable CO standard.
(2)You may use a CO NDIR analyzer that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

HYDROCARBON MEASUREMENTS

§ 1065.360 FID optimization and verification.
(a) Scope and frequency. For all FID analyzers, calibrate the FID upon initial installation. Repeat the calibration as needed using good engineering judgment. For a FID that measures THC, perform the following steps:
(1) Optimize the response to various hydrocarbons after initial analyzer installation and after major maintenance as described in paragraph (c) of this section.
(2) Determine the methane (CH_4) response factor after initial analyzer installation and after major maintenance as described in paragraph (d) of this section.
(3) Verify the CH_4 response within 185 days before testing as described in paragraph (e) of this section.
(b) Calibration. Use good engineering judgment to develop a calibration procedure, such as one based on the FID-analyzer manufacturer's instructions and recommended frequency for calibrating the FID. Alternately, you may remove system components for off-site calibration. For a FID that measures THC, calibrate using C_3H_8 calibration gases that meet the specifications of § 1065.750. For a FID that measures CH_4, calibrate using CH_4 calibration gases that meet the specifications of § 1065.750. We recommend FID analyzer zero and span gases that contain approximately the flow-weighted mean concentration of O_2 expected during testing. If you use a FID to measure CH_4 downstream of a nonmethane cutter, you may calibrate that FID using CH_4 calibration gases with the cutter. Regardless of the calibration gas composition, calibrate on a carbon number basis of one (C_1). For example, if you use a C_3H_8 span gas of concentration 200

μmol/mol, span the FID to respond with a value of 600 μmol/mol. As another example, if you use a CH_4 span gas with a concentration of 200 μmol/mol, span the FID to respond with a value of 200 μmol/mol.

(c) THC FID response optimization. This procedure is only for FID analyzers that measure THC. Use good engineering judgment for initial instrument start-up and basic operating adjustment using FID fuel and zero air. Heated FIDs must be within their required operating temperature ranges. Optimize FID response at the most common analyzer range expected during emission testing. Optimization involves adjusting flows and pressures of FID fuel, burner air, and sample to minimize response variations to various hydrocarbon species in the exhaust. Use good engineering judgment to trade off peak FID response to propane calibration gases to achieve minimal response variations to different hydrocarbon species. For an example of trading off response to propane for relative responses to other hydrocarbon species, see SAE 770141 (incorporated by reference in § 1065.1010). Determine the optimum flow rates and/or pressures for FID fuel, burner air, and sample and record them for future reference.

(d) THC FID CH_4 response factor determination. This procedure is only for FID analyzers that measure THC. Since FID analyzers generally have a different response to CH_4 versus C_3H_8, determine each THC-FID analyzer's CH_4 response factor, $RF_{CH4[THC\text{-}FID]}$, after FID optimization. Use the most recent $RF_{CH4[THC\text{-}FID]}$ measured according to this section in the calculations for HC determination described in § 1065.660 to compensate for CH_4 response. Determine $RF_{CH4[THC\text{-}FID]}$ as follows, noting that you do not determine $RF_{CH4[THC\text{-}FID]}$ for FIDs that are calibrated and spanned using CH_4 with a nonmethane cutter:

(1) Select a C_3H_8 span gas concentration that you use to span your analyzers before emission testing. Use only span gases that meet the specifications of § 1065.750. Record the C_3H_8 concentration of the gas.

(2) Select a CH_4 span gas concentration that you use to span your analyzers before emission testing. Use only span gases that meet the specifications of § 1065.750. Record the CH_4 concentration of the gas.

(3) Start and operate the FID analyzer according to the manufacturer's instructions.

(4) Confirm that the FID analyzer has been calibrated using C_3H_8. Calibrate on a carbon number basis of one (C_1). For example, if you use a C_3H_8 span gas of concentration 200 μmol/mol, span the FID to respond with a value of 600 μmol/mol.

(5) Zero the FID with a zero gas that you use for emission testing.

(6) Span the FID with the C_3H_8 span gas that you selected under paragraph (d)(1) of this section.

(7) Introduce at the sample port of the FID analyzer, the CH_4 span gas that you selected under paragraph (d)(2) of this section.

(8) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the analyzer and to account for its response.

(9) While the analyzer measures the CH_4 concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these values.

(10) For analyzers with multiple ranges, you need to perform the procedure in this paragraph (d) only on a single range.

(11) Divide the mean measured concentration by the recorded span concentration of the CH_4 calibration gas. The result is the FID analyzer's response factor for CH_4, $RF_{CH4[THC\text{-}FID]}$.

(e) THC FID CH_4 response verification. This procedure is only for FID analyzers that measure THC. Verify $RF_{CH4[THC\text{-}FID]}$ as follows:

(1) Perform a CH_4 response factor determination as described in paragraph (d) of this section. If the resulting value of $RF_{CH4[THC\text{-}FID]}$ is within ±5 % of its most recent previously determined value, the THC FID passes the CH_4 response verification. For example, if the most recent previous value for $RF_{CH4[THC\text{-}FID]}$ was 1.05 and it increased by 0.05 to become 1.10 or it decreased by 0.05 to become 1.00, either case would be acceptable because ±4.8 % is less than ±5 %.
(2) If $RF_{CH4[THC\text{-}FID]}$ is not within the tolerance specified in paragraph (e)(1) of this section, use good engineering judgment to verify that the flow rates and/or pressures of FID fuel, burner air, and sample are at their most recent previously recorded values, as determined in paragraph (c) of this section. You may adjust these flow rates as necessary. Then determine the $RF_{CH4[THC\text{-}FID]}$ as described in paragraph (d) of this section and verify that it is within the tolerance specified in this paragraph (e).
(3) If $RF_{CH4[THC\text{-}FID]}$ is not within the tolerance specified in this paragraph (e), re-optimize the FID response as described in paragraph (c) of this section.
(4) Determine a new $RF_{CH4[THC\text{-}FID]}$ as described in paragraph (d) of this section. Use this new value of $RF_{CH4[THC\text{-}FID]}$ in the calculations for HC determination, as described in § 1065.660.
(5) For analyzers with multiple ranges, you need to perform the procedure in this paragraph (e) only on a single range.

§ 1065.362 Non-stoichiometric raw exhaust FID O_2 interference verification.
(a) Scope and frequency. If you use FID analyzers for raw exhaust measurements from engines that operate in a non-stoichiometric mode of combustion (e.g., compression-ignition, lean-burn), verify the amount of FID O_2 interference upon initial installation and after major maintenance.
(b) Measurement principles. Changes in O_2 concentration in raw exhaust can affect FID response by changing FID flame temperature. Optimize FID fuel, burner air, and sample flow to meet this verification. Verify FID performance with the compensation algorithms for FID O_2 interference that you have active during an emission test.
(c) System requirements. Any FID analyzer used during testing must meet the FID O_2 interference verification according to the procedure in this section.
(d) Procedure. Determine FID O_2 interference as follows, noting that you may use one or more gas dividers to create the reference gas concentrations that are required to perform this verification:
(1) Select three span reference gases that contain a C_3H_8 concentration that you use to span your analyzers before emission testing. Use only span gases that meet the specifications of § 1065.750. You may use CH_4 span reference gases for FIDs calibrated on CH_4 with a nonmethane cutter. Select the three balance gas concentrations such that the concentrations of O_2 and N_2 represent the minimum, maximum, and average O_2 concentrations expected during testing. The requirement for using the average O_2 concentration can be removed if you choose to calibrate the FID with span gas balanced with the average expected oxygen concentration.
(2) Confirm that the FID analyzer meets all the specifications of § 1065.360.
(3) Start and operate the FID analyzer as you would before an emission test. Regardless of the FID burner's air source during testing, use zero air as the FID burner's air source for this verification.
(4) Zero the FID analyzer using the zero gas used during emission testing.
(5) Span the FID analyzer using a span gas that you use during emission testing.

(6) Check the zero response of the FID analyzer using the zero gas used during emission testing. If the mean zero response of 30 seconds of sampled data is within ±0.5 % of the span reference value used in paragraph (d)(5) of this section, then proceed to the next step; otherwise restart the procedure at paragraph (d)(4) of this section.
(7) Check the analyzer response using the span gas that has the minimum concentration of O_2 expected during testing. Record the mean response of 30 seconds of stabilized sample data as $x_{O2minHC}$.
(8) Check the zero response of the FID analyzer using the zero gas used during emission testing. If the mean zero response of 30 seconds of stabilized sample data is within ±0.5 % of the span reference value used in paragraph (d)(5) of this section, then proceed to the next step; otherwise restart the procedure at paragraph (d)(4) of this section.
(9) Check the analyzer response using the span gas that has the average concentration of O_2 expected during testing. Record the mean response of 30 seconds of stabilized sample data as $x_{O2avgHC}$.
(10) Check the zero response of the FID analyzer using the zero gas used during emission testing. If the mean zero response of 30 seconds of stabilized sample data is within ±0.5 % of the span reference value used in paragraph (d)(5) of this section, proceed to the next step; otherwise restart the procedure at paragraph (d)(4) of this section.
(11) Check the analyzer response using the span gas that has the maximum concentration of O_2 expected during testing. Record the mean response of 30 seconds of stabilized sample data as $x_{O2maxHC}$.
(12) Check the zero response of the FID analyzer using the zero gas used during emission testing. If the mean zero response of 30 seconds of stabilized sample data is within ±0.5 % of the span reference value used in paragraph (d)(5) of this section, then proceed to the next step; otherwise restart the procedure at paragraph (d)(4) of this section.
(13) Calculate the percent difference between $x_{O2maxHC}$ and its reference gas concentration. Calculate the percent difference between $x_{O2avgHC}$ and its reference gas concentration. Calculate the percent difference between $x_{O2minHC}$ and its reference gas concentration. Determine the maximum percent difference of the three. This is the O_2 interference.
(14) If the O_2 interference is within ±2 %, the FID passes the O_2 interference verification; otherwise perform one or more of the following to address the deficiency:
(i) Repeat the verification to determine if a mistake was made during the procedure.
(ii) Select zero and span gases for emission testing that contain higher or lower O_2 concentrations and repeat the verification.
(iii) Adjust FID burner air, fuel, and sample flow rates. Note that if you adjust these flow rates on a THC FID to meet the O_2 interference verification, you have reset RF_{CH4} for the next RF_{CH4} verification according to § 1065.360. Repeat the O_2 interference verification after adjustment and determine RF_{CH4}.
(iv) Repair or replace the FID and repeat the O_2 interference verification.
(v) Demonstrate that the deficiency does not adversely affect your ability to demonstrate compliance with the applicable emission standards.
(15) For analyzers with multiple ranges, you need to perform the procedure in this paragraph (d) only on a single range.

§ 1065.365 Nonmethane cutter penetration fractions.

(a) Scope and frequency. If you use a FID analyzer and a nonmethane cutter (NMC) to measure methane (CH_4), determine the nonmethane cutter's penetration fractions of CH_4, PF_{CH4}, and ethane, PF_{C2H6}. As detailed in this section, these penetration fractions may be determined as a combination of NMC penetration fractions and FID analyzer response factors, depending on your particular NMC and FID analyzer configuration. Perform this verification after installing the nonmethane cutter. Repeat this verification within 185 days of testing to verify that the catalytic activity of the cutter has not deteriorated. Note that because nonmethane cutters can deteriorate rapidly and without warning if they are operated outside of certain ranges of gas concentrations and outside of certain temperature ranges, good engineering judgment may dictate that you determine a nonmethane cutter's penetration fractions more frequently.
(b) Measurement principles. A nonmethane cutter is a heated catalyst that removes nonmethane hydrocarbons from an exhaust sample stream before the FID analyzer measures the remaining hydrocarbon concentration. An ideal nonmethane cutter would have a CH_4 penetration fraction, PF_{CH4}, of 1.000, and the penetration fraction for all other nonmethane hydrocarbons would be 0.000, as represented by PF_{C2H6}. The emission calculations in § 1065.660 use the measured values from this verification to account for less than ideal NMC performance.
(c) System requirements. We do not limit NMC penetration fractions to a certain range. However, we recommend that you optimize a nonmethane cutter by adjusting its temperature to achieve a $PF_{CH4} > 0.85$ and a $PF_{C2H6} < 0.02$, as determined by paragraphs (d), (e), or (f) of this section, as applicable. If we use a nonmethane cutter for testing, it will meet this recommendation. If adjusting NMC temperature does not result in achieving both of these specifications simultaneously, we recommend that you replace the catalyst material. Use the most recently determined penetration values from this section to calculate HC emissions according to § 1065.660 and § 1065.665 as applicable.
(d) Procedure for a FID calibrated with the NMC. The method described in this paragraph (d) is recommended over the procedures specified in paragraphs (e) and (f) of this section. If your FID arrangement is such that a FID is always calibrated to measure CH_4 with the NMC, then span that FID with the NMC using a CH_4 span gas, set the product of that FID's CH_4 response factor and CH_4 penetration fraction, $RFPF_{CH4[NMC\text{-}FID]}$, equal to 1.0 for all emission calculations, and determine its combined ethane (C_2H_6) response factor and penetration fraction, $RFPF_{C2H6[NMC\text{-}FID]}$ as follows:
(1) Select CH_4 and C_2H_6 analytical gas mixtures and ensure that both mixtures meet the specifications of § 1065.750. Select a CH_4 concentration that you would use for spanning the FID during emission testing and select a C_2H_6 concentration that is typical of the peak NMHC concentration expected at the hydrocarbon standard or equal to the THC analyzer's span value. For CH_4 analyzers with multiple ranges, perform this procedure on the highest range used for emission testing.
(2) Start, operate, and optimize the nonmethane cutter according to the manufacturer's instructions, including any temperature optimization.
(3) Confirm that the FID analyzer meets all the specifications of § 1065.360.
(4) Start and operate the FID analyzer according to the manufacturer's instructions.
(5) Zero and span the FID with the nonmethane cutter as you would during emission testing. Span the FID through the cutter by using CH_4 span gas.
(6) Introduce the C_2H_6 analytical gas mixture upstream of the nonmethane cutter. Use good engineering judgment to address the effect of hydrocarbon contamination if your point of introduction is vastly different from the point of zero/span gas introduction.

(7) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the nonmethane cutter and to account for the analyzer's response.
(8) While the analyzer measures a stable concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these data points.
(9) Divide the mean C_2H_6 concentration by the reference concentration of C_2H_6, converted to a C_1 basis. The result is the C_2H_6 combined response factor and penetration fraction, $RFPF_{C2H6[NMC\text{-}FID]}$. Use this combined response factor and penetration fraction and the product of the CH_4 response factor and CH_4 penetration fraction, $RFPF_{CH4[NMC\text{-}FID]}$, set to 1.0 in emission calculations according to § 1065.660(b)(2)(i), § 1065.660(c)(1)(i), or § 1065.665, as applicable.
(e) Procedure for a FID calibrated with propane, bypassing the NMC. If you use a single FID for THC and CH_4 determination with an NMC that is calibrated with propane, C_3H_8, by bypassing the NMC, determine its penetration fractions, $PF_{C2H6[NMC\text{-}FID]}$ and $PF_{CH4[NMC\text{-}FID]}$, as follows:
(1) Select CH_4 and C_2H_6 analytical gas mixtures and ensure that both mixtures meet the specifications of § 1065.750. Select a CH_4 concentration that you would use for spanning the FID during emission testing and select a C_2H_6 concentration that is typical of the peak NMHC concentration expected at the hydrocarbon standard and the C_2H_6 concentration typical of the peak total hydrocarbon (THC) concentration expected at the hydrocarbon standard or equal to the THC analyzer's span value. For CH_4 analyzers with multiple ranges, perform this procedure on the highest range used for emission testing.
(2) Start and operate the nonmethane cutter according to the manufacturer's instructions, including any temperature optimization.
(3) Confirm that the FID analyzer meets all the specifications of § 1065.360.
(4) Start and operate the FID analyzer according to the manufacturer's instructions.
(5) Zero and span the FID as you would during emission testing. Span the FID by bypassing the cutter and by using C_3H_8 span gas. Note that you must span the FID on a C_1 basis. For example, if your span gas has a propane reference value of 100 μmol/mol, the correct FID response to that span gas is 300 μmol/mol because there are three carbon atoms per C_3H_8 molecule.
(6) Introduce the C_2H_6 analytical gas mixture upstream of the nonmethane cutter. Use good engineering judgment to address the effect of hydrocarbon contamination if your point of introduction is vastly different from the point of zero/span gas introduction.
(7) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the nonmethane cutter and to account for the analyzer's response.
(8) While the analyzer measures a stable concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these data points.
(9) Reroute the flow path to bypass the nonmethane cutter, introduce the C_2H_6 analytical gas mixture, and repeat the steps in paragraphs (e)(7) through (8) of this section.
(10) Divide the mean C_2H_6 concentration measured through the nonmethane cutter by the mean C_2H_6 concentration measured after bypassing the nonmethane cutter. The result is the C_2H_6 penetration fraction, $PF_{C2H6[NMC\text{-}FID]}$. Use this penetration fraction according to § 1065.660(b)(2)(ii), § 1065.660(c)(1)(ii), or § 1065.665, as applicable.
(11) Repeat the steps in paragraphs (e)(6) through (10) of this section, but with the CH_4 analytical gas mixture instead of C_2H_6. The result will be the CH_4 penetration fraction, $PF_{CH4[NMC\text{-}FID]}$. Use this penetration fraction according to § 1065.660(b)(2)(ii) or § 1065.665, as applicable.
(f) Procedure for a FID calibrated with CH_4, bypassing the NMC. If you use a FID with an NMC that is calibrated with CH_4, by bypassing the NMC, determine its combined ethane (C_2H_6)

response factor and penetration fraction, $RFPF_{C2H6[NMC\text{-}FID]}$, as well as its CH_4 penetration fraction, $PF_{CH4[NMC\text{-}FID]}$], as follows:
(1) Select CH_4 and C_2H_6 analytical gas mixtures and ensure that both mixtures meet the specifications of § 1065.750. Select a CH_4 concentration that you would use for spanning the FID during emission testing and select a C_2H_6 concentration that is typical of the peak NMHC concentration expected at the hydrocarbon standard or equal to the THC analyzer's span value. For CH_4 analyzers with multiple ranges, perform this procedure on the highest range used for emission testing.
(2) Start and operate the nonmethane cutter according to the manufacturer's instructions, including any temperature optimization.
(3) Confirm that the FID analyzer meets all the specifications of § 1065.360.
(4) Start and operate the FID analyzer according to the manufacturer's instructions.
(5) Zero and span the FID as you would during emission testing. Span the FID by bypassing the cutter and by using CH_4 span gas.
(6) Introduce the C_2H_6 analytical gas mixture upstream of the nonmethane cutter. Use good engineering judgment to address the effect of hydrocarbon contamination if your point of introduction is vastly different from the point of zero/span gas introduction.
(7) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the nonmethane cutter and to account for the analyzer's response.
(8) While the analyzer measures a stable concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these data points.
(9) Divide the mean C_2H_6 concentration by the reference concentration of C_2H_6, converted to a C_1 basis. The result is the C_2H_6 combined response factor and penetration fraction, $RFPF_{C2H6[NMC\text{-}FID]}$. Use this combined response factor and penetration fraction according to § 1065.660(b)(2)(iii), § 1065.660(c)(1)(iii), or § 1065.665, as applicable.
(10) Introduce the CH_4 analytical gas mixture upstream of the nonmethane cutter. Use good engineering judgment to address the effect of hydrocarbon contamination if your point of introduction is vastly different from the point of zero/span gas introduction.
(11) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the nonmethane cutter and to account for the analyzer's response.
(12) While the analyzer measures a stable concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these data points.
(13) Reroute the flow path to bypass the nonmethane cutter, introduce the CH_4 analytical gas mixture, and repeat the steps in paragraphs (e)(11) and (12) of this section.
(14) Divide the mean CH_4 concentration measured through the nonmethane cutter by the mean CH_4 concentration measured after bypassing the nonmethane cutter. The result is the CH_4 penetration fraction, $PF_{CH4[NMC\text{-}FID]}$. Use this penetration fraction according to § 1065.660(b)(2)(iii), § 1065.660(c)(1)(iii), or § 1065.665, as applicable.

§ 1065.369 H_2O, CO, and CO_2 interference verification for photoacoustic alcohol analyzers.
(a) Scope and frequency. If you measure ethanol or methanol using a photoacoustic analyzer, verify the amount of H_2O, CO, and CO_2 interference after initial analyzer installation and after major maintenance.
(b) Measurement principles. H_2O, CO, and CO_2 can positively interfere with a photoacoustic analyzer by causing a response similar to ethanol or methanol. If the photoacoustic analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference

verification, simultaneously conduct these other measurements to test the compensation algorithms during the analyzer interference verification.
(c) System requirements. Photoacoustic analyzers must have combined interference that is within (0.0 ± 0.5) μmol/mol. We strongly recommend a lower interference that is within (0.0 ± 0.25) μmol/mol.
(d) Procedure. Perform the interference verification by following the procedure in § 1065.375(d), comparing the results to paragraph (c) of this section.

NO_x AND N_2O MEASUREMENTS

§ 1065.370 CLD CO_2 and H_2O quench verification.
(a) Scope and frequency. If you use a CLD analyzer to measure NO_x, verify the amount of H_2O and CO_2 quench after installing the CLD analyzer and after major maintenance.
(b) Measurement principles. H_2O and CO_2 can negatively interfere with a CLD's NO_x response by collisional quenching, which inhibits the chemiluminescent reaction that a CLD utilizes to detect NO_x. This procedure and the calculations in § 1065.675 determine quench and scale the quench results to the maximum mole fraction of H_2O and the maximum CO_2 concentration expected during emission testing. If the CLD analyzer uses quench compensation algorithms that utilize H_2O and/or CO_2 measurement instruments, evaluate quench with these instruments active and evaluate quench with the compensation algorithms applied.
(c) System requirements. A CLD analyzer must have a combined H_2O and CO_2 quench of ±2 % or less, though we strongly recommend a quench of ±1 % or less. Combined quench is the sum of the CO_2 quench determined as described in paragraph (d) of this section, plus the H_2O quench determined in paragraph (e) of this section.
(d) CO_2 quench verification procedure. Use the following method to determine CO_2 quench by using a gas divider that blends binary span gases with zero gas as the diluent and meets the specifications in § 1065.248, or use good engineering judgment to develop a different protocol:
(1) Use PTFE or stainless steel tubing to make necessary connections.
(2) Configure the gas divider such that nearly equal amounts of the span and diluent gases are blended with each other.
(3) If the CLD analyzer has an operating mode in which it detects NO-only, as opposed to total NO_x, operate the CLD analyzer in the NO-only operating mode.
(4) Use a CO_2 span gas that meets the specifications of § 1065.750 and a concentration that is approximately twice the maximum CO_2 concentration expected during emission testing.
(5) Use an NO span gas that meets the specifications of § 1065.750 and a concentration that is approximately twice the maximum NO concentration expected during emission testing.
(6) Zero and span the CLD analyzer. Span the CLD analyzer with the NO span gas from paragraph (d)(5) of this section through the gas divider. Connect the NO span gas to the span port of the gas divider; connect a zero gas to the diluent port of the gas divider; use the same nominal blend ratio selected in paragraph (d)(2) of this section; and use the gas divider's output concentration of NO to span the CLD analyzer. Apply gas property corrections as necessary to ensure accurate gas division.
(7) Connect the CO_2 span gas to the span port of the gas divider.
(8) Connect the NO span gas to the diluent port of the gas divider.
(9) While flowing NO and CO_2 through the gas divider, stabilize the output of the gas divider. Determine the CO_2 concentration from the gas divider output, applying gas property correction

as necessary to ensure accurate gas division, or measure it using an NDIR. Record this concentration, x_{CO2act}, and use it in the quench verification calculations in § 1065.675. Alternatively, you may use a simple gas blending device and use an NDIR to determine this CO_2 concentration. If you use an NDIR, it must meet the requirements of this part for laboratory testing and you must span it with the CO_2 span gas from paragraph (d)(4) of this section.
(10) Measure the NO concentration downstream of the gas divider with the CLD analyzer. Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response. While the analyzer measures the sample's concentration, record the analyzer's output for 30 seconds. Calculate the arithmetic mean concentration from these data, x_{NOmeas}. Record x_{NOmeas}, and use it in the quench verification calculations in § 1065.675.
(11) Calculate the actual NO concentration at the gas divider's outlet, x_{NOact}, based on the span gas concentrations and x_{CO2act} according to Equation 1065.675-2. Use the calculated value in the quench verification calculations in Equation 1065.675-1.
(12) Use the values recorded according to this paragraph (d) and paragraph (e) of this section to calculate quench as described in § 1065.675.
(e) <u>H_2O quench verification procedure</u>. Use the following method to determine H_2O quench, or use good engineering judgment to develop a different protocol:
(1) Use PTFE or stainless steel tubing to make necessary connections.
(2) If the CLD analyzer has an operating mode in which it detects NO-only, as opposed to total NO_x, operate the CLD analyzer in the NO-only operating mode.
(3) Use an NO span gas that meets the specifications of § 1065.750 and a concentration that is near the maximum concentration expected during emission testing.
(4) Zero and span the CLD analyzer. Span the CLD analyzer with the NO span gas from paragraph (e)(3) of this section, record the span gas concentration as x_{NOdry}, and use it in the quench verification calculations in § 1065.675.
(5) Humidify the NO span gas by bubbling it through distilled H_2O in a sealed vessel. If the humidified NO span gas sample does not pass through a sample dryer for this verification test, control the vessel temperature to generate an H_2O level approximately equal to the maximum mole fraction of H_2O expected during emission testing. If the humidified NO span gas sample does not pass through a sample dryer, the quench verification calculations in § 1065.675 scale the measured H_2O quench to the highest mole fraction of H_2O expected during emission testing. If the humidified NO span gas sample passes through a dryer for this verification test, control the vessel temperature to generate an H_2O level at least as high as the level determined in § 1065.145(e)(2). For this case, the quench verification calculations in § 1065.675 do not scale the measured H_2O quench.
(6) Introduce the humidified NO test gas into the sample system. You may introduce it upstream or downstream of any sample dryer that is used during emission testing. Note that the sample dryer must meet the sample dryer verification check in § 1065.342.
(7) Measure the mole fraction of H_2O in the humidified NO span gas downstream of the sample dryer, $x_{H2Omeas}$. We recommend that you measure $x_{H2Omeas}$ as close as possible to the CLD analyzer inlet. You may calculate $x_{H2Omeas}$ from measurements of dewpoint, T_{dew}, and absolute pressure, p_{total}.
(8) Use good engineering judgment to prevent condensation in the transfer lines, fittings, or valves from the point where $x_{H2Omeas}$ is measured to the analyzer. We recommend that you design your system so the wall temperatures in the transfer lines, fittings, and valves from the

point where $x_{H2Omeas}$ is measured to the analyzer are at least 5 °C above the local sample gas dewpoint.
(9) Measure the humidified NO span gas concentration with the CLD analyzer. Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response. While the analyzer measures the sample's concentration, record the analyzer's output for 30 seconds. Calculate the arithmetic mean of these data, x_{NOwet}. Record x_{NOwet} and use it in the quench verification calculations in § 1065.675.
(f) Corrective action. If the sum of the H_2O quench plus the CO_2 quench is less than -2 % or greater than +2 %, take corrective action by repairing or replacing the analyzer. Before running emission tests, verify that the corrective action successfully restored the analyzer to proper functioning.
(g) Exceptions. The following exceptions apply:
(1) You may omit this verification if you can show by engineering analysis that for your NO_x sampling system and your emission calculation procedures, the combined CO_2 and H_2O interference for your NO_x CLD analyzer always affects your brake-specific NO_x emission results within no more than ±1 % of the applicable NO_x standard. If you certify to a combined emission standard (such as a NO_x + NMHC standard), scale your NO_x results to the combined standard based on the measured results (after incorporating deterioration factors, if applicable). For example, if your final NO_x + NMHC value is half of the emission standard, double the NO_x result to estimate the level of NO_x emissions corresponding to the applicable standard.
(2)You may use a NO_x CLD analyzer that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

§ 1065.372 NDUV analyzer HC and H_2O interference verification.
(a) Scope and frequency. If you measure NO_x using an NDUV analyzer, verify the amount of H_2O and hydrocarbon interference after initial analyzer installation and after major maintenance.
(b) Measurement principles. Hydrocarbons and H_2O can positively interfere with an NDUV analyzer by causing a response similar to NO_x. If the NDUV analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference verification, simultaneously conduct such measurements to test the algorithms during the analyzer interference verification.
(c) System requirements. A NO_x NDUV analyzer must have combined H_2O and HC interference within ±2 % of the flow-weighted mean concentration of NO_x expected at the standard, though we strongly recommend keeping interference within ±1 %.
(d) Procedure. Perform the interference verification as follows:
(1) Start, operate, zero, and span the NO_x NDUV analyzer according to the instrument manufacturer's instructions.
(2) We recommend that you extract engine exhaust to perform this verification. Use a CLD that meets the specifications of subpart C of this part to quantify NO_x in the exhaust. Use the CLD response as the reference value. Also measure HC in the exhaust with a FID analyzer that meets the specifications of subpart C of this part. Use the FID response as the reference hydrocarbon value.
(3) Upstream of any sample dryer, if one is used during testing, introduce the engine exhaust to the NDUV analyzer.

(4) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.
(5) While all analyzers measure the sample's concentration, record 30 seconds of sampled data, and calculate the arithmetic means for the three analyzers.
(6) Subtract the CLD mean from the NDUV mean.
(7) Multiply this difference by the ratio of the flow-weighted mean HC concentration expected at the standard to the HC concentration measured during the verification. The analyzer meets the interference verification of this section if this result is within ±2 % of the NO_x concentration expected at the standard.
(e) Exceptions. The following exceptions apply:
(1) You may omit this verification if you can show by engineering analysis that for your NO_x sampling system and your emission calculation procedures, the combined HC and H_2O interference for your NO_x NDUV analyzer always affects your brake-specific NO_x emission results by less than 0.5 % of the applicable NO_x standard.
(2)You may use a NO_x NDUV analyzer that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

§ 1065.375 Interference verification for N_2O analyzers.
(a) Scope and frequency. See § 1065.275 to determine whether you need to verify the amount of interference after initial analyzer installation and after major maintenance.
(b) Measurement principles. Interference gasses can positively interfere with certain analyzers by causing a response similar to N_2O. If the analyzer uses compensation algorithms that utilize measurements of other gases to meet this interference verification, simultaneously conduct these other measurements to test the compensation algorithms during the analyzer interference verification.
(c) System requirements. Analyzers must have combined interference that is within (0.0 ± 1.0) μmol/mol. We strongly recommend a lower interference that is within (0.0 ± 0.5) μmol/mol.
(d) Procedure. Perform the interference verification as follows:
(1) Start, operate, zero, and span the N_2O analyzer as you would before an emission test. If the sample is passed through a dryer during emission testing, you may run this verification test with the dryer if it meets the requirements of § 1065.342. Operate the dryer at the same conditions as you will for an emission test. You may also run this verification test without the sample dryer.
(2) Create a humidified test gas by bubbling a multi component span gas that incorporates the target interference species and meets the specifications in § 1065.750 through distilled H_2O in a sealed vessel. If the sample is not passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the maximum expected during emission testing. If the sample is passed through a dryer during emission testing, control the vessel temperature to generate an H_2O level at least as high as the level determined in § 1065.145(e)(2) for that dryer. Use interference span gas concentrations that are at least as high as the maximum expected during testing.
(3) Introduce the humidified interference test gas into the sample system. You may introduce it downstream of any sample dryer, if one is used during testing.
(4) If the sample is not passed through a dryer during this verification test, measure the H_2O mole fraction, x_{H2O}, of the humidified interference test gas as close as possible to the inlet of the analyzer. For example, measure dewpoint, T_{dew}, and absolute pressure, p_{total}, to calculate x_{H2O}.

Verify that the H_2O content meets the requirement in paragraph (d)(2) of this section. If the sample is passed through a dryer during this verification test, you must verify that the H_2O content of the humidified test gas downstream of the vessel meets the requirement in paragraph (d)(2) of this section based on either direct measurement of the H_2O content (e.g., dewpoint and pressure) or an estimate based on the vessel pressure and temperature. Use good engineering judgment to estimate the H_2O content. For example, you may use previous direct measurements of H_2O content to verify the vessel's level of saturation.
(5) If a sample dryer is not used in this verification test, use good engineering judgment to prevent condensation in the transfer lines, fittings, or valves from the point where x_{H2O} is measured to the analyzer. We recommend that you design your system so that the wall temperatures in the transfer lines, fittings, and valves from the point where x_{H2O} is measured to the analyzer are at least 5 °C above the local sample gas dewpoint.
(6) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the transfer line and to account for analyzer response.
(7) While the analyzer measures the sample's concentration, record its output for 30 seconds. Calculate the arithmetic mean of this data. When performed with all the gases simultaneously, this is the combined interference.
(8) The analyzer meets the interference verification if the result of paragraph (d)(7) of this section meets the tolerance in paragraph (c) of this section.
(9) You may also run interference procedures separately for individual interference gases. If the interference gas levels used are higher than the maximum levels expected during testing, you may scale down each observed interference value (the arithmetic mean of 30 second data described in paragraph (d)(7) of this section) by multiplying the observed interference by the ratio of the maximum expected concentration value to the actual value used during this procedure. You may run separate interference concentrations of H_2O (down to 0.025 mol/mol H_2O content) that are lower than the maximum levels expected during testing, but you must scale up the observed H_2O interference by multiplying the observed interference by the ratio of the maximum expected H_2O concentration value to the actual value used during this procedure. The sum of the scaled interference values must meet the tolerance for combined interference as specified in paragraph (c) of this section.

§ 1065.376 Chiller NO_2 penetration.
(a) Scope and frequency. If you use a chiller to dry a sample upstream of a NO_x measurement instrument, but you don't use an NO_2-to-NO converter upstream of the chiller, you must perform this verification for chiller NO_2 penetration. Perform this verification after initial installation and after major maintenance.
(b) Measurement principles. A chiller removes H_2O, which can otherwise interfere with a NO_x measurement. However, liquid H_2O remaining in an improperly designed chiller can remove NO_2 from the sample. If a chiller is used without an NO_2-to-NO converter upstream, it could remove NO_2 from the sample prior NO_x measurement.
(c) System requirements. A chiller must allow for measuring at least 95 % of the total NO_2 at the maximum expected concentration of NO_2.
(d) Procedure. Use the following procedure to verify chiller performance:
(1) Instrument setup. Follow the analyzer and chiller manufacturers' start-up and operating instructions. Adjust the analyzer and chiller as needed to optimize performance.

(2) Equipment setup and data collection. (i) Zero and span the total NO_x gas analyzer(s) as you would before emission testing.
(ii) Select an NO_2 calibration gas, balance gas of dry air, that has an NO_2 concentration within ±5 % of the maximum NO_2 concentration expected during testing.
(iii) Overflow this calibration gas at the gas sampling system's probe or overflow fitting. Allow for stabilization of the total NO_x response, accounting only for transport delays and instrument response.
(iv) Calculate the mean of 30 seconds of recorded total NO_x data and record this value as x_{NOxref}.
(v) Stop flowing the NO_2 calibration gas.
(vi) Next saturate the sampling system by overflowing a dewpoint generator's output, set at a dewpoint of 50 °C, to the gas sampling system's probe or overflow fitting. Sample the dewpoint generator's output through the sampling system and chiller for at least 10 minutes until the chiller is expected to be removing a constant rate of H_2O.
(vii) Immediately switch back to overflowing the NO_2 calibration gas used to establish x_{NOxref}. Allow for stabilization of the total NO_x response, accounting only for transport delays and instrument response. Calculate the mean of 30 seconds of recorded total NO_x data and record this value as $x_{NOxmeas}$.
(viii) Correct $x_{NOxmeas}$ to x_{NOxdry} based upon the residual H_2O vapor that passed through the chiller at the chiller's outlet temperature and pressure.
(3) Performance evaluation. If x_{NOxdry} is less than 95 % of x_{NOxref}, repair or replace the chiller.
(e) Exceptions. The following exceptions apply:
(1) You may omit this verification if you can show by engineering analysis that for your NO_x sampling system and your emission calculations procedures, the chiller always affects your brake-specific NO_x emission results by less than 0.5 % of the applicable NO_x standard.
(2)You may use a chiller that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

§ 1065.378 NO_2-to-NO converter conversion verification.
(a) Scope and frequency. If you use an analyzer that measures only NO to determine NO_x, you must use an NO_2-to-NO converter upstream of the analyzer. Perform this verification after installing the converter, after major maintenance and within 35 days before an emission test. This verification must be repeated at this frequency to verify that the catalytic activity of the NO_2-to-NO converter has not deteriorated.
(b) Measurement principles. An NO_2-to-NO converter allows an analyzer that measures only NO to determine total NO_x by converting the NO_2 in exhaust to NO.
(c) System requirements. An NO_2-to-NO converter must allow for measuring at least 95 % of the total NO_2 at the maximum expected concentration of NO_2.
(d) Procedure. Use the following procedure to verify the performance of a NO_2-to-NO converter:
(1) Instrument setup. Follow the analyzer and NO_2-to-NO converter manufacturers' start-up and operating instructions. Adjust the analyzer and converter as needed to optimize performance.
(2) Equipment setup. Connect an ozonator's inlet to a zero-air or oxygen source and connect its outlet to one port of a three-way tee fitting. Connect an NO span gas to another port, and connect the NO_2-to-NO converter inlet to the last port.
(3) Adjustments and data collection. Perform this check as follows:

(i) Set ozonator air off, turn ozonator power off, and set the analyzer to NO mode. Allow for stabilization, accounting only for transport delays and instrument response.
(ii) Use an NO concentration that is representative of the peak total NO_x concentration expected during testing. The NO_2 content of the gas mixture shall be less than 5 % of the NO concentration. Record the concentration of NO by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as x_{NOref}.
(iii) Turn on the ozonator O_2 supply and adjust the O_2 flow rate so the NO indicated by the analyzer is about 10 percent less than x_{NOref}. Record the concentration of NO by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as $x_{NO+O2mix}$.
(iv) Switch the ozonator on and adjust the ozone generation rate so the NO measured by the analyzer is 20 percent of x_{NOref} or a value which would simulate the maximum concentration of NO_2 expected during testing, while maintaining at least 10 percent unreacted NO. This ensures that the ozonator is generating NO_2 at the maximum concentration expected during testing. Record the concentration of NO by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as x_{NOmeas}.
(v) Switch the NO_x analyzer to NO_x mode and measure total NO_x. Record the concentration of NO_x by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as $x_{NOxmeas}$.
(vi) Switch off the ozonator but maintain gas flow through the system. The NO_x analyzer will indicate the NO_x in the NO + O_2 mixture. Record the concentration of NO_x by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as $x_{NOx+O2mix}$.
(vii) Turn off the ozonator O_2 supply. The NO_x analyzer will indicate the NO_x in the original NO-in-N_2 mixture. Record the concentration of NO_x by calculating the mean of 30 seconds of sampled data from the analyzer and record this value as x_{NOxref}. This value should be no more than 5 percent above the x_{NOref} value.
(4) Performance evaluation. Calculate the efficiency of the NO_x converter by substituting the concentrations obtained into the following equation:

$$efficiency = \left(1 + \frac{x_{NOxmeas} - x_{NOx+O2mix}}{x_{NO+O2mix} - x_{NOmeas}}\right) \cdot 100\ \%$$

(5) If the result is less than 95 %, repair or replace the NO2-to-NO converter.
(e) Exceptions. The following exceptions apply:
(1) You may omit this verification if you can show by engineering analysis that for your NO_x sampling system and your emission calculations procedures, the converter always affects your brake-specific NO_x emission results by less than 0.5 % of the applicable NO_x standard.
(2)You may use a converter that you determine does not meet this verification, as long as you try to correct the problem and the measurement deficiency does not adversely affect your ability to show that engines comply with all applicable emission standards.

PM MEASUREMENTS

§ 1065.390 PM balance verifications and weighing process verification.
(a) Scope and frequency. This section describes three verifications.
(1) Independent verification of PM balance performance within 370 days before weighing any filter.
(2) Zero and span the balance within 12 h before weighing any filter.

(3) Verify that the mass determination of reference filters before and after a filter weighing session are less than a specified tolerance.
(b) Independent verification. Have the balance manufacturer (or a representative approved by the balance manufacturer) verify the balance performance within 370 days of testing.
(c) Zeroing and spanning. You must verify balance performance by zeroing and spanning it with at least one calibration weight, and any weights you use must that meet the specifications in § 1065.790 to perform this verification.
(1) Use a manual procedure in which you zero the balance and span the balance with at least one calibration weight. If you normally use mean values by repeating the weighing process to improve the accuracy and precision of PM measurements, use the same process to verify balance performance.
(2) You may use an automated procedure to verify balance performance. For example many balances have internal calibration weights that are used automatically to verify balance performance.
(d) Reference sample weighing. Verify all mass readings during a weighing session by weighing reference PM sample media (e.g. filters) before and after a weighing session. A weighing session may be as short as desired, but no longer than 80 hours, and may include both pre-test and post-test mass readings. We recommend that weighing sessions be eight hours or less. Successive mass determinations of each reference PM sample media (e.g., filter) must return the same value within ±10 μg or ±10 % of the net PM mass expected at the standard (if known), whichever is higher. If successive reference PM sample media (e.g. filter) weighing events fail this criterion, invalidate all individual test media (e.g., filter) mass readings occurring between the successive reference media (e.g., filter) mass determinations. You may reweigh these media (e.g. filter) in another weighing session. If you invalidate a pre-test media (e.g. filter) mass determination, that test interval is void. Perform this verification as follows:
(1) Keep at least two samples of unused PM sample media (e.g., filters) in the PM-stabilization environment. Use these as references. If you collect PM with filters, select unused filters of the same material and size for use as references. You may periodically replace references, using good engineering judgment.
(2) Stabilize references in the PM stabilization environment. Consider references stabilized if they have been in the PM-stabilization environment for a minimum of 30 min, and the PM-stabilization environment has been within the specifications of § 1065.190(d) for at least the preceding 60 min.
(3) Exercise the balance several times with a reference sample. We recommend weighing ten samples without recording the values.
(4) Zero and span the balance. Using good engineering judgment, place a test mass such as a calibration weight on the balance, then remove it. After spanning, confirm that the balance returns to a zero reading within the normal stabilization time.
(5) Weigh each of the reference media (e.g. filters) and record their masses. We recommend using substitution weighing as described in § 1065.590(j). If you normally use mean values by repeating the weighing process to improve the accuracy and precision of the reference media (e.g. filter) mass, you must use mean values of sample media (e.g. filter) masses.
(6) Record the balance environment dewpoint, ambient temperature, and atmospheric pressure.
(7) Use the recorded ambient conditions to correct results for buoyancy as described in § 1065.690. Record the buoyancy-corrected mass of each of the references.

(8) Subtract each reference media's (e.g. filter's) buoyancy-corrected reference mass from its previously measured and recorded buoyancy-corrected mass.
(9) If any of the reference filters' observed mass changes by more than that allowed under this paragraph, you must invalidate all PM mass determinations made since the last successful reference media (e.g. filter) mass validation. You may discard reference PM media (e.g. filters) if only one of the filter's mass changes by more than the allowable amount and you can positively identify a special cause for that filter's mass change that would not have affected other in-process filters. Thus, the validation can be considered a success. In this case, you do not have to include the contaminated reference media when determining compliance with paragraph (d)(10) of this section, but the affected reference filter must be immediately discarded and replaced prior to the next weighing session.
(10) If any of the reference masses change by more than that allowed under this paragraph (d), invalidate all PM results that were determined between the two times that the reference masses were determined. If you discarded reference PM sample media according to paragraph (d)(9) of this section, you must still have at least one reference mass difference that meets the criteria in this paragraph (d). Otherwise, you must invalidate all PM results that were determined between the two times that the reference media (e.g. filters) masses were determined.

§ 1065.395 Inertial PM balance verifications.
This section describes how to verify the performance of an inertial PM balance.
(a) Independent verification. Have the balance manufacturer (or a representative approved by the balance manufacturer) verify the inertial balance performance within 370 days before testing.
(b) Other verifications. Perform other verifications using good engineering judgment and instrument manufacturer recommendations.

Subpart E—ENGINE SELECTION, PREPARATION, AND MAINTENANCE

§ 1065.401 Test engine selection.

While all engine configurations within a certified engine family must comply with the applicable standards in the standard-setting part, you need not test each configuration for certification.
(a) Select an engine configuration within the engine family for testing, as follows:
(1) Test the engine that we specify, whether we issue general guidance or give you specific instructions.
(2) If we do not tell you which engine to test, follow any instructions in the standard-setting part.
(3) If we do not tell you which engine to test and the standard-setting part does not include specifications for selecting test engines, use good engineering judgment to select the engine configuration within the engine family that is most likely to exceed an emission standard.
(b) In the absence of other information, the following characteristics are appropriate to consider when selecting the engine to test:
(1) Maximum fueling rates.
(2) Maximum loads.
(3) Maximum in-use speeds.
(4) Highest sales volume.
(c) For our testing, we may select any engine configuration within the engine family.

§ 1065.405 Test engine preparation and maintenance.

This part 1065 describes how to test engines for a variety of purposes, including certification testing, production-line testing, and in-use testing. Depending on which type of testing is being conducted, different preparation and maintenance requirements apply for the test engine.
(a) If you are testing an emission-data engine for certification, make sure it is built to represent production engines, consistent with paragraph (f) of this section. This includes governors that you normally install on production engines. Production engines should also be tested with their installed governors. If your engine is equipped with multiple user-selectable governor types and if the governor does not manipulate the emission control system (i.e., the governor only modulates an "operator demand" signal such as commanded fuel rate, torque, or power), choose the governor type that allows the test cell to most accurately follow the duty cycle. If the governor manipulates the emission control system, treat it as an adjustable parameter. See paragraph (b) of this section for guidance on setting adjustable parameters. If you do not install governors on production engines, simulate a governor that is representative of a governor that others will install on your production engines. In certain circumstances, you may incorporate test cell components to simulate an in-use configuration, consistent with good engineering judgment. For example, § § 1065.122 and 1065.125 allow the use of test cell components to represent engine cooling and intake air systems. The provisions in § 1065.110(e) also apply to emission-data engines for certification.
(b) We may set adjustable parameters to any value in the valid range, and you are responsible for controlling emissions over the full valid range. For each adjustable parameter, if the standard-setting part has no unique requirements and if we have not specified a value, use good engineering judgment to select the most common setting. If information on the most common setting is not available, select the setting representing the engine's original shipped configuration. If information on the most common and original settings is not available, set the adjustable parameter in the middle of the valid range.

(c) Testing generally occurs only after the test engine has undergone a stabilization step (or in-use operation). If the engine has not already been stabilized, run the test engine, with all emission control systems operating, long enough to stabilize emission levels. Note that you must generally use the same stabilization procedures for emission-data engines for which you apply the same deterioration factors so low-hour emission-data engines are consistent with the low-hour engine used to develop the deterioration factor.
(1) Unless otherwise specified in the standard-setting part, you may consider emission levels stable without measurement after 50 h of operation. If the engine needs less operation to stabilize emission levels, record your reasons and the methods for doing this, and give us these records if we ask for them. If the engine will be tested for certification as a low-hour engine, see the standard-setting part for limits on testing engines to establish low-hour emission levels.
(2) You may stabilize emissions from a catalytic exhaust aftertreatment device by operating it on a different engine, consistent with good engineering judgment. Note that good engineering judgment requires that you consider both the purpose of the test and how your stabilization method will affect the development and application of deterioration factors. For example, this method of stabilization is generally not appropriate for production engines. We may also allow you to stabilize emissions from a catalytic exhaust aftertreatment device by operating it on an engine-exhaust simulator.
(d) Record any maintenance, modifications, parts changes, diagnostic or emissions testing and document the need for each event. You must provide this information if we request it.
(e) For accumulating operating hours on your test engines, select engine operation that represents normal in-use operation for the engine family.
(f) If your engine will be used in a vehicle equipped with a canister for storing evaporative hydrocarbons for eventual combustion in the engine and the test sequence involves a cold-start or hot-start duty cycle, attach a canister to the engine before running an emission test. You may omit using an evaporative canister for any hot-stabilized duty cycles. You may request to omit using an evaporative canister during testing if you can show that it would not affect your ability to show compliance with the applicable emission standards. You may operate the engine without an installed canister for service accumulation. Prior to an emission test, use the following steps to precondition a canister and attach it to your engine:
(1) Use a canister and plumbing arrangement that represents the in-use configuration of the largest capacity canister in all expected applications.
(2) Precondition the canister as described in 40 CFR 86.132-96(j).
(3) Connect the canister's purge port to the engine.
(4) Plug the canister port that is normally connected to the fuel tank.
(g) This paragraph (g) defines the components that are considered to be part of the engine for laboratory testing. See § 1065.110 for provisions related to system boundaries with respect to work inputs and outputs.
(1) This paragraph (g)(1) describes certain criteria for considering a component to be part of the test engine. The criteria are intended to apply broadly, such that a component would generally be considered part of the engine in cases of uncertainty. Except as specified in paragraph (g)(2) of this section, an engine-related component meeting both the following criteria is considered to be part of the test engine for purposes of testing and for stabilizing emission levels, preconditioning, and measuring emission levels:

(i) The component directly affects the functioning of the engine, is related to controlling emissions, or transmits engine power. This would include engine cooling systems, engine controls, and transmissions.
(ii) The component is covered by the applicable certificate of conformity. For example, this criterion would typically exclude radiators not described in an application for certification.
(2) This paragraph (g)(2) applies for engine-related components that meet the criteria of paragraph (g)(1) of this section, but that are part of the laboratory setup or are used for other engines. Such components are considered to be part of the test engine for preconditioning, but not for engine stabilization. For example, if you test your engines using the same laboratory exhaust tubing for all tests, there would be no restrictions on the number of test hours that could be accumulated with the tubing, but it would need to be preconditioned separately for each engine.

§ 1065.410 Maintenance limits for stabilized test engines.
(a) After you stabilize the test engine's emission levels, you may do maintenance as allowed by the standard-setting part. However, you may not do any maintenance based on emission measurements from the test engine (i.e., unscheduled maintenance).
(b) For any critical emission-related maintenance—other than what we specifically allow in the standard-setting part—you must completely test an engine for emissions before and after doing any maintenance that might affect emissions, unless we waive this requirement.
(c) If you inspect an engine, keep a record of the inspection and update your application to document any changes that result. You may use any kind of equipment, instrument, or tool to identify bad engine components or perform maintenance if it is available at dealerships and other service outlets.
(d) If we determine that a part failure, system malfunction, or associated repairs have made the engine's emission controls unrepresentative of production engines, you may no longer use it as an emission-data engine. Also, if your test engine has a major mechanical failure that requires you to take it apart, you may no longer use it as an emission-data engine.

§ 1065.415 Durability demonstration.
If the standard-setting part requires durability testing, you must accumulate service in a way that represents how you expect the engine to operate in use. You may accumulate service hours using an accelerated schedule, such as through continuous operation or by using duty cycles that are more aggressive than in-use operation, subject to any pre-approval requirements established in the applicable standard-setting part.
(a) Maintenance. The following limits apply to the maintenance that we allow you to do on an emission-data engine:
(1) You may perform scheduled maintenance that you recommend to operators, but only if it is consistent with the standard-setting part's restrictions.
(2) You may perform additional maintenance only as specified in § 1065.410 or allowed by the standard-setting part.
(b) Emission measurements. Perform emission tests following the provisions of the standard setting part and this part, as applicable. Perform emission tests to determine deterioration factors consistent with good engineering judgment. Evenly space any tests between the first and last test points throughout the durability period, unless we approve otherwise.

Subpart F—PERFORMING AN EMISSION TEST OVER SPECIFIED DUTY CYCLES

§ 1065.501 Overview.

(a) Use the procedures detailed in this subpart to measure engine emissions over a specified duty cycle. Refer to subpart J of this part for field test procedures that describe how to measure emissions during in-use engine operation. This section describes how to:

(1) Map your engine, if applicable, by recording specified speed and torque data, as measured from the engine's primary output shaft.

(2) Transform normalized duty cycles into reference duty cycles for your engine by using an engine map.

(3) Prepare your engine, equipment, and measurement instruments for an emission test.

(4) Perform pre-test procedures to verify proper operation of certain equipment and analyzers.

(5) Record pre-test data.

(6) Start or restart the engine and sampling systems.

(7) Sample emissions throughout the duty cycle.

(8) Record post-test data.

(9) Perform post-test procedures to verify proper operation of certain equipment and analyzers.

(10) Weigh PM samples.

(b) Unless we specify otherwise, you may control the regeneration timing of infrequently regenerated aftertreatment devices such as diesel particulate filters using good engineering judgment. You may control the regeneration timing using a sequence of engine operating conditions or you may initiate regeneration with an external regeneration switch or other command. This provision also allows you to ensure that a regeneration event does not occur during an emission test.

(c) An emission test generally consists of measuring emissions and other parameters while an engine follows one or more duty cycles that are specified in the standard-setting part. There are two general types of duty cycles:

(1) Transient cycles. Transient duty cycles are typically specified in the standard-setting part as a second-by-second sequence of speed commands and normalized torque (or power) commands. Operate an engine over a transient cycle such that the speed and torque of the engine's primary output shaft follows the target values. Proportionally sample emissions and other parameters and use the calculations in subpart G of this part to calculate emissions. Start a transient test according to the standard-setting part, as follows:

(i) A cold-start transient cycle where you start to measure emissions just before starting an engine that has not been warmed up.

(ii) A hot-start transient cycle where you start to measure emissions just before starting a warmed-up engine.

(iii) A hot running transient cycle where you start to measure emissions after an engine is started, warmed up, and running.

(2) Steady-state cycles. Steady-state duty cycles are typically specified in the standard-setting part as a list of discrete operating points (modes or notches), where each operating point has one value of a normalized speed command and one value of a normalized torque (or power) command. Ramped-modal cycles for steady-state testing also list test times for each mode and transition times between modes where speed and torque are linearly ramped between modes, even for cycles with % power. Start a steady-state cycle as a hot running test, where you start to

measure emissions after an engine is started, warmed up and running. Run a steady-state duty cycle as a discrete-mode cycle or a ramped-modal cycle, as follows:
(i) Discrete-mode cycles. Before emission sampling, stabilize an engine at the first discrete mode of the duty cycle specified in the standard-setting part. Sample emissions and other parameters for that mode in the same manner as a transient cycle, with the exception that reference speed and torque values are constant. Record data for that mode, transition to the next mode, and then stabilize the engine at the next mode. Continue to sample each mode discretely as a separate test interval and calculate composite brake-specific emission results according to § 1065.650(g)(2).
(A) Use good engineering judgment to determine the time required to stabilize the engine. You may make this determination before starting the test based on prior experience, or you may make this determination in real time based an automated stability criteria. If needed, you may continue to operate the engine after reaching stability to get laboratory equipment ready for sampling.
(B) Collect PM on separate PM sample media for each mode.
(C) The minimum sample time is 60 seconds. We recommend that you sample both gaseous and PM emissions over the same test interval. If you sample gaseous and PM emissions over different test intervals, there must be no change in engine operation between the two test intervals. These two test intervals may completely or partially overlap, they may run consecutively, or they may be separated in time.
(ii) Ramped-modal cycles. Perform ramped-modal cycles similar to the way you would perform transient cycles, except that ramped-modal cycles involve mostly steady-state engine operation. Generate a ramped-modal duty cycle as a sequence of second-by-second (1 Hz) reference speed and torque points. Run the ramped-modal duty cycle in the same manner as a transient cycle and use the 1 Hz reference speed and torque values to validate the cycle, even for cycles with % power. Proportionally sample emissions and other parameters during the cycle and use the calculations in subpart G of this part to calculate emissions.
(d) Other subparts in this part identify how to select and prepare an engine for testing (subpart E), how to perform the required engine service accumulation (subpart E), and how to calculate emission results (subpart G).
(e) Subpart J of this part describes how to perform field testing.

§ 1065.510 Engine mapping.
(a) Applicability, scope, and frequency. An engine map is a data set that consists of a series of paired data points that represent the maximum brake torque versus engine speed, measured at the engine's primary output shaft. Map your engine if the standard-setting part requires engine mapping to generate a duty cycle for your engine configuration. Map your engine while it is connected to a dynamometer or other device that can absorb work output from the engine's primary output shaft according to § 1065.110. To establish speed and torque values for mapping, we generally recommend that you stabilize an engine for at least 15 seconds at each setpoint and record the mean feedback speed and torque of the last (4 to 6) seconds. Configure any auxiliary work inputs and outputs such as hybrid, turbo-compounding, or thermoelectric systems to represent their in-use configurations, and use the same configuration for emission testing. See Figure 1 of § 1065.210. This may involve configuring initial states of charge and rates and times of auxiliary-work inputs and outputs. We recommend that you contact the Designated Compliance Officer before testing to determine how you should configure any auxiliary-work inputs and outputs. Use the most recent engine map to transform a normalized duty cycle from the standard-setting part to a reference duty cycle specific to your engine. Normalized duty

cycles are specified in the standard-setting part. You may update an engine map at any time by repeating the engine-mapping procedure. You must map or re-map an engine before a test if any of the following apply:
(1) If you have not performed an initial engine map.
(2) If the atmospheric pressure near the engine's air inlet is not within ±5 kPa of the atmospheric pressure recorded at the time of the last engine map.
(3) If the engine or emission-control system has undergone changes that might affect maximum torque performance. This includes changing the configuration of auxiliary work inputs and outputs.
(4) If you capture an incomplete map on your first attempt or you do not complete a map within the specified time tolerance. You may repeat mapping as often as necessary to capture a complete map within the specified time.
(b) Mapping variable-speed engines. Map variable-speed engines as follows:
(1) Record the atmospheric pressure.
(2) Warm up the engine by operating it. We recommend operating the engine at any speed and at approximately 75 % of its expected maximum power. Continue the warm-up until the engine coolant, block, or head absolute temperature is within ±2 % of its mean value for at least 2 min or until the engine thermostat controls engine temperature.
(3) Operate the engine at its warm idle speed as follows:
(i) For engines with a low-speed governor, set the operator demand to minimum, use the dynamometer or other loading device to target a torque of zero on the engine's primary output shaft, and allow the engine to govern the speed. Measure this warm idle speed; we recommend recording at least 30 values of speed and using the mean of those values.
(ii) For engines without a low-speed governor, operate the engine at warm idle speed and zero torque on the engine's primary output shaft. You may use the dynamometer to target a torque of zero on the engine's primary output shaft, and manipulate the operator demand to control the speed to target the manufacturer-declared value for the lowest engine speed possible with minimum load (also known as manufacturer-declared warm idle speed). You may alternatively use the dynamometer to target the manufacturer-declared warm idle speed and manipulate the operator demand to control the torque on the engine's primary output shaft to zero.
(iii) For variable-speed engines with or without a low-speed governor, if a nonzero idle torque is representative of in-use operation, you may use the dynamometer or operator demand to target the manufacturer-declared idle torque instead of targeting zero torque as specified in paragraphs (b)(3)(i) and (ii) of this section. Control speed as specified in paragraph (b)(3)(i) or (ii) of this section, as applicable. If you use this option for engines with a low-speed governor to measure the warm idle speed with the manufacturer-declared torque at this step, you may use this as the warm-idle speed for cycle generation as specified in paragraph (b)(6) of this section. However, if you identify multiple warm idle torques under paragraph (f)(4)(i) of this section, measure the warm idle speed at only one torque level for this paragraph (b)(3).
(4) Set operator demand to maximum and control engine speed at (95 ±1) % of its warm idle speed determined above for at least 15 seconds. For engines with reference duty cycles whose lowest speed is greater than warm idle speed, you may start the map at (95 ±1) % of the lowest reference speed.
(5) Perform one of the following:
(i) For any engine subject only to steady-state duty cycles, you may perform an engine map by using discrete speeds. Select at least 20 evenly spaced setpoints from 95% of warm idle speed to

the highest speed above maximum power at which 50 % of maximum power occurs. We refer to this 50 % speed as the check point speed as described in paragraph (b)(5)(iii) of this section. At each setpoint, stabilize speed and allow torque to stabilize. Record the mean speed and torque at each setpoint. Use linear interpolation to determine intermediate speeds and torques. Use this series of speeds and torques to generate the power map as described in paragraph (e) of this section.

(ii) For any variable-speed engine, you may perform an engine map by using a continuous sweep of speed by continuing to record the mean feedback speed and torque at 1 Hz or more frequently and increasing speed at a constant rate such that it takes (4 to 6) min to sweep from 95 % of warm idle speed to the check point speed as described in paragraph (b)(5)(iii) of this section. Use good engineering judgment to determine when to stop recording data to ensure that the sweep is complete. In most cases, this means that you can stop the sweep at any point after the power falls to 50 % of the maximum value. From the series of mean speed and maximum torque values, use linear interpolation to determine intermediate values. Use this series of speeds and torques to generate the power map as described in paragraph (e) of this section.

(iii) The check point speed of the map is the highest speed above maximum power at which 50 % of maximum power occurs. If this speed is unsafe or unachievable (e.g., for ungoverned engines or engines that do not operate at that point), use good engineering judgment to map up to the maximum safe speed or maximum achievable speed. For discrete mapping, if the engine cannot be mapped to the check point speed, make sure the map includes at least 20 points from 95% of warm idle to the maximum mapped speed. For continuous mapping, if the engine cannot be mapped to the check point speed, verify that the sweep time from 95 % of warm idle to the maximum mapped speed is (4 to 6) min.

(iv) Note that under § 1065.10(c)(1) we may allow you to disregard portions of the map when selecting maximum test speed if the specified procedure would result in a duty cycle that does not represent in-use operation.

(6) Use one of the following methods to determine warm high-idle speed for engines with a high-speed governor if they are subject to transient testing with a duty cycle that includes reference speed values above 100 %:

(i) You may use a manufacturer-declared warm high-idle speed if the engine is electronically governed. For engines with a high-speed governor that shuts off torque output at a manufacturer-specified speed and reactivates at a lower manufacturer-specified speed (such as engines that use ignition cut-off for governing), declare the middle of the specified speed range as the warm high-idle speed.

(ii) Measure the warm high-idle speed using the following procedure:

(A) Set operator demand to maximum and use the dynamometer to target zero torque on the engine's primary output shaft. If the mean feedback torque is within ±1 % of $T_{\text{max mapped}}$, you may use the observed mean feedback speed at that point as the measured warm high-idle speed.

(B) If the engine is unstable as a result of in-use production components (such as engines that use ignition cut-off for governing, as opposed to unstable dynamometer operation), you must use the mean feedback speed from paragraph (b)(6)(ii)(A) of this section as the measured warm high-idle speed. The engine is considered unstable if any of the 1 Hz speed feedback values are not within ±2 % of the calculated mean feedback speed. We recommend that you determine the mean as the value representing the midpoint between the observed maximum and minimum recorded feedback speed.

(C) If your dynamometer is not capable of achieving a mean feedback torque within ±1 % of $T_{max\ mapped}$, operate the engine at a second point with operator demand set to maximum with the dynamometer set to target a torque equal to the recorded mean feedback torque on the previous point plus 20 % of $T_{max\ mapped}$. Use this data point and the data point from paragraph (b)(6)(ii)(A) of this section to extrapolate the engine speed where torque is equal to zero.
(D) You may use a manufacturer-declared T_{max} instead of the measured $T_{max\ mapped}$. If you do this, or if you are able to determine mean feedback speed as described in paragraphs (b)(6)(ii)(A) and (B) of this section, you may measure the warm high-idle speed before running the speed sweep specified in paragraph (b)(5) of this section.
(7) For engines with a low-speed governor, if a nonzero idle torque is representative of in-use operation, operate the engine at warm idle with the manufacturer-declared idle torque. Set the operator demand to minimum, use the dynamometer to target the declared idle torque, and allow the engine to govern the speed. Measure this speed and use it as the warm idle speed for cycle generation in § 1065.512. We recommend recording at least 30 values of speed and using the mean of those values. If you identify multiple warm idle torques under paragraph (f)(4)(i) of this section, measure the warm idle speed at each torque. You may map the idle governor at multiple load levels and use this map to determine the measured warm idle speed at the declared idle torque(s).
(c) Negative torque mapping. If your engine is subject to a reference duty cycle that specifies negative torque values (i.e., engine motoring), generate a motoring torque curve by any of the following procedures:

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(1) Multiply the positive torques from your map by –40 %. Use linear interpolation to determine intermediate values.
(2) Map the amount of negative torque required to motor the engine by repeating paragraph (b) of this section with minimum operator demand. You may start the negative torque map at either the minimum or maximum speed from paragraph (b) of this section.
(3) Determine the amount of negative torque required to motor the engine at the following two points near the ends of the engine's speed range. Operate the engine at these two points at minimum operator demand. Use linear interpolation to determine intermediate values.
(i) Low speed point. For engines without a low-speed governor, determine the amount of negative torque at warm idle speed. For engines with a low-speed governor, motor the engine above warm idle speed so the governor is inactive and determine the amount of negative torque at that speed.
(ii) High speed point. For engines without a high-speed governor, determine the amount of negative torque at the maximum safe speed or the maximum representative speed. For engines with a high-speed governor, determine the amount of negative torque at a speed at or above n_{hi} per § 1065.610(c)(2).
(d) Mapping constant-speed engines. For constant-speed engines, generate a map as follows:
(1) Record the atmospheric pressure.
(2) Warm up the engine by operating it. We recommend operating the engine at approximately 75 % of the engine's expected maximum power. Continue the warm-up until the engine coolant, block, or head absolute temperature is within ±2 % of its mean value for at least 2 min or until the engine thermostat controls engine temperature.
(3) You may operate the engine with a production constant-speed governor or simulate a constant-speed governor by controlling engine speed with an operator demand control system

described in § 1065.110. Use either isochronous or speed-droop governor operation, as appropriate.

(4) With the governor or simulated governor controlling speed using operator demand, operate the engine at no-load governed speed (at high speed, not low idle) for at least 15 seconds.

(5) Perform one of the following:

(i) For constant-speed engines subject only to steady-state testing, you may perform an engine map by using a series of discrete torques. Select at least five evenly spaced torque setpoints from no-load to 80 % of the manufacturer-declared test torque or to a torque derived from your published maximum power level if the declared test torque is unavailable. Starting at the 80 % torque point, select setpoints in 2.5 % intervals, stopping at the endpoint torque. The endpoint torque is defined as the first discrete mapped torque value greater than the torque at maximum observed power where the engine outputs 90 % of the maximum observed power; or the torque when engine stall has been determined using good engineering judgment (i.e. sudden deceleration of engine speed while adding torque). You may continue mapping at higher torque setpoints. At each setpoint, allow torque and speed to stabilize. Record the mean feedback speed and torque at each setpoint. From this series of mean feedback speed and torque values, use linear interpolation to determine intermediate values. Use this series of mean feedback speeds and torques to generate the power map as described in paragraph (e) of this section.

(ii) For any constant-speed engine, you may perform an engine map with a continuous torque sweep by continuing to record the mean feedback speed and torque at 1 Hz or more frequently. Use the dynamometer to increase torque. Increase the reference torque at a constant rate from no-load to the endpoint torque as defined in paragraph (d)(5)(i) of this section. You may continue mapping at higher torque setpoints. Unless the standard-setting part specifies otherwise, target a torque sweep rate equal to the manufacturer-declared test torque (or a torque derived from your published power level if the declared test torque is not known) divided by 180 seconds. Stop recording after you complete the sweep. Verify that the average torque sweep rate over the entire map is within ±7 % of the target torque sweep rate. Use linear interpolation to determine intermediate values from this series of mean feedback speed and torque values. Use this series of mean feedback speeds and torques to generate the power map as described in paragraph (e) of this section.

(iii) For any isochronous governed (0 % speed droop) constant-speed engine, you may map the engine with two points as described in this paragraph (d)(5)(iii). After stabilizing at the no-load governed speed in paragraph (d)(4) of this section, record the mean feedback speed and torque. Continue to operate the engine with the governor or simulated governor controlling engine speed using operator demand, and control the dynamometer to target a speed of 99.5 % of the recorded mean no-load governed speed. Allow speed and torque to stabilize. Record the mean feedback speed and torque. Record the target speed. The absolute value of the speed error (the mean feedback speed minus the target speed) must be no greater than 0.1 % of the recorded mean no-load governed speed. From this series of two mean feedback speed and torque values, use linear interpolation to determine intermediate values. Use this series of two mean feedback speeds and torques to generate a power map as described in paragraph (e) of this section. Note that the measured maximum test torque as determined in § 1065.610(b)(1) will be the mean feedback torque recorded on the second point.

(e) Power mapping. For all engines, create a power-versus-speed map by transforming torque and speed values to corresponding power values. Use the mean values from the recorded map data. Do not use any interpolated values. Multiply each torque by its corresponding speed and

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apply the appropriate conversion factors to arrive at units of power (kW). Interpolate intermediate power values between these power values, which were calculated from the recorded map data.

(f) Measured and declared test speeds and torques. You must select test speeds and torques for cycle generation as required in this paragraph (f). "Measured" values are either directly measured during the engine mapping process or they are determined from the engine map. "Declared" values are specified by the manufacturer. When both measured and declared values are available, you may use declared test speeds and torques instead of measured speeds and torques if they meet the criteria in this paragraph (f). Otherwise, you must use measured speeds and torques derived from the engine map.

(1) Measured speeds and torques. Determine the applicable speeds and torques for the duty cycles you will run:

(i) Measured maximum test speed for variable-speed engines according to § 1065.610.

(ii) Measured maximum test torque for constant-speed engines according to § 1065.610.

(iii) Measured "A", "B", and "C" speeds for variable-speed engines according to § 1065.610.

(iv) Measured intermediate speed for variable-speed engines according to § 1065.610.

(v) For variable-speed engines with a low-speed governor, measure warm idle speed according to § 1065.510(b) and use this speed for cycle generation in § 1065.512. For engines with no low-speed governor, instead use the manufacturer-declared warm idle speed.

(2) Required declared speeds. You must declare the lowest engine speed possible with minimum load (i.e., manufacturer-declared warm idle speed). This is applicable only to variable-speed engines with no low-speed governor. For engines with no low-speed governor, the declared warm idle speed is used for cycle generation in § 1065.512. Declare this speed in a way that is representative of in-use operation. For example, if your engine is typically connected to an automatic transmission or a hydrostatic transmission, declare this speed at the idle speed at which your engine operates when the transmission is engaged.

(3) Optional declared speeds. You may use declared speeds instead of measured speeds as follows:

(i) You may use a declared value for maximum test speed for variable-speed engines if it is within (97.5 to 102.5) % of the corresponding measured value. You may use a higher declared speed if the length of the "vector" at the declared speed is within 2 % of the length of the "vector" at the measured value. The term vector refers to the square root of the sum of normalized engine speed squared and the normalized full-load power (at that speed) squared, consistent with the calculations in § 1065.610.

(ii) You may use a declared value for intermediate, "A", "B", or "C" speeds for steady-state tests if the declared value is within (97.5 to 102.5) % of the corresponding measured value.

(iii) For electronically governed engines, you may use a declared warm high-idle speed for calculating the alternate maximum test speed as specified in § 1065.610.

(4) Required declared torques. If a nonzero idle or minimum torque is representative of in-use operation, you must declare the appropriate torque as follows:

(i) For variable-speed engines, declare a warm idle torque that is representative of in-use operation. For example, if your engine is typically connected to an automatic transmission or a hydrostatic transmission, declare the torque that occurs at the idle speed at which your engine operates when the transmission is engaged. Use this value for cycle generation. You may use multiple warm idle torques and associated idle speeds in cycle generation for representative testing. For example, for cycles that start the engine and begin with idle, you may start a cycle in

idle with the transmission in neutral with zero torque and later switch to a different idle with the transmission in drive with the Curb-Idle Transmission Torque (CITT). For variable-speed engines intended primarily for propulsion of a vehicle with an automatic transmission where that engine is subject to a transient duty cycle with idle operation, you must declare a CITT. You must specify a CITT based on typical applications at the mean of the range of idle speeds you specify at stabilized temperature conditions.
(ii) For constant-speed engines, declare a warm minimum torque that is representative of in-use operation. For example, if your engine is typically connected to a machine that does not operate below a certain minimum torque, declare this torque and use it for cycle generation.
(5) Optional declared torques. (i) For variable-speed engines you may declare a maximum torque over the engine operating range. You may use the declared value for measuring warm high-idle speed as specified in this section.
(ii) For constant-speed engines you may declare a maximum test torque. You may use the declared value for cycle generation if it is within (95 to 100) % of the measured value.
(g) Mapping variable-speed engines with an electric hybrid system. Map variable-speed engines that include electric hybrid systems as described in this paragraph (g). You may ask to apply these provisions to other types of hybrid engines, consistent with good engineering judgment. However, do not use this procedure for engines used in hybrid vehicles where the hybrid system is certified as part of the vehicle rather than the engine. Follow the steps for mapping a variable-speed engine as given in paragraph (b)(5) of this section except as noted in this paragraph (g). You must generate one engine map with the hybrid system inactive as described in paragraph (g)(1) of this section, and a separate map with the hybrid system active as described in paragraph (g)(2) of this section. See the standard-setting part to determine how to use these maps. The map with the system inactive is typically used to generate steady-state duty cycles, but may also be used to generate transient cycles, such as those that do not involve engine motoring. This hybrid-inactive map is also used for generating the hybrid-active map. The hybrid-active map is typically used to generate transient duty cycles that involve engine motoring.
(1) Prepare the engine for mapping by either deactivating the hybrid system or by operating the engine as specified in paragraph (b)(4) of this section and remaining at this condition until the rechargeable energy storage system (RESS) is depleted. Once the hybrid has been disabled or the RESS is depleted, perform an engine map as specified in paragraph (b)(5) of this section. If the RESS was depleted instead of deactivated, ensure that instantaneous power from the RESS remains less than 2 % of the instantaneous measured power from the engine (or engine-hybrid system) at all engine speeds.
(2) The purpose of the mapping procedure in this paragraph (g) is to determine the maximum torque available at each speed, such as what might occur during transient operation with a fully charged RESS. Use one of the following methods to generate a hybrid-active map:
(i) Perform an engine map by using a series of continuous sweeps to cover the engine's full range of operating speeds. Prepare the engine for hybrid-active mapping by ensuring that the RESS state of charge is representative of normal operation. Perform the sweep as specified in paragraph (b)(5)(ii) of this section, but stop the sweep to charge the RESS when the power measured from the RESS drops below the expected maximum power from the RESS by more than 2 % of total system power (including engine and RESS power). Unless good engineering judgment indicates otherwise, assume that the expected maximum power from the RESS is equal to the measured RESS power at the start of the sweep segment. For example, if the 3-second rolling average of total engine-RESS power is 200 kW and the power from the RESS at the

beginning of the sweep segment is 50 kW, once the power from the RESS reaches 46 kW, stop the sweep to charge the RESS. Note that this assumption is not valid where the hybrid motor is torque-limited. Calculate total system power as a 3-second rolling average of instantaneous total system power. After each charging event, stabilize the engine for 15 seconds at the speed at which you ended the previous segment with operator demand set to maximum before continuing the sweep from that speed. Repeat the cycle of charging, mapping, and recharging until you have completed the engine map. You may shut down the system or include other operation between segments to be consistent with the intent of this paragraph (g)(2)(i). For example, for systems in which continuous charging and discharging can overheat batteries to an extent that affects performance, you may operate the engine at zero power from the RESS for enough time after the system is recharged to allow the batteries to cool. Use good engineering judgment to smooth the torque curve to eliminate discontinuities between map intervals.

(ii) Perform an engine map by using discrete speeds. Select map setpoints at intervals defined by the ranges of engine speed being mapped. From 95 % of warm idle speed to 90 % of the expected maximum test speed, select setpoints that result in a minimum of 13 equally spaced speed setpoints. From 90 % to 110 % of expected maximum test speed, select setpoints in equally spaced intervals that are nominally 2 % of expected maximum test speed. Above 110 % of expected maximum test speed, select setpoints based on the same speed intervals used for mapping from 95 % warm idle speed to 90 % maximum test speed. You may stop mapping at the highest speed above maximum power at which 50 % of maximum power occurs. We refer to the speed at 50 % power as the check point speed as described in paragraph (b)(5)(iii) of this section. Stabilize engine speed at each setpoint, targeting a torque value at 70 % of peak torque at that speed without hybrid-assist. Make sure the engine is fully warmed up and the RESS state of charge is within the normal operating range. Snap the operator demand to maximum, operate the engine there for at least 10 seconds, and record the 3-second rolling average feedback speed and torque at 1 Hz or higher. Record the peak 3-second average torque and 3-second average speed at that point. Use linear interpolation to determine intermediate speeds and torques. Follow § 1065.610(a) to calculate the maximum test speed. Verify that the measured maximum test speed falls in the range from 92 to 108 % of the estimated maximum test speed. If the measured maximum test speed does not fall in this range, rerun the map using the measured value of maximum test speed.

(h) Other mapping procedures. You may use other mapping procedures if you believe the procedures specified in this section are unsafe or unrepresentative for your engine. Any alternate techniques you use must satisfy the intent of the specified mapping procedures, which is to determine the maximum available torque at all engine speeds that occur during a duty cycle. Identify any deviations from this section's mapping procedures when you submit data to us.

§ 1065.512 Duty cycle generation.

(a) Generate duty cycles according to this section if the standard-setting part requires engine mapping to generate a duty cycle for your engine configuration. The standard-setting part generally defines applicable duty cycles in a normalized format. A normalized duty cycle generally consists of a sequence of paired values for speed and torque or for speed and power.

(b) Transform normalized values of speed, torque, and power using the following conventions:

(1) Engine speed for variable-speed engines. For variable-speed engines, normalized speed may be expressed as a percentage between warm idle speed, f_{nidle}, and maximum test speed, f_{ntest}, or speed may be expressed by referring to a defined speed by name, such as "warm idle,"

"intermediate speed," or "A," "B," or "C" speed. Section 1065.610 describes how to transform these normalized values into a sequence of reference speeds, f_{nref}. Running duty cycles with negative or small normalized speed values near warm idle speed may cause low-speed idle governors to activate and the engine torque to exceed the reference torque even though the operator demand is at a minimum. In such cases, we recommend controlling the dynamometer so it gives priority to follow the reference torque instead of the reference speed and let the engine govern the speed. Note that the cycle-validation criteria in § 1065.514 allow an engine to govern itself. This allowance permits you to test engines with enhanced-idle devices and to simulate the effects of transmissions such as automatic transmissions. For example, an enhanced-idle device might be an idle speed value that is normally commanded only under cold-start conditions to quickly warm up the engine and aftertreatment devices. In this case, negative and very low normalized speeds will generate reference speeds below this higher enhanced idle speed and we recommend controlling the dynamometer so it gives priority to follow the reference torque, controlling the operator demand so it gives priority to follow reference speed and let the engine govern the speed when the operator demand is at minimum.

(2) Engine torque for variable-speed engines. For variable-speed engines, normalized torque is expressed as a percentage of the mapped torque at the corresponding reference speed. Section 1065.610 describes how to transform normalized torques into a sequence of reference torques, T_{ref}. Section 1065.610 also describes special requirements for modifying transient duty cycles for variable-speed engines intended primarily for propulsion of a vehicle with an automatic transmission. Section 1065.610 also describes under what conditions you may command T_{ref} greater than the reference torque you calculated from a normalized duty cycle. This provision permits you to command T_{ref} values that are limited by a declared minimum torque. For any negative torque commands, command minimum operator demand and use the dynamometer to control engine speed to the reference speed, but if reference speed is so low that the idle governor activates, we recommend using the dynamometer to control torque to zero, CITT, or a declared minimum torque as appropriate. Note that you may omit power and torque points during motoring from the cycle-validation criteria in § 1065.514. Also, use the maximum mapped torque at the minimum mapped speed as the maximum torque for any reference speed at or below the minimum mapped speed.

(3) Engine torque for constant-speed engines. For constant-speed engines, normalized torque is expressed as a percentage of maximum test torque, T_{test}. Section 1065.610 describes how to transform normalized torques into a sequence of reference torques, T_{ref}. Section 1065.610 also describes under what conditions you may command T_{ref} greater than the reference torque you calculated from the normalized duty cycle. This provision permits you to command T_{ref} values that are limited by a declared minimum torque.

(4) Engine power. For all engines, normalized power is expressed as a percentage of mapped power at maximum test speed, f_{ntest}, unless otherwise specified by the standard-setting part. Section 1065.610 describes how to transform these normalized values into a sequence of reference powers, P_{ref}. Convert these reference powers to corresponding torques for operator demand and dynamometer control. Use the reference speed associated with each reference power point for this conversion. As with cycles specified with % torque, issue torque commands more frequently and linearly interpolate between these reference torque values generated from cycles with % power.

(5) Ramped-modal cycles. For ramped-modal cycles, generate reference speed and torque values at 1 Hz and use this sequence of points to run the cycle and validate it in the same manner as

with a transient cycle. During the transition between modes, linearly ramp the denormalized reference speed and torque values between modes to generate reference points at 1 Hz. Do not linearly ramp the normalized reference torque values between modes and then denormalize them. Do not linearly ramp normalized or denormalized reference power points. These cases will produce nonlinear torque ramps in the denormalized reference torques. If the speed and torque ramp runs through a point above the engine's torque curve, continue to command the reference torques and allow the operator demand to go to maximum. Note that you may omit power and either torque or speed points from the cycle-validation criteria under these conditions as specified in § 1065.514.

(c) For variable-speed engines, command reference speeds and torques sequentially to perform a duty cycle. Issue speed and torque commands at a frequency of at least 5 Hz for transient cycles and at least 1 Hz for steady-state cycles (i.e., discrete-mode and ramped-modal). Linearly interpolate between the 1 Hz reference values specified in the standard-setting part to determine more frequently issued reference speeds and torques. During an emission test, record the feedback speeds and torques at a frequency of at least 5 Hz for transient cycles and at least 1 Hz for steady-state cycles. For transient cycles, you may record the feedback speeds and torques at lower frequencies (as low as 1 Hz) if you record the average value over the time interval between recorded values. Calculate the average values based on feedback values updated at a frequency of at least 5 Hz. Use these recorded values to calculate cycle-validation statistics and total work.

(d) For constant-speed engines, operate the engine with the same production governor you used to map the engine in § 1065.510 or simulate the in-use operation of a governor the same way you simulated it to map the engine in § 1065.510. Command reference torque values sequentially to perform a duty cycle. Issue torque commands at a frequency of at least 5 Hz for transient cycles and at least 1 Hz for steady-state cycles (i.e., discrete-mode, ramped-modal). Linearly interpolate between the 1 Hz reference values specified in the standard-setting part to determine more frequently issued reference torque values. During an emission test, record the feedback speeds and torques at a frequency of at least 5 Hz for transient cycles and at least 1 Hz for steady-state cycles. For transient cycles, you may record the feedback speeds and torques at lower frequencies (as low as 1 Hz) if you record the average value over the time interval between recorded values. Calculate the average values based on feedback values updated at a frequency of at least 5 Hz. Use these recorded values to calculate cycle-validation statistics and total work.

(e) You may perform practice duty cycles with the test engine to optimize operator demand and dynamometer controls to meet the cycle-validation criteria specified in § 1065.514.

§ 1065.514 Cycle-validation criteria for operation over specified duty cycles.

Validate the execution of your duty cycle according to this section unless the standard-setting part specifies otherwise. This section describes how to determine if the engine's operation during the test adequately matched the reference duty cycle. This section applies only to speed, torque, and power from the engine's primary output shaft. Other work inputs and outputs are not subject to cycle-validation criteria. You must compare the original reference duty cycle points generated as described in § 1065.512 to the corresponding feedback values recorded during the test. You may compare reference duty cycle points recorded during the test to the corresponding feedback values recorded during the test as long as the recorded reference values match the original points generated in § 1065.512. The number of points in the validation regression are based on the number of points in the original reference duty cycle generated in § 1065.512. For example if the original cycle has 1199 reference points at 1 Hz, then the regression will have up

to 1199 pairs of reference and feedback values at the corresponding moments in the test. The feedback speed and torque signals may be filtered – either in real-time while the test is run or afterward in the analysis program. Any filtering that is used on the feedback signals used for cycle validation must also be used for calculating work. Feedback signals for control loops may use different filtering.

(a) Testing performed by EPA. Our tests must meet the specifications of paragraph (f) of this section, unless we determine that failing to meet the specifications is related to engine performance rather than to shortcomings of the dynamometer or other laboratory equipment.

(b) Testing performed by manufacturers. Emission tests that meet the specifications of paragraph (f) of this section satisfy the standard-setting part's requirements for duty cycles. You may ask to use a dynamometer or other laboratory equipment that cannot meet those specifications. We will approve your request as long as using the alternate equipment does not adversely affect your ability to show compliance with the applicable emission standards.

(c) Time-alignment. Because time lag between feedback values and the reference values may bias cycle-validation results, you may advance or delay the entire sequence of feedback engine speed and torque pairs to synchronize them with the reference sequence. If you advance or delay feedback signals for cycle validation, you must make the same adjustment for calculating work. You may use linear interpolation between successive recorded feedback signals to time shift an amount that is a fraction of the recording period.

(d) Omitting additional points. Besides engine cranking, you may omit additional points from cycle-validation statistics as described in the following table:

TABLE 1 OF § 1065.514—
PERMISSIBLE CRITERIA FOR OMITTING POINTS FROM DUTY-CYCLE REGRESSION STATISTICS

For reference duty cycles that are specified in terms of speed and torque (f_{nref}, T_{ref})		
When operator demand is at its...	you may omit...	if...
minimum	power and torque	$T_{ref} < 0$ % (motoring)
minimum	power and speed	$f_{nref} = 0$ % (idle speed) and $T_{ref} = 0$ % (idle torque) and $T_{ref} - (2\ \% \cdot T_{max\ mapped}) < T < T_{ref} + (2\ \% \cdot T_{max\ mapped})$
minimum	power and either torque or speed	$f_n > f_{nref}$ or $T > T_{ref}$ but not if $f_n > (f_{nref} \cdot 102\%)$ and $T > T_{ref} + (2\ \% \cdot T_{max\ mapped})$
maximum	power and either torque or speed	$f_n < f_{nref}$ or $T < T_{ref}$ but not if $f_n < (f_{nref} \cdot 98\ \%)$ and $T < T_{ref} - (2\ \% \cdot T_{max\ mapped})$
For reference duty cycles that are specified in terms of speed and power (f_{nref}, P_{ref})		
When operator demand is at its...	you may omit...	if...
minimum	power and torque	$P_{ref} < 0$ % (motoring)
minimum	power and speed	$f_{nref} = 0$ % (idle speed) and $P_{ref} = 0$ % (idle power) and $P_{ref} - (2\ \% \cdot P_{max\ mapped}) < P < P_{ref} + (2\ \% \cdot P_{max\ mapped})$
minimum	power and either torque or speed	$f_n > f_{nref}$ or $P > P_{ref}$ but not if $f_n > (f_{nref} \cdot 102\ \%)$ and $P > P_{ref} + (2\ \% \cdot P_{max\ mapped})$
maximum	power and either torque or speed	$f_n < f_{nref}$ or $P < P_{ref}$ but not if $f_n < (f_{nref} \cdot 98\ \%)$ and $P < P_{ref} - (2\ \% \cdot P_{max\ mapped})$

(e) Statistical parameters. Use the remaining points to calculate regression statistics described in § 1065.602. Round calculated regression statistics to the same number of significant digits as the criteria to which they are compared. Refer to Table 2 of § 1065.514 for the default criteria and refer to the standard-setting part to determine if there are other criteria for your engine. Calculate the following regression statistics:
(1) Slopes for feedback speed, a_{1fn}, feedback torque, a_{1T}, and feedback power a_{1P}.
(2) Intercepts for feedback speed, a_{0fn}, feedback torque, a_{0T}, and feedback power a_{0P}.
(3) Standard estimates of error for feedback speed, SEE_{fn}, feedback torque, SEE_T, and feedback power SEE_P.
(4) Coefficients of determination for feedback speed, r_{fn}^2, feedback torque, r_T^2, and feedback power r_P^2.
(f) Cycle-validation criteria. Unless the standard-setting part specifies otherwise, use the following criteria to validate a duty cycle:
(1) For variable-speed engines, apply all the statistical criteria in Table 2 of this section.
(2) For constant-speed engines, apply only the statistical criteria for torque in Table 2 of this section.
(3) For discrete-mode steady-state testing, apply cycle-validation criteria by treating the sampling periods from the series of test modes as a continuous sampling period, analogous to ramped-modal testing and apply statistical criteria as described in paragraph (f)(1) or (f)(2) of this section. Note that if the gaseous and particulate test intervals are different periods of time, separate validations are required for the gaseous and particulate test intervals. Table 2 follows:

TABLE 2 OF § 1065.514—DEFAULT STATISTICAL CRITERIA FOR VALIDATING DUTY CYCLES

Parameter	Speed	Torque	Power
Slope, a_1	$0.950 \le a_1 \le 1.030$	$0.830 \le a_1 \le 1.030$	$0.830 \le a_1 \le 1.030$
Absolute value of intercept, $\lvert a_0 \rvert$	≤ 10 % of warm idle	≤ 2 % of maximum mapped torque	≤ 2 % of maximum mapped power
Standard error of estimate, *SEE*	≤ 5 % of maximum test speed	≤ 10 % of maximum mapped torque	≤ 10 % of maximum mapped power
Coefficient of determination, r^2	≥ 0.970	≥ 0.850	≥ 0.910

§ 1065.516 Sample system decontamination and preconditioning.
This section describes how to manage the impact of sampling system contamination on emission measurements. Use good engineering judgment to determine if you should decontaminate and precondition your sampling system. Contamination occurs when a regulated pollutant accumulates in the sample system in a high enough concentration to cause release during emission tests. Hydrocarbons and PM are generally the only regulated pollutants that contaminate sample systems. Note that although this section focuses on avoiding excessive contamination of sampling systems, you must also use good engineering judgment to avoid loss of sample to a sampling system that is too clean. The goal of decontamination is not to perfectly clean the sampling system, but rather to achieve equilibrium between the sampling system and the exhaust so emission components are neither lost to nor entrained from the sampling system.
(a) You may perform contamination checks as follows to determine if decontamination is needed:

(1) For dilute exhaust sampling systems, measure hydrocarbon and PM emissions by sampling with the CVS dilution air turned on, without an engine connected to it.
(2) For raw analyzers and systems that collect PM samples from raw exhaust, measure hydrocarbon and PM emissions by sampling purified air or nitrogen.
(3) When calculating zero emission levels, apply all applicable corrections, including initial THC contamination and diluted (CVS) exhaust background corrections.
(4) Sampling systems are considered contaminated if either of the following conditions applies:
(i) The hydrocarbon emission level exceeds 2 % of the flow-weighted mean concentration expected at the HC standard.
(ii) The PM emission level exceeds 5 % of the level expected at the standard and exceeds 20 μg on a 47 mm PTFE membrane filter.
(b) To precondition or decontaminate sampling systems, use the following recommended procedure or select a different procedure using good engineering judgment:
(1) Start the engine and use good engineering judgment to operate it at a condition that generates high exhaust temperatures at the sample probe inlet.
(2) Operate any dilution systems at their expected flow rates. Prevent aqueous condensation in the dilution systems.
(3) Operate any PM sampling systems at their expected flow rates.
(4) Sample PM for at least 10 min using any sample media. You may change sample media at any time during this process and you may discard them without weighing them.
(5) You may purge any gaseous sampling systems that do not require decontamination during this procedure.
(6) You may conduct calibrations or verifications on any idle equipment or analyzers during this procedure.
(c) If your sampling system is still contaminated following the procedures specified in paragraph (b) of this section, you may use more aggressive procedures to decontaminate the sampling system, as long as the decontamination does not cause the sampling system to be cleaner than an equilibrium condition such that artificially low emission measurements may result.

§ 1065.518 Engine preconditioning.
(a) This section applies for engines where measured emissions are affected by prior operation, such as with a diesel engine that relies on urea-based selective catalytic reduction. Note that § 1065.520(e) allows you to run practice duty cycles before the emission test; this section recommends how to do this for the purpose of preconditioning the engine. Follow the standard-setting part if it specifies a different engine preconditioning procedure.
(b) The intent of engine preconditioning is to manage the representativeness of emissions and emission controls over the duty cycle and to reduce bias.
(c) This paragraph (c) specifies the engine preconditioning procedures for different types of duty cycles. You must identify the amount of preconditioning before starting to precondition. You must run the predefined amount of preconditioning. You may measure emissions during preconditioning. You may not abort an emission test sequence based on emissions measured during preconditioning. For confirmatory testing, you may ask us to run more preconditioning cycles than we specify in this paragraph (c); we will agree to this only if you show that additional preconditioning cycles are required to meet the intent of paragraph (b) of this section, for example, due to the effect of DPF regeneration on NH_3 storage in the SCR catalyst. Perform

preconditioning as follows, noting that the specific cycles for preconditioning are the same ones that apply for emission testing:
(1) Cold-start transient cycle. Precondition the engine by running at least one hot-start transient cycle. We will precondition your engine by running two hot-start transient cycles. Immediately after completing each preconditioning cycle, shut down the engine and complete the engine-off soak period. Immediately after completing the last preconditioning cycle, shut down the engine and begin the cold soak as described in § 1065.530(a)(1).
(2) Hot-start transient cycle. Precondition the engine by running at least one hot-start transient cycle. We will precondition your engine by running two hot-start transient cycles. Immediately after completing each preconditioning cycle, shut down the engine, then start the next cycle (including the emission test) as soon as practical. For any repeat cycles, start the next cycle within 60 seconds after completing the last preconditioning cycle (this is optional for manufacturer testing).
(3) Hot-running transient cycle. Precondition the engine by running at least one hot-running transient cycle. We will precondition your engine by running two hot-running transient cycles. Do not shut down the engine between cycles. Immediately after completing each preconditioning cycle, start the next cycle (including the emission test) as soon as practical. For any repeat cycles, start the next cycle within 60 seconds after completing the last preconditioning cycle (this is optional for manufacturer testing). See § 1065.530(a)(1)(iii) for additional instructions if the cycle begins and ends under different operating conditions.
(4) Discrete-mode cycle for steady-state testing. Precondition the engine at the same operating condition as the next test mode, unless the standard-setting part specifies otherwise. We will precondition your engine by running it for at least five minutes before sampling.
(5) Ramped-modal cycle for steady-state testing. Precondition the engine by running at least the second half of the ramped-modal cycle, based on the number of test modes. For example, for the five-mode cycle specified in 40 CFR 1039.505(b)(1), the second half of the cycle consists of modes three through five. We will precondition your engine by running one complete ramped-modal cycle. Do not shut down the engine between cycles. Immediately after completing each preconditioning cycle, start the next cycle (including the emission test) as soon as practical. For any repeat cycles, start the next cycle within 60 seconds after completing the last preconditioning cycle. See § 1065.530(a)(1)(iii) for additional instructions if the cycle begins and ends under different operating conditions.
(d) You may conduct calibrations or verifications on any idle equipment or analyzers during engine preconditioning.

§ 1065.520 Pre-test verification procedures and pre-test data collection.
(a) For tests in which you measure PM emissions, follow the procedures for PM sample preconditioning and tare weighing according to § 1065.590.
(b) Unless the standard-setting part specifies different tolerances, verify at some point before the test that ambient conditions are within the tolerances specified in this paragraph (b). For purposes of this paragraph (b), "before the test" means any time from a point just prior to engine starting (excluding engine restarts) to the point at which emission sampling begins.
(1) Ambient temperature of (20 to 30) °C. See § 1065.530(j) for circumstances under which ambient temperatures must remain within this range during the test.

(2) Atmospheric pressure of (80.000 to 103.325) kPa and within ±5 kPa of the value recorded at the time of the last engine map. You are not required to verify atmospheric pressure prior to a hot start test interval for testing that also includes a cold start.
(3) Dilution air conditions as specified in § 1065.140, except in cases where you preheat your CVS before a cold start test. We recommend verifying dilution air conditions just prior to the start of each test interval.
(c) You may test engines at any intake-air humidity, and we may test engines at any intake-air humidity.
(d) Verify that auxiliary-work inputs and outputs are configured as they were during engine mapping, as described in§ 1065.510(a).
(e) You may perform a final calibration of the speed, torque, and proportional-flow control systems, which may include performing practice duty cycles (or portions of duty cycles). This may be done in conjunction with the preconditioning in § 1065.518.
(f) Verify the amount of nonmethane hydrocarbon contamination in the exhaust and background HC sampling systems within 8 hours before the start of the first test interval of each duty-cycle sequence for laboratory tests. You may verify the contamination of a background HC sampling system by reading the last bag fill and purge using zero gas. For any NMHC measurement system that involves separately measuring CH_4 and subtracting it from a THC measurement or for any CH_4 measurement system that uses an NMC, verify the amount of THC contamination using only the THC analyzer response. There is no need to operate any separate CH_4 analyzer for this verification; however, you may measure and correct for THC contamination in the CH_4 sample path for the cases where NMHC is determined by subtracting CH_4 from THC or, where CH_4 is determined, using an NMC as configured in § 1065.365(d), (e), and (f); and using the calculations in § 1065.660(b)(2). Perform this verification as follows:
(1) Select the HC analyzer range for measuring the flow-weighted mean concentration expected at the HC standard.
(2) Zero the HC analyzer at the analyzer zero or sample port. Note that FID zero and span balance gases may be any combination of purified air or purified nitrogen that meets the specifications of § 1065.750. We recommend FID analyzer zero and span gases that contain approximately the flow-weighted mean concentration of O_2 expected during testing.
(3) Span the HC analyzer using span gas introduced at the analyzer span or sample port. Span on a carbon number basis of one (C_1). For example, if you use a C_3H_8 span gas of concentration 200 μmol/mol, span the FID to respond with a value of 600 μmol/mol.
(4) Overflow zero gas at the HC probe inlet or into a tee near the probe outlet.
(5) Measure the THC concentration in the sampling and background systems as follows:
(i) For continuous sampling, record the mean THC concentration as overflow zero gas flows.
(ii) For batch sampling, fill the sample medium (e.g., bag) and record its mean THC concentration.
(iii) For the background system, record the mean THC concentration of the last fill and purge.
(6) Record this value as the initial THC concentration, $x_{THC[THC\text{-}FID]init}$, and use it to correct measured values as described in § 1065.660.
(7) You may correct the measured initial THC concentration for drift as follows:
(i) For batch and continuous HC analyzers, after determining the initial THC concentration, flow zero gas to the analyzer zero or sample port. When the analyzer reading is stable, record the mean analyzer value.

(ii) Flow span gas to the analyzer span or sample port. When the analyzer reading is stable, record the mean analyzer value.
(iii) Use mean analyzer values from paragraphs (f)(2), (f)(3), (f)(7)(i), and (f)(7)(ii) of this section to correct the initial THC concentration recorded in paragraph (f)(6) of this section for drift, as described in § 1065.550.
(8) If any of the $_{xTHC[THC\text{-}FID]init}$ values exceed the greatest of the following values, determine the source of the contamination and take corrective action, such as purging the system during an additional preconditioning cycle or replacing contaminated portions:
(i) 2 % of the flow-weighted mean concentration expected at the HC (THC or NMHC) standard.
(ii) 2 % of the flow-weighted mean concentration of HC (THC or NMHC) measured during testing.
(iii) 2 μmol/mol.
(9) If corrective action does not resolve the deficiency, you may request to use the contaminated system as an alternate procedure under § 1065.10.

§ 1065.525 Engine starting, restarting, and shutdown.
(a) For test intervals that require emission sampling during engine starting, start the engine using one of the following methods:
(1) Start the engine as recommended in the owners manual using a production starter motor or air-start system and either an adequately charged battery, a suitable power supply, or a suitable compressed air source.
(2) Use the dynamometer to start the engine. To do this, motor the engine within ±25 % of its typical in-use cranking speed. Stop cranking within 1 second of starting the engine.
(3) In the case of hybrid engines, activate the system such that the engine will start when its control algorithms determine that the engine should provide power instead of or in addition to power from the RESS. Unless we specify otherwise, engine starting throughout this part generally refers to this step of activating the system on hybrid engines, whether or not that causes the engine to start running.
(b) If the engine does not start after 15 seconds of cranking, stop cranking and determine why the engine failed to start, unless the owners manual or the service-repair manual describes the longer cranking time as normal.
(c) Respond to engine stalling with the following steps:
(1) If the engine stalls during warm-up before emission sampling begins, restart the engine and continue warm-up.
(2) If the engine stalls during preconditioning before emission sampling begins, restart the engine and restart the preconditioning sequence.
(3) Void the entire test if the engine stalls at any time after emission sampling begins, except as described in § 1065.526. If you do not void the entire test, you must void the individual test mode or test interval in which the engine stalls.
(d) Shut down the engine according to the manufacturer's specifications.

§ 1065.526 Repeating of void modes or test intervals.
(a) Test modes and test intervals can be voided because of instrument malfunction, engine stalling, emissions exceeding instrument ranges, and other unexpected deviations from the specified procedures. This section specifies circumstances for which a test mode or test interval can be repeated without repeating the entire test.

(b) This section is intended to result in replicate test modes and test intervals that are identical to what would have occurred if the cause of the voiding had not occurred. It does not allow you to repeat test modes or test intervals in any circumstances that would be inconsistent with good engineering judgment. For example, the procedures specified here for repeating a mode or interval may not apply for certain engines that include hybrid energy storage features or emission controls that involve physical or chemical storage of pollutants. This section applies for circumstances in which emission concentrations exceed the analyzer range only if it is due to operator error or analyzer malfunction. It does not apply for circumstances in which the emission concentrations exceed the range because they were higher than expected.
(c) If one of the modes of a discrete-mode duty cycle is voided while running the duty cycle as provided in this section, you may void the results for that individual mode and continue the duty cycle as follows:
(1) If the engine has stalled or been shut down, restart the engine.
(2) Use good engineering judgment to restart the duty cycle using the appropriate steps in § 1065.530(b).
(3) Stabilize the engine by operating it at the mode at which the duty cycle was interrupted and continue with the duty cycle as specified in the standard-setting part.
(d) If an individual mode of a discrete-mode duty cycle sequence is voided after running the full duty cycle, you may void results for that mode and repeat testing for that mode as follows:
(1) Use good engineering judgment to restart the test sequence using the appropriate steps in § 1065.530(b).
(2) Stabilize the engine by operating it at that mode.
(3) Sample emissions over an appropriate test interval.
(4) If you sampled gaseous and PM emissions over separate test intervals for a voided mode, you must void both test intervals and repeat sampling of both gaseous and PM emissions for that mode.
(e) If a transient or ramped-modal cycle test interval is voided as provided in this section, you may repeat the test interval as follows:
(1) Use good engineering judgment to restart (as applicable) and precondition the engine to the same condition as would apply for normal testing. This may require you to complete the voided test interval. For example, you may generally repeat a hot-start test of a heavy-duty highway engine after completing the voided hot-start test and allowing the engine to soak for 20 minutes.
(2) Complete the remainder of the test according to the provisions in this subpart.
(f) Keep records from the voided test mode or test interval in the same manner as required for unvoided tests.

§ 1065.530 Emission test sequence.
(a) Time the start of testing as follows:
(1) Perform one of the following if you precondition the engine as described in § 1065.518:
(i) For cold-start duty cycles, shut down the engine. Unless the standard-setting part specifies that you may only perform a natural engine cooldown, you may perform a forced engine cooldown. Use good engineering judgment to set up systems to send cooling air across the engine, to send cool oil through the engine lubrication system, to remove heat from coolant through the engine cooling system, and to remove heat from any exhaust aftertreatment systems. In the case of a forced aftertreatment cooldown, good engineering judgment would indicate that you not start flowing cooling air until the aftertreatment system has cooled below its catalytic

activation temperature. For platinum-group metal catalysts, this temperature is about 200 °C. Once the aftertreatment system has naturally cooled below its catalytic activation temperature, good engineering judgment would indicate that you use clean air with a temperature of at least 15 °C, and direct the air through the aftertreatment system in the normal direction of exhaust flow. Do not use any cooling procedure that results in unrepresentative emissions (see § 1065.10(c)(1)). You may start a cold-start duty cycle when the temperatures of an engine's lubricant, coolant, and aftertreatment systems are all between (20 and 30) °C.
(ii) For hot-start emission measurements, shut down the engine immediately after completing the last preconditioning cycle. For any repeat cycles, start the hot-start transient emission test within 60 seconds after completing the last preconditioning cycle (this is optional for manufacturer testing).
(iii) For testing that involves hot-stabilized emission measurements, such as any steady-state testing with a ramped-modal cycle, start the hot-stabilized emission test within 60 seconds after completing the last preconditioning cycle (the time between cycles is optional for manufacturer testing). If the hot-stabilized cycle begins and ends with different operating conditions, add a linear transition period of 20 seconds between hot-stabilized cycles where you linearly ramp the (denormalized) reference speed and torque values over the transition period. See § 1065.501(c)(2)(i) for discrete-mode cycles.
(2) If you do not precondition the engine as described in § 1065.518, perform one of the following:
(i) For cold-start duty cycles, prepare the engine according to paragraph (a)(1)(i) of this section.
(ii) For hot-start duty cycles, first operate the engine at any speed above peak-torque speed and at (65 to 85) % of maximum mapped power until either the engine coolant, block, or head absolute temperature is within ±2 % of its mean value for at least 2 min or until the engine thermostat controls engine temperature. Shut down the engine. Start the duty cycle within 20 min of engine shutdown.
(iii) For testing that involves hot-stabilized emission measurements, bring the engine either to warm idle or the first operating point of the duty cycle. Start the test within 10 min of achieving temperature stability. Determine temperature stability either as the point at which the engine coolant, block, or head absolute temperature is within ±2 % of its mean value for at least 2 min, or as the point at which the engine thermostat controls engine temperature.
(b) Take the following steps before emission sampling begins:
(1) For batch sampling, connect clean storage media, such as evacuated bags or tare-weighed filters.
(2) Start all measurement instruments according to the instrument manufacturer's instructions and using good engineering judgment.
(3) Start dilution systems, sample pumps, cooling fans, and the data-collection system.
(4) Pre-heat or pre-cool heat exchangers in the sampling system to within their operating temperature tolerances for a test.
(5) Allow heated or cooled components such as sample lines, filters, chillers, and pumps to stabilize at their operating temperatures.
(6) Verify that there are no significant vacuum-side leaks according to § 1065.345.
(7) Adjust the sample flow rates to desired levels, using bypass flow, if desired.
(8) Zero or re-zero any electronic integrating devices, before the start of any test interval.
(9) Select gas analyzer ranges. You may automatically or manually switch gas analyzer ranges during a test only if switching is performed by changing the span over which the digital

resolution of the instrument is applied. During a test you may not switch the gains of an analyzer's analog operational amplifier(s).
(10) Zero and span all continuous analyzers using NIST-traceable gases that meet the specifications of § 1065.750. Span FID analyzers on a carbon number basis of one (1), C_1. For example, if you use a C_3H_8 span gas of concentration 200 μmol/mol, span the FID to respond with a value of 600 μmol/mol. Span FID analyzers consistent with the determination of their respective response factors, *RF*, and penetration fractions, *PF*, according to § 1065.365.
(11) We recommend that you verify gas analyzer responses after zeroing and spanning by sampling a calibration gas that has a concentration near one-half of the span gas concentration. Based on the results and good engineering judgment, you may decide whether or not to re-zero, re-span, or re-calibrate a gas analyzer before starting a test.
(12) Drain any accumulated condensate from the intake air system before starting a duty cycle, as described in § 1065.125(e)(1). If engine and aftertreatment preconditioning cycles are run before the duty cycle, treat the preconditioning cycles and any associated soak period as part of the duty cycle for the purpose of opening drains and draining condensate. Note that you must close any intake air condensate drains that are not representative of those normally open during in-use operation.
(c) Start and run each test interval as described in this paragraph (c). The procedure varies depending on whether the test interval is part of a discrete-mode cycle, and whether the test interval includes engine starting. Note that the standard-setting part may apply different requirements for running test intervals. For example, 40 CFR part 1033 specifies a different way to perform discrete-mode testing.
(1) For steady-state discrete-mode duty cycles, start the duty cycle with the engine warmed-up and running as described in § 1065.501(c)(2)(i). Run each mode in the sequence specified in the standard-setting part. This will require controlling engine speed, engine load, or other operator demand settings as specified in the standard-setting part. Simultaneously start any electronic integrating devices, continuous data recording, and batch sampling. We recommend that you stabilize the engine for at least 5 minutes for each mode. Once sampling begins, sample continuously for at least 1 minute. Note that longer sample times may be needed for accurately measuring very low emission levels.
(2) For transient and steady-state ramped-modal duty cycles that do not include engine starting, start the test interval with the engine running as soon as practical after completing engine preconditioning. Simultaneously start any electronic integrating devices, continuous data recording, batch sampling, and execution of the duty cycle.
(3) If engine starting is part of the test interval, simultaneously start any electronic integrating devices, continuous data recording, and batch sampling before attempting to start the engine. Initiate the sequence of points in the duty cycle when the engine starts.
(4) For batch sampling systems, you may advance or delay the start and end of sampling at the beginning and end of the test interval to improve the accuracy of the batch sample, consistent with good engineering judgment.
(d) At the end of each test interval, continue to operate all sampling and dilution systems to allow the sampling system's response time to elapse. Then stop all sampling and recording, including the recording of background samples. Finally, stop any integrating devices and indicate the end of the duty cycle in the recorded data.
(e) Shut down the engine if you have completed testing or if it is part of the duty cycle.

(f) If testing involves another duty cycle after a soak period with the engine off, start a timer when the engine shuts down, and repeat the steps in paragraphs (b) through (e) of this section as needed.
(g) Take the following steps after emission sampling is complete:
(1) For any proportional batch sample, such as a bag sample or PM sample, verify that proportional sampling was maintained according to § 1065.545. Void any samples that did not maintain proportional sampling according to § 1065.545.
(2) Place any used PM samples into covered or sealed containers and return them to the PM-stabilization environment. Follow the PM sample post-conditioning and total weighing procedures in § 1065.595.
(3) As soon as practical after the duty cycle is complete, or during the soak period if practical, perform the following:
(i) Zero and span all batch gas analyzers no later than 30 minutes after the duty cycle is complete, or during the soak period if practical.
(ii) Analyze any conventional gaseous batch samples no later than 30 minutes after the duty cycle is complete, or during the soak period if practical.
(iii) Analyze background samples no later than 60 minutes after the duty cycle is complete.
(iv) Analyze non-conventional gaseous batch samples, such as ethanol (NMHCE) as soon as practical using good engineering judgment.
(4) After quantifying exhaust gases, verify drift as follows:
(i) For batch and continuous gas analyzers, record the mean analyzer value after stabilizing a zero gas to the analyzer. Stabilization may include time to purge the analyzer of any sample gas, plus any additional time to account for analyzer response.
(ii) Record the mean analyzer value after stabilizing the span gas to the analyzer. Stabilization may include time to purge the analyzer of any sample gas, plus any additional time to account for analyzer response.
(iii) Use these data to validate and correct for drift as described in § 1065.550.
(h) Unless the standard-setting part specifies otherwise, determine whether or not the test meets the cycle-validation criteria in § 1065.514.
(1) If the criteria void the test, you may retest using the same denormalized duty cycle, or you may re-map the engine, denormalize the reference duty cycle based on the new map and retest the engine using the new denormalized duty cycle.
(2) If the criteria void the test for a constant-speed engine only during commands of maximum test torque, you may do the following:
(i) Determine the first and last feedback speeds at which maximum test torque was commanded.
(ii) If the last speed is greater than or equal to 90 % of the first speed, the test is void. You may retest using the same denormalized duty cycle, or you may re-map the engine, denormalize the reference duty cycle based on the new map and retest the engine using the new denormalized duty cycle.
(iii) If the last speed is less than 90 % of the first speed, reduce maximum test torque by 5 %, and proceed as follows:
(A) Denormalize the entire duty cycle based on the reduced maximum test torque according to § 1065.512.
(B) Retest the engine using the denormalized test cycle that is based on the reduced maximum test torque.

(C) If your engine still fails the cycle criteria, reduce the maximum test torque by another 5 % of the original maximum test torque.
(D) If your engine fails after repeating this procedure four times, such that your engine still fails after you have reduced the maximum test torque by 20 % of the original maximum test torque, notify us and we will consider specifying a more appropriate duty cycle for your engine under the provisions of § 1065.10(c).
(i) [Reserved]
(j) Measure and record ambient temperature, pressure, and humidity, as appropriate. For testing the following engines, you must record ambient temperature continuously to verify that it remains within the pre-test temperature range as specified in § 1065.520(b):
(1) Air-cooled engines.
(2) Engines equipped with auxiliary emission control devices that sense and respond to ambient temperature.
(3) Any other engine for which good engineering judgment indicates this is necessary to remain consistent with § 1065.10(c)(1).

§ 1065.545 Verification of proportional flow control for batch sampling.
For any proportional batch sample such as a bag or PM filter, demonstrate that proportional sampling was maintained using one of the following, noting that you may omit up to 5 % of the total number of data points as outliers:
(a) For any pair of flow rates, use recorded sample and total flow rates, where total flow rate means the raw exhaust flow rate for raw exhaust sampling and the dilute exhaust flow rate for CVS sampling, or their 1 Hz means with the statistical calculations in § 1065.602. Determine the standard error of the estimate, *SEE*, of the sample flow rate versus the total flow rate. For each test interval, demonstrate that *SEE* was less than or equal to 3.5 % of the mean sample flow rate.
(b) For any pair of flow rates, use recorded sample and total flow rates, where total flow rate means the raw exhaust flow rate for raw exhaust sampling and the dilute exhaust flow rate for CVS sampling, or their 1 Hz means to demonstrate that each flow rate was constant within ±2.5 % of its respective mean or target flow rate. You may use the following options instead of recording the respective flow rate of each type of meter:
(1) Critical-flow venturi option. For critical-flow venturis, you may use recorded venturi-inlet conditions or their 1 Hz means. Demonstrate that the flow density at the venturi inlet was constant within ±2.5 % of the mean or target density over each test interval. For a CVS critical-flow venturi, you may demonstrate this by showing that the absolute temperature at the venturi inlet was constant within ±4 % of the mean or target absolute temperature over each test interval.
(2) Positive-displacement pump option. You may use recorded pump-inlet conditions or their 1 Hz means. Demonstrate that the flow density at the pump inlet was constant within ±2.5 % of the mean or target density over each test interval. For a CVS pump, you may demonstrate this by showing that the absolute temperature at the pump inlet was constant within ±2 % of the mean or target absolute temperature over each test interval.
(c) Using good engineering judgment, demonstrate with an engineering analysis that the proportional-flow control system inherently ensures proportional sampling under all circumstances expected during testing. For example, you might use CFVs for both sample flow and total dilute exhaust (CVS) flow and demonstrate that they always have the same inlet pressures and temperatures and that they always operate under critical-flow conditions.

§ 1065.546 Verification of minimum dilution ratio for PM batch sampling.
Use continuous flows and/or tracer gas concentrations for transient and ramped-modal cycles to verify the minimum dilution ratios for PM batch sampling as specified in § 1065.140(e)(2) over the test interval. You may use mode-average values instead of continuous measurements for discrete mode steady-state duty cycles. Determine the minimum primary and minimum overall dilution ratios using one of the following methods (you may use a different method for each stage of dilution):
(a) Determine minimum dilution ratio based on molar flow data. This involves determination of at least two of the following three quantities: raw exhaust flow (or previously diluted flow), dilution air flow, and dilute exhaust flow. You may determine the raw exhaust flow rate based on the measured intake air or fuel flow rate and the raw exhaust chemical balance terms as given in § 1065.655(e). You may determine the raw exhaust flow rate based on the measured intake air and dilute exhaust molar flow rates and the dilute exhaust chemical balance terms as given in § 1065.655(f). You may alternatively estimate the molar raw exhaust flow rate based on intake air, fuel rate measurements, and fuel properties, consistent with good engineering judgment.
(b) Determine minimum dilution ratio based on tracer gas (e.g., CO_2) concentrations in the raw (or previously diluted) and dilute exhaust corrected for any removed water.
(c) Use good engineering judgment to develop your own method of determining dilution ratios.

§ 1065.550 Gas analyzer range verification and drift verification.
(a) Range verification. If an analyzer operated above 100 % of its range at any time during the test, perform the following steps:
(1) For batch sampling, re-analyze the sample using the lowest analyzer range that results in a maximum instrument response below 100 %. Report the result from the lowest range from which the analyzer operates below 100 % of its range.
(2) For continuous sampling, repeat the entire test using the next higher analyzer range. If the analyzer again operates above 100 % of its range, repeat the test using the next higher range. Continue to repeat the test until the analyzer always operates at less than 100 % of its range.
(b) Drift verification. Gas analyzer drift verification is required for all gaseous exhaust constituents for which an emission standard applies. It is also required for CO_2 even if there is no CO_2 emission standard. It is not required for other gaseous exhaust constituents for which only a reporting requirement applies (such as CH_4 and N_2O).
(1) Verify drift using one of the following methods:
(i) For regulated exhaust constituents determined from the mass of a single component, perform drift verification based on the regulated constituent. For example, when NO_x mass is determined with a dry sample measured with a CLD and the removed water is corrected based on measured CO_2, CO, THC, and NO_x concentrations, you must verify the calculated NO_x value.
(ii) For regulated exhaust constituents determined from the masses of multiple subcomponents, perform the drift verification based on either the regulated constituent or all the mass subcomponents. For example, when NO_x is measured with separate NO and NO_2 analyzers, you must verify either the NO_x value or both the NO and NO_2 values.
(iii) For regulated exhaust constituents determined from the concentrations of multiple gaseous emission subcomponents prior to performing mass calculations, perform drift verification on the regulated constituent. You may not verify the concentration subcomponents (e.g., THC and CH_4

for NMHC) separately. For example, for NMHC measurements, perform drift verification on NMHC; do not verify THC and CH_4 separately.
(2) Drift verification requires two sets of emission calculations. For each set of calculations, include all the constituents in the drift verification. Calculate one set using the data before drift correction and calculate the other set after correcting all the data for drift according to § 1065.672. Note that for purposes of drift verification, you must leave unaltered any negative emission results over a given test interval (i.e., do not set them to zero). These unaltered results are used when verifying either test interval results or composite brake-specific emissions over the entire duty cycle for drift. For each constituent to be verified, both sets of calculations must include the following:
(i) Calculated mass (or mass rate) emission values over each test interval.
(ii) If you are verifying each test interval based on brake-specific values, calculate brake-specific emission values over each test interval.
(iii) If you are verifying over the entire duty cycle, calculate composite brake-specific emission values.
(3) The duty cycle is verified for drift if you satisfy the following criteria:
(i) For each regulated gaseous exhaust constituent, you must satisfy one of the following:
(A) For each test interval of the duty cycle, the difference between the uncorrected and the corrected brake-specific emission values of the regulated constituent must be within ±4 % of the uncorrected value or the applicable emissions standard, whichever is greater. Alternatively, the difference between the uncorrected and the corrected emission mass (or mass rate) values of the regulated constituent must be within ±4 % of the uncorrected value or the composite work (or power) multiplied by the applicable emissions standard, whichever is greater. For purposes of verifying each test interval, you may use either the reference or actual composite work (or power).
(B) For each test interval of the duty cycle and for each mass subcomponent of the regulated constituent, the difference between the uncorrected and the corrected brake-specific emission values must be within ±4 % of the uncorrected value. Alternatively, the difference between the uncorrected and the corrected emissions mass (or mass rate) values must be within ±4 % of the uncorrected value.
(C) For the entire duty cycle, the difference between the uncorrected and the corrected composite brake-specific emission values of the regulated constituent must be within ±4 % of the uncorrected value or applicable emission standard, whichever is greater.
(D) For the entire duty cycle and for each subcomponent of the regulated constituent, the difference between the uncorrected and the corrected composite brake-specific emission values must be within ±4 % of the uncorrected value.
(ii) Where no emission standard applies for CO_2, you must satisfy one of the following:
(A) For each test interval of the duty cycle, the difference between the uncorrected and the corrected brake-specific CO_2 values must be within ±4 % of the uncorrected value; or the difference between the uncorrected and the corrected CO_2 mass (or mass rate) values must be within ±4 % of the uncorrected value.
(B) For the entire duty cycle, the difference between the uncorrected and the corrected composite brake-specific CO_2 values must be within ±4 % of the uncorrected value.
(4) If the test is not verified for drift as described in paragraph (b)(1) of this section, you may consider the test results for the duty cycle to be valid only if, using good engineering judgment, the observed drift does not affect your ability to demonstrate compliance with the applicable

emission standards. For example, if the drift-corrected value is less than the standard by at least two times the absolute difference between the uncorrected and corrected values, you may consider the data to be verified for demonstrating compliance with the applicable standard.

§ 1065.590 PM sampling media (e.g., filters) preconditioning and tare weighing.
Before an emission test, take the following steps to prepare PM sampling media (e.g., filters) and equipment for PM measurements:
(a) Make sure the balance and PM-stabilization environments meet the periodic verifications in § 1065.390.
(b) Visually inspect unused sample media (e.g., filters) for defects and discard defective media.
(c) To handle PM sampling media (e.g., filters), use electrically grounded tweezers or a grounding strap, as described in § 1065.190.
(d) Place unused sample media (e.g., filters) in one or more containers that are open to the PM-stabilization environment. If you are using filters, you may place them in the bottom half of a filter cassette.
(e) Stabilize sample media (e.g., filters) in the PM-stabilization environment. Consider an unused sample medium stabilized as long as it has been in the PM-stabilization environment for a minimum of 30 min, during which the PM-stabilization environment has been within the specifications of § 1065.190.
(f) Weigh the sample media (e.g., filters) automatically or manually, as follows:
(1) For automatic weighing, follow the automation system manufacturer's instructions to prepare samples for weighing. This may include placing the samples in a special container.
(2) For manual weighing, use good engineering judgment to determine if substitution weighing is necessary to show that an engine meets the applicable standard. You may follow the substitution weighing procedure in paragraph (j) of this section, or you may develop your own procedure.
(g) Correct the measured mass of each sample medium (e.g., filter) for buoyancy as described in § 1065.690. These buoyancy-corrected values are subsequently subtracted from the post-test mass of the corresponding sample media (e.g., filters) and collected PM to determine the mass of PM emitted during the test.
(h) You may repeat measurements to determine the mean mass of each sample medium (e.g., filter). Use good engineering judgment to exclude outliers from the calculation of mean mass values.
(i) If you use filters as sample media, load unused filters that have been tare-weighed into clean filter cassettes and place the loaded cassettes in a clean, covered or sealed container before removing them from the stabilization environment for transport to the test site for sampling. We recommend that you keep filter cassettes clean by periodically washing or wiping them with a compatible solvent applied using a lint-free cloth. Depending upon your cassette material, ethanol (C_2H_5OH) might be an acceptable solvent. Your cleaning frequency will depend on your engine's level of PM and HC emissions.
(j) Substitution weighing involves measurement of a reference weight before and after each weighing of PM sampling media (e.g., filters). While substitution weighing requires more measurements, it corrects for a balance's zero-drift and it relies on balance linearity only over a small range. This is most advantageous when quantifying net PM masses that are less than 0.1 % of the sample medium's mass. However, it may not be advantageous when net PM masses exceed 1 % of the sample medium's mass. If you utilize substitution weighing, it must be used for both pre-test and post-test weighing. The same substitution weight must be used for both

pre-test and post-test weighing. Correct the mass of the substitution weight for buoyancy if the density of the substitution weight is less than 2.0 g/cm^3. The following steps are an example of substitution weighing:
(1) Use electrically grounded tweezers or a grounding strap, as described in § 1065.190.
(2) Use a static neutralizer as described in § 1065.190 to minimize static electric charge on any object before it is placed on the balance pan.
(3) Select a substitution weight that meets the requirements for calibration weights found in § 1065.790. The substitution weight must also have the same density as the weight you use to span the microbalance, and be similar in mass to an unused sample medium (e.g., filter). A 47 mm PTFE membrane filter will typically have a mass in the range of 80 to 100 mg.
(4) Record the stable balance reading, then remove the calibration weight.
(5) Weigh an unused sample medium (e.g., a new filter), record the stable balance reading and record the balance environment's dewpoint, ambient temperature, and atmospheric pressure.
(6) Reweigh the calibration weight and record the stable balance reading.
(7) Calculate the arithmetic mean of the two calibration-weight readings that you recorded immediately before and after weighing the unused sample. Subtract that mean value from the unused sample reading, then add the true mass of the calibration weight as stated on the calibration-weight certificate. Record this result. This is the unused sample's tare weight without correcting for buoyancy.
(8) Repeat these substitution-weighing steps for the remainder of your unused sample media.
(9) Once weighing is completed, follow the instructions given in paragraphs (g) through (i) of this section.

§ 1065.595 PM sample post-conditioning and total weighing.
After testing is complete, return the sample media (e.g., filters) to the weighing and PM-stabilization environments.
(a) Make sure the weighing and PM-stabilization environments meet the ambient condition specifications in § 1065.190(e)(1). If those specifications are not met, leave the test sample media (e.g., filters) covered until proper conditions have been met.
(b) In the PM-stabilization environment, remove PM samples from sealed containers. If you use filters, you may remove them from their cassettes before or after stabilization. We recommend always removing the top portion of the cassette before stabilization. When you remove a filter from a cassette, separate the top half of the cassette from the bottom half using a cassette separator designed for this purpose.
(c) To handle PM samples, use electrically grounded tweezers or a grounding strap, as described in § 1065.190.
(d) Visually inspect the sampling media (e.g., filters) and collected particulate. If either the sample media (e.g. filters) or particulate sample appear to have been compromised, or the particulate matter contacts any surface other than the filter, the sample may not be used to determine particulate emissions. In the case of contact with another surface, clean the affected surface before continuing.
(e) To stabilize PM samples, place them in one or more containers that are open to the PM-stabilization environment, as described in § 1065.190. If you expect that a sample medium's (e.g., filter's) total surface concentration of PM will be less than 400 μg, assuming a 38 mm diameter filter stain area, expose the filter to a PM-stabilization environment meeting the specifications of § 1065.190 for at least 30 minutes before weighing. If you expect a higher PM

concentration or do not know what PM concentration to expect, expose the filter to the stabilization environment for at least 60 minutes before weighing. Note that 400 μg on sample media (e.g., filters) is an approximate net mass of 0.07 g/kW·hr for a hot-start test with compression-ignition engines tested according to 40 CFR part 86, subpart N, or 50 mg/mile for light-duty vehicles tested according to 40 CFR part 86, subpart B.

(f) Repeat the procedures in § 1065.590(f) through (i) to determine post-test mass of the sample media (e.g., filters).

(g) Subtract each buoyancy-corrected tare mass of the sample medium (e.g., filter) from its respective buoyancy-corrected mass. The result is the net PM mass, m_{PM}. Use m_{PM} in emission calculations in § 1065.650.

Subpart G—CALCULATIONS AND DATA REQUIREMENTS

§ 1065.601 Overview.

(a) This subpart describes how to–

(1) Use the signals recorded before, during, and after an emission test to calculate brake-specific emissions of each regulated pollutant.

(2) Perform calculations for calibrations and performance checks.

(3) Determine statistical values.

(b) You may use data from multiple systems to calculate test results for a single emission test, consistent with good engineering judgment. You may also make multiple measurements from a single batch sample, such as multiple weighings of a PM filter or multiple readings from a bag sample. Although you may use an average of multiple measurements from a single test, you may not use test results from multiple emission tests to report emissions.

(1) We allow weighted means where appropriate.

(2) You may discard statistical outliers, but you must report all results.

(3) For emission measurements related to durability testing, we may allow you to exclude certain test points other than statistical outliers relative to compliance with emission standards, consistent with good engineering judgment and normal measurement variability; however, you must include these results when calculating the deterioration factor. This would allow you to use durability data from an engine that has an intermediate test result above the standard that cannot be discarded as a statistical outlier, as long as good engineering judgment indicates that the test result does not represent the engine's actual emission level. Note that good engineering judgment would preclude you from excluding endpoints. Also, if normal measurement variability causes emission results below zero, include the negative result in calculating the deterioration factor to avoid an upward bias. These provisions related to durability testing are intended to address very stringent standards where measurement variability is large relative to the emission standard.

(c) You may use any of the following calculations instead of the calculations specified in this subpart G:

(1) Mass-based emission calculations prescribed by the International Organization for Standardization (ISO), according to ISO 8178, except the following:

(i) ISO 8178-1 Section 14.4, NO_x Correction for Humidity and Temperature. See § 1065.670 for approved methods for humidity corrections.

(ii) ISO 8178-1 Section 15.1, Particulate Correction Factor for Humidity.

(2) Other calculations that you show are equivalent to within ±0.1 % of the brake-specific emission results determined using the calculations specified in this subpart G.

§ 1065.602 Statistics.

(a) Overview. This section contains equations and example calculations for statistics that are specified in this part. In this section we use the letter "y" to denote a generic measured quantity, the superscript over-bar "$^{-}$" to denote an arithmetic mean, and the subscript "$_{ref}$" to denote the reference quantity being measured.

(b) Arithmetic mean. Calculate an arithmetic mean, $\overline{y}$, as follows:

$$\overline{y} = \frac{\sum_{i=1}^{N} y_i}{N}$$

Eq. 1065.602-1

Example:

$N = 3$

$y_1 = 10.60$

$y_2 = 11.91$

$y_N = y_3 = 11.09$

$$\overline{y} = \frac{10.60 + 11.91 + 11.09}{3}$$

$\overline{y} = 11.20$

(c) Standard deviation. Calculate the standard deviation for a non-biased (e.g., N–1) sample, σ , as follows:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{N}(y_i - \overline{y})^2}{(N-1)}}$$

Eq. 1065.602-2

Example:

$N = 3$

$y_1 = 10.60$

$y_2 = 11.91$

$y_N = y_3 = 11.09$

$\overline{y} = 11.20$

$$\sigma_y = \sqrt{\frac{(10.60 - 11.2)^2 + (11.91 - 11.2)^2 + (11.09 - 11.2)^2}{2}}$$

$\sigma_y = 0.6619$

(d) Root mean square. Calculate a root mean square, rms_y, as follows:

$$rms_y = \sqrt{\frac{1}{N}\sum_{i=1}^{N} y_i^2}$$

Eq. 1065.602-3

Example:

$N = 3$

$y_1 = 10.60$

$y_2 = 11.91$

$y_N = y_3 = 11.09$

$$rms_y = \sqrt{\frac{10.60^2 + 11.91^2 + 11.09^2}{3}}$$

$rms_y = 11.21$

(e) Accuracy. Determine accuracy as described in this paragraph (e).. Make multiple measurements of a standard quantity to create a set of observed values, y_i, and compare each observed value to the known value of the standard quantity. The standard quantity may have a single known value, such as a gas standard, or a set of known values of negligible range, such as a known applied pressure produced by a calibration device during repeated applications. The

known value of the standard quantity is represented by y_{ref_i}. If you use a standard quantity with a single value, y_{ref_i} would be constant. Calculate an accuracy value as follows:

$$accuracy = \left| \frac{1}{N} \sum_{i=1}^{N} \left(y_i - y_{ref_i} \right) \right|$$

Eq. 1065.602-4

Example:

$y_{ref} = 1800.0$
$N = 3$
$y_1 = 1806.4$
$y_2 = 1803.1$
$y_3 = 1798.9$

$$accuracy = \left| \frac{1}{3} \left((1806.4 - 1800.0) + (1803.1 - 1800.0) + (1798.9 - 1800.0) \right) \right|$$

$$accuracy = \left| \frac{1}{3} \left((6.4) + (3.1) + (-1.1) \right) \right|$$

$accuracy = 2.8$

(f) t-test. Determine if your data passes a *t*-test by using the following equations and tables:

(1) For an unpaired *t*-test, calculate the *t* statistic and its number of degrees of freedom, v, as follows:

$$t = \frac{\left| \overline{y}_{ref} - \overline{y} \right|}{\sqrt{\frac{\sigma_{ref}^2}{N_{ref}} + \frac{\sigma_y^2}{N}}}$$

Eq. 1065.602-5

$$v = \frac{\left(\frac{\sigma_{ref}^2}{N_{ref}} + \frac{\sigma_y^2}{N} \right)^2}{\frac{\left(\frac{\sigma_{ref}^2}{N_{ref}} \right)^2}{N_{ref} - 1} + \frac{\left(\frac{\sigma_y^2}{N} \right)^2}{N - 1}}$$

Eq. 1065.602-6

Example:

$\overline{y}_{ref} = 1205.3$

$\overline{y} = 1123.8$

$\sigma_{ref} = 9.399$
$\sigma_y = 10.583$
$N_{ref} = 11$
$N = 7$

$$t = \frac{|1205.3 - 1123.8|}{\sqrt{\frac{9.399^2}{11} + \frac{10.583^2}{7}}}$$

$t = 16.63$

$\sigma_{ref} = 9.399$
$\sigma_y = 10.583$
$N_{ref} = 11$
$N = 7$

$$v = \frac{\left(\frac{9.399^2}{11} + \frac{10.583^2}{7}\right)^2}{\frac{\left(\frac{9.399^2}{11}\right)^2}{11-1} + \frac{\left(\frac{10.583^2}{7}\right)^2}{7-1}}$$

$v = 11.76$

(2) For a paired t-test, calculate the t statistic and its number of degrees of freedom, $\underline{v}$, as follows, noting that the ε_i are the errors (e.g., differences) between each pair of y_{refi} and y_i:

$$t = \frac{|\bar{\varepsilon}| \cdot \sqrt{N}}{\sigma_\varepsilon}$$

Eq. 1065.602-7

Example:
$\bar{\varepsilon} = -0.12580$
$N = 16$
$\sigma_\varepsilon = 0.04837$

$$t = \frac{|-0.12580| \cdot \sqrt{16}}{0.04837}$$

$t = 10.403$

$v = N - 1$
Example:
$N = 16$
$v = 16 - 1$
$v = 15$

(3) Use Table 1 of this section to compare t to the t_{crit} values tabulated versus the number of degrees of freedom. If t is less than t_{crit}, then t passes the t-test. The Microsoft Excel software has a TINV function that returns results equivalent results and may be used in place of Table 1, which follows:

TABLE 1 OF § 1065.602–
CRITICAL t VALUES VERSUS NUMBER OF DEGREES OF FREEDOM, ν[1]

ν	Confidence	
	90%	95%
1	6.314	12.706
2	2.920	4.303
3	2.353	3.182
4	2.132	2.776
5	2.015	2.571
6	1.943	2.447
7	1.895	2.365
8	1.860	2.306
9	1.833	2.262
10	1.812	2.228
11	1.796	2.201
12	1.782	2.179
13	1.771	2.160
14	1.761	2.145
15	1.753	2.131
16	1.746	2.120
18	1.734	2.101
20	1.725	2.086
22	1.717	2.074
24	1.711	2.064
26	1.706	2.056
28	1.701	2.048
30	1.697	2.042
35	1.690	2.030
40	1.684	2.021
50	1.676	2.009
70	1.667	1.994
100	1.660	1.984
1000+	1.645	1.960

[1] Use linear interpolation to establish values not shown here.

(g) F-test. Calculate the F statistic as follows:

$$F_y = \frac{\sigma_y^2}{\sigma_{ref}^2}$$

Eq. 1065.602-8

Example:

$$\sigma_{\mathrm{y}} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{N}\left(y_{\mathrm{i}} - \overline{y}\right)^2}{\left(N-1\right)}} = 10.583$$

$$\sigma_{\mathrm{ref}} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{N_{\mathrm{ref}}}\left(y_{\mathrm{refi}} - \overline{y}_{\mathrm{ref}}\right)^2}{\left(N_{\mathrm{ref}}-1\right)}} = 9.399$$

$$F = \frac{10.583^2}{9.399^2}$$

$F = 1.268$

(1) For a 90 % confidence F-test, use Table 2 of this section to compare F to the F_{crit90} values tabulated versus (N–1) and (N_{ref} –1). If F is less than F_{crit90}, then F passes the F-test at 90 % confidence.

(2) For a 95 % confidence F-test, use Table 3 of this section to compare F to the F_{crit95} values tabulated versus (N–1) and (N_{ref} –1). If F is less than F_{crit95}, then F passes the F-test at 95 % confidence.

TABLE 2 OF § 1065.602–CRITICAL F VALUES, F_{CRIT90}, VERSUS N–1 AND N_{REF}–1 AT 90 % CONFIDENCE

N–1	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	1000+
N_{ref}–1																			
1	39.86	49.50	53.59	55.83	57.24	58.20	58.90	59.43	59.85	60.19	60.70	61.22	61.74	62.00	62.26	62.52	62.79	63.06	63.32
2	8.526	9.000	9.162	9.243	9.293	9.326	9.349	9.367	9.381	9.392	9.408	9.425	9.441	9.450	9.458	9.466	9.475	9.483	9.491
3	5.538	5.462	5.391	5.343	5.309	5.285	5.266	5.252	5.240	5.230	5.216	5.200	5.184	5.176	5.168	5.160	5.151	5.143	5.134
4	4.545	4.325	4.191	4.107	4.051	4.010	3.979	3.955	3.936	3.920	3.896	3.870	3.844	3.831	3.817	3.804	3.790	3.775	3.761
5	4.060	3.780	3.619	3.520	3.453	3.405	3.368	3.339	3.316	3.297	3.268	3.238	3.207	3.191	3.174	3.157	3.140	3.123	3.105
6	3.776	3.463	3.289	3.181	3.108	3.055	3.014	2.983	2.958	2.937	2.905	2.871	2.836	2.818	2.800	2.781	2.762	2.742	2.722
7	3.589	3.257	3.074	2.961	2.883	2.827	2.785	2.752	2.725	2.703	2.668	2.632	2.595	2.575	2.555	2.535	2.514	2.493	2.471
8	3.458	3.113	2.924	2.806	2.726	2.668	2.624	2.589	2.561	2.538	2.502	2.464	2.425	2.404	2.383	2.361	2.339	2.316	2.293
9	3.360	3.006	2.813	2.693	2.611	2.551	2.505	2.469	2.440	2.416	2.379	2.340	2.298	2.277	2.255	2.232	2.208	2.184	2.159
10	3.285	2.924	2.728	2.605	2.522	2.461	2.414	2.377	2.347	2.323	2.284	2.244	2.201	2.178	2.155	2.132	2.107	2.082	2.055
11	3.225	2.860	2.660	2.536	2.451	2.389	2.342	2.304	2.274	2.248	2.209	2.167	2.123	2.100	2.076	2.052	2.026	2.000	1.972
12	3.177	2.807	2.606	2.480	2.394	2.331	2.283	2.245	2.214	2.188	2.147	2.105	2.060	2.036	2.011	1.986	1.960	1.932	1.904
13	3.136	2.763	2.560	2.434	2.347	2.283	2.234	2.195	2.164	2.138	2.097	2.053	2.007	1.983	1.958	1.931	1.904	1.876	1.846
14	3.102	2.726	2.522	2.395	2.307	2.243	2.193	2.154	2.122	2.095	2.054	2.010	1.962	1.938	1.912	1.885	1.857	1.828	1.797
15	3.073	2.695	2.490	2.361	2.273	2.208	2.158	2.119	2.086	2.059	2.017	1.972	1.924	1.899	1.873	1.845	1.817	1.787	1.755
16	3.048	2.668	2.462	2.333	2.244	2.178	2.128	2.088	2.055	2.028	1.985	1.940	1.891	1.866	1.839	1.811	1.782	1.751	1.718
17	3.026	2.645	2.437	2.308	2.218	2.152	2.102	2.061	2.028	2.001	1.958	1.912	1.862	1.836	1.809	1.781	1.751	1.719	1.686
18	3.007	2.624	2.416	2.286	2.196	2.130	2.079	2.038	2.005	1.977	1.933	1.887	1.837	1.810	1.783	1.754	1.723	1.691	1.657
19	2.990	2.606	2.397	2.266	2.176	2.109	2.058	2.017	1.984	1.956	1.912	1.865	1.814	1.787	1.759	1.730	1.699	1.666	1.631
20	2.975	2.589	2.380	2.249	2.158	2.091	2.040	1.999	1.965	1.937	1.892	1.845	1.794	1.767	1.738	1.708	1.677	1.643	1.607
21	2.961	2.575	2.365	2.233	2.142	2.075	2.023	1.982	1.948	1.920	1.875	1.827	1.776	1.748	1.719	1.689	1.657	1.623	1.586
20	2.949	2.561	2.351	2.219	2.128	2.061	2.008	1.967	1.933	1.904	1.859	1.811	1.759	1.731	1.702	1.671	1.639	1.604	1.567
23	2.937	2.549	2.339	2.207	2.115	2.047	1.995	1.953	1.919	1.890	1.845	1.796	1.744	1.716	1.686	1.655	1.622	1.587	1.549
24	2.927	2.538	2.327	2.195	2.103	2.035	1.983	1.941	1.906	1.877	1.832	1.783	1.730	1.702	1.672	1.641	1.607	1.571	1.533
25	2.918	2.528	2.317	2.184	2.092	2.024	1.971	1.929	1.895	1.866	1.820	1.771	1.718	1.689	1.659	1.627	1.593	1.557	1.518
26	2.909	2.519	2.307	2.174	2.082	2.014	1.961	1.919	1.884	1.855	1.809	1.760	1.706	1.677	1.647	1.615	1.581	1.544	1.504
27	2.901	2.511	2.299	2.165	2.073	2.005	1.952	1.909	1.874	1.845	1.799	1.749	1.695	1.666	1.636	1.603	1.569	1.531	1.491
28	2.894	2.503	2.291	2.157	2.064	1.996	1.943	1.900	1.865	1.836	1.790	1.740	1.685	1.656	1.625	1.593	1.558	1.520	1.478
29	2.887	2.495	2.283	2.149	2.057	1.988	1.935	1.892	1.857	1.827	1.781	1.731	1.676	1.647	1.616	1.583	1.547	1.509	1.467
30	2.881	2.489	2.276	2.142	2.049	1.980	1.927	1.884	1.849	1.819	1.773	1.722	1.667	1.638	1.606	1.573	1.538	1.499	1.456
40	2.835	2.440	2.226	2.091	1.997	1.927	1.873	1.829	1.793	1.763	1.715	1.662	1.605	1.574	1.541	1.506	1.467	1.425	1.377
60	2.791	2.393	2.177	2.041	1.946	1.875	1.819	1.775	1.738	1.707	1.657	1.603	1.543	1.511	1.476	1.437	1.395	1.348	1.291
120	2.748	2.347	2.130	1.992	1.896	1.824	1.767	1.722	1.684	1.652	1.601	1.545	1.482	1.447	1.409	1.368	1.320	1.265	1.193
1000+	2.706	2.303	2.084	1.945	1.847	1.774	1.717	1.670	1.632	1.599	1.546	1.487	1.421	1.383	1.342	1.295	1.240	1.169	1.000

TABLE 3 OF § 1065.602–CRITICAL F VALUES, F_{CRIT95}, VERSUS N–1 AND N_{REF}–1 AT 95 % CONFIDENCE

N–1	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	1000+
N_{ref}–1																			
1	161.4	199.5	215.7	224.5	230.1	233.9	236.7	238.8	240.5	241.8	243.9	245.9	248.0	249.0	250.1	251.1	252.2	253.2	254.3
2	18.51	19.00	19.16	19.24	19.29	19.33	19.35	19.37	19.38	19.39	19.41	19.42	19.44	19.45	19.46	19.47	19.47	19.48	19.49
3	10.12	9.552	9.277	9.117	9.014	8.941	8.887	8.845	8.812	8.786	8.745	8.703	8.660	8.639	8.617	8.594	8.572	8.549	8.526
4	7.709	6.944	6.591	6.388	6.256	6.163	6.094	6.041	5.999	5.964	5.912	5.858	5.803	5.774	5.746	5.717	5.688	5.658	5.628
5	6.608	5.786	5.410	5.192	5.050	4.950	4.876	4.818	4.773	4.735	4.678	4.619	4.558	4.527	4.496	4.464	4.431	4.399	4.365
6	5.987	5.143	4.757	4.534	4.387	4.284	4.207	4.147	4.099	4.060	4.000	3.938	3.874	3.842	3.808	3.774	3.740	3.705	3.669
7	5.591	4.737	4.347	4.120	3.972	3.866	3.787	3.726	3.677	3.637	3.575	3.511	3.445	3.411	3.376	3.340	3.304	3.267	3.230
8	5.318	4.459	4.066	3.838	3.688	3.581	3.501	3.438	3.388	3.347	3.284	3.218	3.150	3.115	3.079	3.043	3.005	2.967	2.928
9	5.117	4.257	3.863	3.633	3.482	3.374	3.293	3.230	3.179	3.137	3.073	3.006	2.937	2.901	2.864	2.826	2.787	2.748	2.707
10	4.965	4.103	3.708	3.478	3.326	3.217	3.136	3.072	3.020	2.978	2.913	2.845	2.774	2.737	2.700	2.661	2.621	2.580	2.538
11	4.844	3.982	3.587	3.357	3.204	3.095	3.012	2.948	2.896	2.854	2.788	2.719	2.646	2.609	2.571	2.531	2.490	2.448	2.405
12	4.747	3.885	3.490	3.259	3.106	2.996	2.913	2.849	2.796	2.753	2.687	2.617	2.544	2.506	2.466	2.426	2.384	2.341	2.296
13	4.667	3.806	3.411	3.179	3.025	2.915	2.832	2.767	2.714	2.671	2.604	2.533	2.459	2.420	2.380	2.339	2.297	2.252	2.206
14	4.600	3.739	3.344	3.112	2.958	2.848	2.764	2.699	2.646	2.602	2.534	2.463	2.388	2.349	2.308	2.266	2.223	2.178	2.131
15	4.543	3.682	3.287	3.056	2.901	2.791	2.707	2.641	2.588	2.544	2.475	2.403	2.328	2.288	2.247	2.204	2.160	2.114	2.066
16	4.494	3.634	3.239	3.007	2.852	2.741	2.657	2.591	2.538	2.494	2.425	2.352	2.276	2.235	2.194	2.151	2.106	2.059	2.010
17	4.451	3.592	3.197	2.965	2.810	2.699	2.614	2.548	2.494	2.450	2.381	2.308	2.230	2.190	2.148	2.104	2.058	2.011	1.960
18	4.414	3.555	3.160	2.928	2.773	2.661	2.577	2.510	2.456	2.412	2.342	2.269	2.191	2.150	2.107	2.063	2.017	1.968	1.917
19	4.381	3.522	3.127	2.895	2.740	2.628	2.544	2.477	2.423	2.378	2.308	2.234	2.156	2.114	2.071	2.026	1.980	1.930	1.878
20	4.351	3.493	3.098	2.866	2.711	2.599	2.514	2.447	2.393	2.348	2.278	2.203	2.124	2.083	2.039	1.994	1.946	1.896	1.843
21	4.325	3.467	3.073	2.840	2.685	2.573	2.488	2.421	2.366	2.321	2.250	2.176	2.096	2.054	2.010	1.965	1.917	1.866	1.812
22	4.301	3.443	3.049	2.817	2.661	2.549	2.464	2.397	2.342	2.297	2.226	2.151	2.071	2.028	1.984	1.938	1.889	1.838	1.783
23	4.279	3.422	3.028	2.796	2.640	2.528	2.442	2.375	2.320	2.275	2.204	2.128	2.048	2.005	1.961	1.914	1.865	1.813	1.757
24	4.260	3.403	3.009	2.776	2.621	2.508	2.423	2.355	2.300	2.255	2.183	2.108	2.027	1.984	1.939	1.892	1.842	1.790	1.733
25	4.242	3.385	2.991	2.759	2.603	2.490	2.405	2.337	2.282	2.237	2.165	2.089	2.008	1.964	1.919	1.872	1.822	1.768	1.711
26	4.225	3.369	2.975	2.743	2.587	2.474	2.388	2.321	2.266	2.220	2.148	2.072	1.990	1.946	1.901	1.853	1.803	1.749	1.691
27	4.210	3.354	2.960	2.728	2.572	2.459	2.373	2.305	2.250	2.204	2.132	2.056	1.974	1.930	1.884	1.836	1.785	1.731	1.672
28	4.196	3.340	2.947	2.714	2.558	2.445	2.359	2.291	2.236	2.190	2.118	2.041	1.959	1.915	1.869	1.820	1.769	1.714	1.654
29	4.183	3.328	2.934	2.701	2.545	2.432	2.346	2.278	2.223	2.177	2.105	2.028	1.945	1.901	1.854	1.806	1.754	1.698	1.638
30	4.171	3.316	2.922	2.690	2.534	2.421	2.334	2.266	2.211	2.165	2.092	2.015	1.932	1.887	1.841	1.792	1.740	1.684	1.622
40	4.085	3.232	2.839	2.606	2.450	2.336	2.249	2.180	2.124	2.077	2.004	1.925	1.839	1.793	1.744	1.693	1.637	1.577	1.509
60	4.001	3.150	2.758	2.525	2.368	2.254	2.167	2.097	2.040	1.993	1.917	1.836	1.748	1.700	1.649	1.594	1.534	1.467	1.389
120	3.920	3.072	2.680	2.447	2.290	2.175	2.087	2.016	1.959	1.911	1.834	1.751	1.659	1.608	1.554	1.495	1.429	1.352	1.254
1000+	3.842	2.996	2.605	2.372	2.214	2.099	2.010	1.938	1.880	1.831	1.752	1.666	1.571	1.517	1.459	1.394	1.318	1.221	1.000

(h) Slope. Calculate a least-squares regression slope, a_{1y}, as follows:

$$a_{1y} = \frac{\sum_{i=1}^{N}(y_i - \overline{y}) \cdot \left(y_{refi} - \overline{y}_{ref}\right)}{\sum_{i=1}^{N}(y_{refi} - \overline{y}_{ref})^2}$$

Eq. 1065.602-9

Example:

$N = 6000$

$y_1 = 2045.8$

$\overline{y} = 1050.1$

$y_{ref\,1} = 2045.0$

$\overline{y}_{ref} = 1055.3$

$$a_{1y} = \frac{(2045.8 - 1050.1) \cdot (2045.0 - 1055.3) + \ldots + (y_{6000} - 1050.1) \cdot (y_{ref6000} - 1055.3)}{(2045.0 - 1055.3)^2 + \ldots + (y_{ref6000} - 1055.3)^2}$$

$a_{1y} = 1.0110$

(i) Intercept. Calculate a least-squares regression intercept, a_{0y}, as follows:

$$a_{0y} = \overline{y} - \left(a_{1y} \cdot \overline{y}_{ref}\right)$$

Eq. 1065.602-10

Example:

$\overline{y} = 1050.1$

$a_{1y} = 1.0110$

$\overline{y}_{ref} = 1055.3$

$a_{0y} = 1050.1 - (1.0110 \cdot 1055.3)$

$a_{0y} = -16.8083$

(j) Standard estimate of error. Calculate a standard estimate of error, *SEE*, as follows:

$$SEE_y = \sqrt{\frac{\sum_{i=1}^{N}\left[y_i - a_{0y} - (a_{1y} \cdot y_{refi})\right]^2}{N-2}}$$

Eq. 1065.602-11

Example:

$N = 6000$

$y_1 = 2045.8$

$a_{0y} = -16.8083$

$a_{1y} = 1.0110$

$y_{ref1} = 2045.0$

$$SEE_y = \sqrt{\frac{\left[2045.8 - (-16.8083) - (1.0110 \cdot 2045.0)\right]^2 + \ldots \left[y_{6000} - (-16.8083) - (1.0110 \cdot y_{ref\,6000})\right]^2}{6000 - 2}}$$

$SEE_y = 5.348$

(k) Coefficient of determination. Calculate a coefficient of determination, r_y^2, as follows:

$$r_y^2 = 1 - \frac{\sum_{i=1}^{N}\left[y_i - a_{0y} - (a_{1y} \cdot y_{refi})\right]^2}{\sum_{i=1}^{N}\left[y_i - \bar{y}\right]^2}$$

Eq. 1065.602-12

Example:
$N = 6000$
$y_1 = 2045.8$
$a_{0y} = -16.8083$
$a_{1y} = 1.0110$
$y_{refl} = 2045.0$
$\bar{y} = 1480.5$

$$r_y^2 = 1 - \frac{\left[2045.8 - (-16.8083) - (1.0110 \times 2045.0)\right]^2 + \ldots\left[y_{6000} - (-16.8083) - (1.0110 \cdot y_{ref6000})\right]^2}{\left[2045.8 - 1480.5\right]^2 + \ldots\left[y_{6000} - 1480.5\right]^2}$$

$r_y^2 = 0.9859$

(l) Flow-weighted mean concentration. In some sections of this part, you may need to calculate a flow-weighted mean concentration to determine the applicability of certain provisions. A flow-weighted mean is the mean of a quantity after it is weighted proportional to a corresponding flow rate. For example, if a gas concentration is measured continuously from the raw exhaust of an engine, its flow-weighted mean concentration is the sum of the products of each recorded concentration times its respective exhaust molar flow rate, divided by the sum of the recorded flow rate values. As another example, the bag concentration from a CVS system is the same as the flow-weighted mean concentration because the CVS system itself flow-weights the bag concentration. You might already expect a certain flow-weighted mean concentration of an emission at its standard based on previous testing with similar engines or testing with similar equipment and instruments. If you need to estimate your expected flow-weighted mean concentration of an emission at its standard, we recommend using the following examples as a guide for how to estimate the flow-weighted mean concentration expected at the standard. Note that these examples are not exact and that they contain assumptions that are not always valid. Use good engineering judgment to determine if you can use similar assumptions.

(1) To estimate the flow-weighted mean raw exhaust NO_x concentration from a turbocharged heavy-duty compression-ignition engine at a NO_x standard of 2.5 g/(kW·hr), you may do the following:

(i) Based on your engine design, approximate a map of maximum torque versus speed and use it with the applicable normalized duty cycle in the standard-setting part to generate a reference duty cycle as described in § 1065.610. Calculate the total reference work, W_{ref}, as described in § 1065.650. Divide the reference work by the duty cycle's time interval, $\Delta t_{dutycycle}$, to determine mean reference power, $\bar{P}_{ref}$.

(ii) Based on your engine design, estimate maximum power, P_{max}, the design speed at maximum power, f_{nmax}, the design maximum intake manifold boost pressure, p_{inmax}, and temperature, T_{inmax}. Also, estimate a mean fraction of power that is lost due to friction and pumping, $\bar{P}_{frict}$. Use this information along with the engine displacement volume, V_{disp}, an approximate volumetric efficiency, η_V, and the number of engine strokes per power stroke (two-stroke or four-stroke),

N_{stroke}, to estimate the maximum raw exhaust molar flow rate, $\dot{n}_{exhmax}$.

(iii) Use your estimated values as described in the following example calculation:

$$\overline{x}_{exp} = \frac{e_{std} \cdot W_{ref}}{M \cdot \dot{n}_{exhmax} \cdot \Delta t_{duty\ cycle} \cdot \left(\frac{\overline{P}_{ref} + \left(\overline{P}_{frict} \cdot P_{max} \right)}{P_{max}} \right)}$$

Eq. 1065.602-13

$$\dot{n}_{exhmax} = \frac{p_{max} \cdot V_{disp} \cdot f_{nmax} \cdot \frac{2}{N_{stroke}} \cdot \eta_V}{R \cdot T_{max}}$$

Eq. 1065.602-14

Example:

e_{NOx} = 2.5 g/(kW·hr)
W_{ref} = 11.883 kW·hr
M_{NOx} = 46.0055 g/mol = $46.0055 \cdot 10^{-6}$ g/µmol
$\Delta t_{dutycycle}$ = 20 min = 1200 s
$\overline{P}_{ref}$ = 35.65 kW
$\overline{P}_{frict}$ = 15 %
P_{max} = 125 kW

p_{max} = 300 kPa = 300000 Pa
V_{disp} = 3.0 l = 0.0030 m^3/r
f_{nmax} = 2800 r/min = 46.67 r/s
N_{stroke} = 4
η_V= 0.9
R = 8.314472 J/(mol·K)
T_{max} = 348.15 K

$$\dot{n}_{exhmax} = \frac{300000 \cdot 0.0030 \cdot 46.67 \cdot \frac{2}{4} \cdot 0.9}{8.314472 \cdot 348.15}$$

$\dot{n}_{exhmax}$ = 6.53 mol/s

$$\overline{x}_{exp} = \frac{2.5 \cdot 11.883}{46.0055 \cdot 10^{-6} \cdot 6.53 \cdot 1200 \cdot \left(\frac{35.65 + (0.15 \cdot 125)}{125} \right)}$$

$\overline{x}_{exp}$ = 189.4 µmol/mol

(2) To estimate the flow-weighted mean NMHC concentration in a CVS from a naturally aspirated nonroad spark-ignition engine at an NMHC standard of 0.5 g/(kW·hr), you may do the following:

(i) Based on your engine design, approximate a map of maximum torque versus speed and use it with the applicable normalized duty cycle in the standard-setting part to generate a reference duty cycle as described in § 1065.610. Calculate the total reference work, W_{ref}, as described in §

1065.650.
(ii) Multiply your CVS total molar flow rate by the time interval of the duty cycle, $\Delta t_{dutycycle}$. The result is the total diluted exhaust flow of the n_{dexh}.
(iii) Use your estimated values as described in the following example calculation:

$$\overline{x}_{NMHC} = \frac{e_{std} \cdot W_{ref}}{M \cdot \dot{n}_{dexh} \cdot \Delta t_{duty\ cycle}}$$

Eq. 1065.602-15

Example:
e_{NMHC} = 1.5 g/(kW·hr)
W_{ref} = 5.389 kW·hr
M_{NMHC} = 13.875389 g/mol = $13.875389 \cdot 10^{-6}$ g/μmol
$\dot{n}_{dexh}$ = 6.021 mol/s
$\Delta t_{dutycycle}$= 30 min = 1800 s

$$\overline{x}_{NMHC} = \frac{1.5 \cdot 5.389}{13.875389 \cdot 10^{-6} \cdot 6.021 \cdot 1800}$$

$\overline{x}_{NMHC}$ = 53.8 μmol/mol

§ 1065.610 Duty cycle generation.
This section describes how to generate duty cycles that are specific to your engine, based on the normalized duty cycles in the standard-setting part. During an emission test, use a duty cycle that is specific to your engine to command engine speed, torque, and power, as applicable, using an engine dynamometer and an engine operator demand. Paragraph (a) of this section describes how to "normalize" your engine's map to determine the maximum test speed and torque for your engine. The rest of this section describes how to use these values to "denormalize" the duty cycles in the standard-setting parts, which are all published on a normalized basis. Thus, the term "normalized" in paragraph (a) of this section refers to different values than it does in the rest of the section.
(a) Maximum test speed, f_{ntest}. This section generally applies to duty cycles for variable-speed engines. For constant-speed engines subject to duty cycles that specify normalized speed commands, use the no-load governed speed as the measured f_{ntest}. This is the highest engine speed where an engine outputs zero torque. For variable-speed engines, determine f_{ntest} from the power-versus-speed map, generated according to § 1065.510, as follows:
(1) Develop a measured value for f_{ntest} as follows:
(i) Determine maximum power, P_{max}, from the engine map generated according to § 1065.510 and calculate the value for power equal to 98 % of P_{max}.
(ii) Determine the lowest and highest engine speeds corresponding to 98 % of P_{max}, using linear interpolation, and no extrapolation, as appropriate.
(iii) Determine the engine speed corresponding to maximum power, f_{nPmax}, by calculating the average of the two speed values from paragraph (a)(1)(ii) of this section. If there is only one speed where power is equal to 98 % of P_{max}, take f_{nPmax} as the speed at which P_{max} occurs.
(iv) Transform the map into a normalized power-versus-speed map by dividing power terms by P_{max} and dividing speed terms by f_{nPmax}. Use the following equation to calculate a quantity representing the sum of squares from the normalized map:

$$\text{Sum of squares} = f_{nnormi}^2 + P_{normi}^2$$

Eq. 1065.610-1

Where:

i = an indexing variable that represents one recorded value of an engine map.

f_{nnormi} = an engine speed normalized by dividing it by f_{nPmax}.

P_{normi} = an engine power normalized by dividing it by P_{max}.

(v) Determine the maximum value for the sum of the squares from the map and multiply that value by 0.98.

(vi) Determine the lowest and highest engine speeds corresponding to the value calculated in paragraph (a)(1)(v) of this section, using linear interpolation as appropriate. Calculate f_{ntest} as the average of these two speed values. If there is only one speed corresponding to the value calculated in paragraph (a)(1)(v) of this section, take f_{ntest} as the speed where the maximum of the sum of the squares occurs.

(vii) The following example illustrates a calculation of f_{ntest}:

$P_{max} = 230.0$

($f_{n1} = 2360$, $P_1 = 222.5$, $f_{nnorm1} = 1.002$, $P_{norm1} = 0.9675$)

($f_{n2} = 2364$, $P_2 = 226.8$, $f_{nnorm2} = 1.004$, $P_{norm2} = 0.9859$)

($f_{n3} = 2369$, $P_3 = 228.6$, $f_{nnorm3} = 1.006$, $P_{norm3} = 0.9940$)

($f_{n4} = 2374$, $P_4 = 218.7$, $f_{nnorm4} = 1.008$, $P_{norm4} = 0.9508$)

Sum of squares = $(1.002^2 + 0.9675^2) = 1.94$

Sum of squares = $(1.004^2 + 0.9859^2) = 1.98$

Sum of squares = $(1.006^2 + 0.9940^2) = 2.00$

Sum of squares = $(1.008^2 + 0.9508^2) = 1.92$

$$f_{ntest} = \frac{\left(\left(2360 + (2364 - 2360)\cdot\frac{0.98\cdot 2.0 - 1.94}{1.98 - 1.94}\right) + \left(2369 + (2374 - 2369)\cdot\frac{0.98\cdot 2.0 - 2.0}{1.92 - 2.0}\right)\right)}{2}$$

$$= \frac{2362.0 + 2371.5}{2} = 2366.8 \text{ r/min}$$

$$f_{npmax} = \frac{\left(\left(2360 + (2364 - 2360)\cdot\frac{0.98\cdot 230.0 - 222.5}{226.8 - 222.5}\right) + \left(2369 + (2374 - 2369)\cdot\frac{0.98\cdot 230.0 - 228.6}{218.7 - 228.6}\right)\right)}{2}$$

$$= \frac{2362.7 + 2370.6}{2} = 2366.7 \text{ r/min}$$

(2) For engines with a high-speed governor that will be subject to a reference duty cycle that specifies normalized speeds greater than 100 %, calculate an alternate maximum test speed, $f_{ntest,alt}$, as specified in this paragraph (a)(2). If $f_{ntest,alt}$ is less than the measured maximum test speed, f_{ntest}, determined in paragraph (a)(1) of this section, replace f_{ntest} with $f_{ntest,alt}$. In this case, $f_{ntest,alt}$ becomes the "maximum test speed" for that engine. Note that § 1065.510 allows you to apply an optional declared maximum test speed to the final measured maximum test speed determined as an outcome of the comparison between f_{ntest}, and $f_{ntest,alt}$ in this paragraph (a)(2). Determine $f_{ntest,alt}$ as follows:

$$f_{ntest,alt} = (f_{nhi,idle} - f_{nidle})/\%\ speed_{max} + f_{nidle}$$

Eq. 1065.610-2

Where:
$f_{ntest,alt}$ = alternate maximum test speed
$f_{nhi,idle}$ = warm high-idle speed
f_{nidle} = warm idle speed
$\%\ speed_{max}$ = maximum normalized speed from duty cycle

Example:
$f_{nhi,idle}$ = 2200 r/min
f_{nidle} = 800 r/min
$\%\ speed_{max}$ = 105 % (Nonroad CI Transient Cycle)
$f_{ntest,alt}$ = (2200 – 800)/105 % + 800
$f_{ntest,alt}$ = 2133 r/min

(3) For variable-speed engines, transform normalized speeds to reference speeds according to paragraph (c) of this section by using the measured maximum test speed determined according to paragraphs (a)(1) and (2) of this section—or use your declared maximum test speed, as allowed in § 1065.510.

(4) For constant-speed engines, transform normalized speeds to reference speeds according to paragraph (c) of this section by using the measured no-load governed speed—or use your declared maximum test speed, as allowed in § 1065.510.

(b) Maximum test torque, T_{test}. For constant-speed engines, determine the measured T_{test} from the torque and power-versus-speed maps, generated according to § 1065.510, as follows:

(1) For constant speed engines mapped using the methods in § 1065.510(d)(5)(i) or (ii), determine T_{test} as follows:

(i) Determine maximum power, P_{max}, from the engine map generated according to § 1065.510 and calculate the value for power equal to 98 % of P_{max}.

(ii) Determine the lowest and highest engine speeds corresponding to 98 % of P_{max}, using linear interpolation, and no extrapolation, as appropriate.

(iii) Determine the engine speed corresponding to maximum power, f_{nPmax}, by calculating the average of the two speed values from paragraph (a)(1)(ii) of this section. If there is only one speed where power is equal to 98 % of P_{max}, take f_{nPmax} as the speed at which P_{max} occurs.

(iv) Transform the map into a normalized power-versus-speed map by dividing power terms by P_{max} and dividing speed terms by f_{nPmax}. Use the Equation 1065.610-1 to calculate a quantity representing the sum of squares from the normalized map.

(v) Determine the maximum value for the sum of the squares from the map and multiply that value by 0.98.

(vi) Determine the lowest and highest engine speeds corresponding to the value calculated in paragraph (a)(1)(v) of this section, using linear interpolation as appropriate. Calculate f_{ntest} as the average of these two speed values. If there is only one speed corresponding to the value calculated in paragraph (a)(1)(v) of this section, take f_{ntest} as the speed where the maximum of the sum of the squares occurs.

(vii) The measured T_{test} is the mapped torque at f_{ntest}.

(2) For constant speed engines using the two point mapping method in §1065.510(d)(5)(iii), you may follow paragraph (a)(1) of this section to determine the measured T_{test}, or you may use the measured torque of the second point as the measured T_{test} directly.

(3) Transform normalized torques to reference torques according to paragraph (d) of this section by using the measured maximum test torque determined according to paragraph (b)(1) of this

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Based on the map, determine maximum power, P_{max}, and the speed at which maximum power occurs, f_{nPmax}. If maximum power occurs at multiple speeds, take f_{nPmax} as the lowest of these speeds. Divide every recorded power by P_{max} and divide every recorded speed by f_{nPmax}. The result is a normalized power-versus-speed map. Your measured T_{test} is the torque at which the sum of the squares of normalized speed and power is maximum. Note that that if multiple maximum values are found, T_{test} should be taken as the highest torque of all points with the same maximum sum of squares. Determine T_{test} as follows:¶

$T_{test} = T_i$ at the maximum of $\left(f_{nnormi}^2 + P_{no}\right.$

¶

Eq. 1065.610-3¶
Where: ¶
T_{test} = maximum test torque.¶
¶
Example:¶
(f_{nnorm1} = 1.002, P_{norm1} = 0.978, T_1 = 722.62 N·m)¶
(f_{nnorm2} = 1.004, P_{norm2} = 0.977, T_2 = 720.44 N·m)¶
(f_{nnorm3} = 1.006, P_{norm3} = 0.974, T_3 = 716.80 N·m)¶
$(f_{nnorm1}^2 + P_{norm1}^2) = (1.002^2 + 0.978^2) = 1.960$¶
$(f_{nnorm1}^2 + P_{norm1}^2) = (1.004^2 + 0.977^2) = 1.963$¶
$(f_{nnorm1}^2 + P_{norm1}^2) = (1.006^2 + 0.974^2) = 1.961$¶
maximum = 1.963 at i = 2¶
T_{test} = 720.44 N·m

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section—or use your declared maximum test torque, as allowed in § 1065.510.

(c) Generating reference speed values from normalized duty cycle speeds. Transform normalized speed values to reference values as follows:

(1) % speed. If your normalized duty cycle specifies % speed values, use your warm idle speed and your maximum test speed to transform the duty cycle, as follows:

$f_{nref} = \%\ speed \cdot (f_{ntest} - f_{nidle}) + f_{nidle}$

Eq. 1065.610-3

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Example:

$\%\ speed = 85\ \%$

$f_{ntest} = 2364$ r/min

$f_{nidle} = 650$ r/min

$f_{nref} = 85\ \% \cdot (2364 - 650) + 650$

$f_{nref} = 2107$ r/min

(2) A, B, and C speeds. If your normalized duty cycle specifies speeds as A, B, or C values, use your power-versus-speed curve to determine the lowest speed below maximum power at which 50 % of maximum power occurs. Denote this value as n_{lo}. Take n_{lo} to be warm idle speed if all power points at speeds below the maximum power speed are higher than 50 % of maximum power. Also determine the highest speed above maximum power at which 70 % of maximum power occurs. Denote this value as n_{hi}. If all power points at speeds above the maximum power speed are higher than 70% of maximum power, take n_{hi} to be the declared maximum safe engine speed or the declared maximum representative engine speed, whichever is lower. Use n_{hi} and n_{lo} to calculate reference values for A, B, or C speeds as follows:

$f_{nrefA} = 0.25 \cdot (n_{hi} - n_{lo}) + n_{lo}$

Eq. 1065.610-4

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$f_{nrefB} = 0.50 \cdot (n_{hi} - n_{lo}) + n_{lo}$

Eq. 1065.610-5

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$f_{nrefC} = 0.75 \cdot (n_{hi} - n_{lo}) + n_{lo}$

Eq. 1065.610-6

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Example:

$n_{lo} = 1005$ r/min

$n_{hi} = 2385$ r/min

$f_{nrefA} = 0.25 \cdot (2385 - 1005) + 1005$

$f_{nrefB} = 0.50 \cdot (2385 - 1005) + 1005$

$f_{nrefC} = 0.75 \cdot (2385 - 1005) + 1005$

$f_{nrefA} = 1350$ r/min

$f_{nrefB} = 1695$ r/min

$f_{nrefC} = 2040$ r/min

(3) Intermediate speed. Based on the map, determine maximum torque, T_{max}, and the corresponding speed, f_{nTmax}, calculated as the average of the lowest and highest speeds at which torque is equal to 98 % of T_{max}. Use linear interpolation between points to determine the speeds where torque is equal to 98% of T_{max}. Identify your reference intermediate speed as one of the following values:

(i) f_{nTmax} if it is between (60 and 75) % of maximum test speed.

(ii) 60 % of maximum test speed if f_{nTmax} is less than 60 % of maximum test speed.

(iii) 75 % of maximum test speed if f_{nTmax} is greater than 75 % of maximum test speed.

(d) Generating reference torques from normalized duty-cycle torques. Transform normalized

torques to reference torques using your map of maximum torque versus speed.
(1) Reference torque for variable-speed engines. For a given speed point, multiply the corresponding % torque by the maximum torque at that speed, according to your map. If your engine is subject to a reference duty cycle that specifies negative torque values (i.e., engine motoring), use negative torque for those motoring points (i.e., the motoring torque). If you map negative torque as allowed under § 1065.510(c)(2) and the low-speed governor activates, resulting in positive torques, you may replace those positive motoring mapped torques with negative values between zero and the largest negative motoring torque. For both maximum and motoring torque maps, linearly interpolate mapped torque values to determine torque between mapped speeds. If the reference speed is below the minimum mapped speed (i.e., 95% of idle speed or 95% of lowest required speed, whichever is higher), use the mapped torque at the minimum mapped speed as the reference torque. The result is the reference torque for each speed point.
(2) Reference torque for constant-speed engines. Multiply a % torque value by your maximum test torque. The result is the reference torque for each point.
(3) Required deviations. We require the following deviations for variable-speed engines intended primarily for propulsion of a vehicle with an automatic transmission where that engine is subject to a transient duty cycle with idle operation. These deviations are intended to produce a more representative transient duty cycle for these applications. For steady-state duty cycles or transient duty cycles with no idle operation, these requirements do not apply. Idle points for steady state duty cycles of such engines are to be run at conditions simulating neutral or park on the transmission.
(i) Zero-percent speed is the warm idle speed measured according to § 1065.510(b)(6) with CITT applied, i.e., measured warm idle speed in drive.
(ii) If the cycle begins with a set of contiguous idle points (zero-percent speed, and zero-percent torque), leave the reference torques set to zero for this initial contiguous idle segment. This is to represent free idle operation with the transmission in neutral or park at the start of the transient duty cycle, after the engine is started. If the initial idle segment is longer than 24 seconds, change the reference torques for the remaining idle points in the initial contiguous idle segment to CITT (i.e., change idle points corresponding to 25 seconds to the end of the initial idle segment to CITT). This is to represent shifting the transmission to drive.
(iii) For all other idle points, change the reference torque to CITT. This is to represent the transmission operating in drive.
(iv) If the engine is intended primarily for automatic transmissions with a Neutral-When-Stationary feature that automatically shifts the transmission to neutral after the vehicle is stopped for a designated time and automatically shifts back to drive when the operator increases demand (i.e., pushes the accelerator pedal), change the reference torque back to zero for idle points in drive after the designated time.
(v) For all points with normalized speed at or below zero percent and reference torque from zero to CITT, set the reference torque to CITT. This is to provide smoother torque references below idle speed.
(vi) For motoring points, make no changes.
(vii) For consecutive points with reference torques from zero to CITT that immediately follow idle points, change their reference torques to CITT. This is to provide smooth torque transition out of idle operation. This does not apply if the Neutral-When-Stationary feature is used and the transmission has shifted to neutral.

(viii) For consecutive points with reference torque from zero to CITT that immediately precede idle points, change their reference torques to CITT. This is to provide smooth torque transition into idle operation.

(4) Permissible deviations for any engine. If your engine does not operate below a certain minimum torque under normal in-use conditions, you may use a declared minimum torque as the reference value instead of any value denormalized to be less than the declared value. For example, if your engine is connected to a hydrostatic transmission and it has a minimum torque even when all the driven hydraulic actuators and motors are stationary and the engine is at idle, then you may use this declared minimum torque as a reference torque value instead of any reference torque value generated under paragraph (d)(1) or (2) of this section that is between zero and this declared minimum torque.

(e) Generating reference power values from normalized duty cycle powers. Transform normalized power values to reference speed and power values using your map of maximum power versus speed.

(1) First transform normalized speed values into reference speed values. For a given speed point, multiply the corresponding % power by the mapped power at maximum test speed, f_{ntest}, unless specified otherwise by the standard-setting part. The result is the reference power for each speed point, P_{ref}. Convert these reference powers to corresponding torques for operator demand and dynamometer control and for duty cycle validation per 1065.514. Use the reference speed associated with each reference power point for this conversion. As with cycles specified with % torque, linearly interpolate between these reference torque values generated from cycles with % power.

(2) Permissible deviations for any engine. If your engine does not operate below a certain power under normal in-use conditions, you may use a declared minimum power as the reference value instead of any value denormalized to be less than the declared value. For example, if your engine is directly connected to a propeller, it may have a minimum power called idle power. In this case, you may use this declared minimum power as a reference power value instead of any reference power value generated per paragraph (e)(1) of this section that is from zero to this declared minimum power.

§ 1065.630 Local acceleration of gravity.

(a) The acceleration of Earth's gravity, a_g, varies depending on the test location. Determine a_g at your location by entering latitude, longitude, and elevation data into the U.S. National Oceanographic and Atmospheric Administration's surface gravity prediction Web site at http://www.ngs.noaa.gov/cgi-bin/grav_pdx.prl.

(b) If the Web site specified in paragraph (a) of this section is unavailable, you may calculate a_g for your latitude as follows:

$$a_g = 9.7803267715 \cdot [1 + 5.2790414 \cdot 10^{-3} \cdot \sin^2(\theta) + 2.32718 \cdot 10^{-5} \cdot \sin^4(\theta) + 1.262 \cdot 10^{-7} \cdot \sin^6(\theta) + 7 \cdot 10^{-10} \cdot \sin^8(\theta)]$$

Eq. 1065.630-1

Where:

θ = Degrees north or south latitude.

Example:

$\theta = 45\ °$

$$a_g = 9.7803267715 \cdot (1 + 5.2790414 \cdot 10^{-3} \cdot \sin^2(45) + 2.32718 \cdot 10^{-5} \cdot \sin^4(45) + 1.262 \cdot 10^{-7} \cdot \sin^6(45) + 7 \cdot 10^{-10} \cdot \sin^8(45)$$

$a_g = 9.8061992026\ \text{m/s}^2$

§ 1065.640 Flow meter calibration calculations.

This section describes the calculations for calibrating various flow meters. After you calibrate a flow meter using these calculations, use the calculations described in § 1065.642 to calculate flow during an emission test. Paragraph (a) of this section first describes how to convert reference flow meter outputs for use in the calibration equations, which are presented on a molar basis. The remaining paragraphs describe the calibration calculations that are specific to certain types of flow meters.

(a) Reference meter conversions. The calibration equations in this section use molar flow rate, $\dot{n}_{ref}$, as a reference quantity. If your reference meter outputs a flow rate in a different quantity, such as standard volume rate, $\dot{V}_{stdref}$, actual volume rate, $\dot{V}_{actref}$, or mass rate, $\dot{m}_{ref}$, convert your reference meter output to a molar flow rate using the following equations, noting that while values for volume rate, mass rate, pressure, temperature, and molar mass may change during an emission test, you should ensure that they are as constant as practical for each individual set point during a flow meter calibration:

$$\dot{n}_{ref} = \frac{\dot{V}_{stdref} \cdot p_{std}}{T_{std} \cdot R} = \frac{\dot{V}_{actref} \cdot p_{act}}{T_{act} \cdot R} = \frac{\dot{m}_{ref}}{M_{mix}}$$

Eq. 1065.640-1

Where:

$\dot{n}_{ref}$ = reference molar flow rate.

$\dot{V}_{stdref}$ = reference volume flow rate, corrected to a standard pressure and a standard temperature.

$\dot{V}_{actref}$ = reference volume flow rate at the actual pressure and temperature of the flow rate.

$\dot{m}_{ref}$ = reference mass flow.

p_{std} = standard pressure.

p_{act} = actual pressure of the flow rate.

T_{std} = standard temperature.

T_{act} = actual temperature of the flow rate.

R = molar gas constant.

M_{mix} = molar mass of the flow rate.

Example 1:

$\dot{V}_{stdref} = 1000.00\ \text{ft}^3/\text{min} = 0.471948\ \text{m}^3/\text{s}$

$p_{std} = 29.9213$ in Hg @ 32 °F = 101.325 kPa = 101325 Pa = 101325 kg/(m·s^2)

$T_{std} = 68.0$ °F = 293.15 K

$R = 8.314472\ \text{J/(mol·K)} = 8.314472\ (\text{m}^2\cdot\text{kg})/(\text{s}^2\cdot\text{mol}\cdot\text{K})$

$$\dot{n}_{ref} = \frac{0.471948 \cdot 101325}{293.15 \cdot 8.314472}$$

$\dot{n}_{ref} = 19.619$ mol/s

Example 2:

$\dot{m}_{ref} = 17.2683$ kg/min = 287.805 g/s

$M_{mix} = 28.7805$ g/mol

$$\dot{n}_{\text{ref}} = \frac{287.805}{28.7805}$$

$\dot{n}_{\text{ref}} = 10.0000$ mol/s

(b) PDP calibration calculations. For each restrictor position, calculate the following values from the mean values determined in § 1065.340, as follows:

(1) PDP volume pumped per revolution, V_{rev} (m^3/r):

$$V_{\text{rev}} = \frac{\overline{\dot{n}}_{\text{ref}} \cdot R \cdot \overline{T}_{\text{in}}}{\overline{p}_{\text{in}} \cdot \overline{f}_{\text{nPDP}}}$$

Eq. 1065.640-2

Example:

$\overline{\dot{n}}_{\text{ref}} = 25.096$ mol/s

$R = 8.314472$ J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)

$\overline{T}_{\text{in}} = 299.5$ K

$\overline{p}_{\text{in}} = 98.290$ kPa = 98290 Pa = 98290 kg/(m·s^2)

$\overline{f}_{\text{nPDP}} = 1205.1$ r/min = 20.085 r/s

$$V_{rev} = \frac{25.096 \cdot 8.314472 \cdot 299.5}{98290 \cdot 20.085}$$

$V_{rev} = 0.03166$ m^3/r

(2) PDP slip correction factor, K_s (s/r):

$$K_s = \frac{1}{\overline{f}_{\text{nPDP}}} \cdot \sqrt{\frac{\overline{p}_{\text{out}} - \overline{p}_{\text{in}}}{\overline{p}_{\text{out}}}}$$

Eq. 1065.640-3

Example:

$\overline{f}_{\text{nPDP}} = 1205.1$ r/min = 20.085 r/s

$\overline{p}_{\text{out}} = 100.103$ kPa

$\overline{p}_{\text{in}} = 98.290$ kPa

$$K_s = \frac{1}{20.085} \cdot \sqrt{\frac{100.103 - 98.290}{100.103}}$$

$K_s = 0.006700$ s/r

(3) Perform a least-squares regression of PDP volume pumped per revolution, V_{rev}, versus PDP slip correction factor, K_s, by calculating slope, a_1, and intercept, a_0, as described in § 1065.602.

(4) Repeat the procedure in paragraphs (b)(1) through (3) of this section for every speed that you run your PDP.

(5) The following example illustrates these calculations:

TABLE 1 OF § 1065.640–
EXAMPLE OF PDP CALIBRATION DATA

$\bar{f}_{nPDP}$ (revolution/s)	a_1 (m^3/s)	a_0 (m^3/revolution)
12.6	0.841	0.056
16.5	0.831	-0.013
20.9	0.809	0.028
23.4	.788	-0.061

(6) For each speed at which you operate the PDP, use the corresponding slope, a_1, and intercept, a_0, to calculate flow rate during emission testing as described in § 1065.642.

(c) Venturi governing equations and permissible assumptions. This section describes the governing equations and permissible assumptions for calibrating a venturi and calculating flow using a venturi. Because a subsonic venturi (SSV) and a critical-flow venturi (CFV) both operate similarly, their governing equations are nearly the same, except for the equation describing their pressure ratio, r (i.e., r_{SSV} versus r_{CFV}). These governing equations assume one-dimensional isentropic inviscid compressible flow of an ideal gas. In paragraph (c)(4) of this section, we describe other assumptions that you may make, depending upon how you conduct your emission tests. If we do not allow you to assume that the measured flow is an ideal gas, the governing equations include a first-order correction for the behavior of a real gas; namely, the compressibility factor, Z. If good engineering judgment dictates using a value other than Z=1, you may either use an appropriate equation of state to determine values of Z as a function of measured pressures and temperatures, or you may develop your own calibration equations based on good engineering judgment. Note that the equation for the flow coefficient, C_f, is based on the ideal gas assumption that the isentropic exponent, γ, is equal to the ratio of specific heats, C_p/C_v. If good engineering judgment dictates using a real gas isentropic exponent, you may either use an appropriate equation of state to determine values of γ as a function of measured pressures and temperatures, or you may develop your own calibration equations based on good engineering judgment. Calculate molar flow rate, $\dot{n}$, as follows:

$$\dot{n} = C_d \cdot C_f \cdot \frac{A_t \cdot p_{in}}{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}$$

Eq. 1065.640-4

Where:
C_d = discharge coefficient, as determined in paragraph (c)(1) of this section.
C_f = flow coefficient, as determined in paragraph (c)(2) of this section.
A_t = venturi throat cross-sectional area.
p_{in} = venturi inlet absolute static pressure.
Z = compressibility factor.
M_{mix} = molar mass of gas mixture.
R = molar gas constant.
T_{in} = venturi inlet absolute temperature.

(1) Using the data collected in § 1065.340, calculate C_d using the following equation:

$$C_d = \dot{n}_{ref} \cdot \frac{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}{C_f \cdot A_t \cdot p_{in}}$$

Eq. 1065.640-5

Where:

$\dot{n}_{ref}$ = a reference molar flow rate.

(2) Determine C_f using one of the following methods:

(i) For CFV flow meters only, determine C_{fCFV} from the following table based on your values for β and γ, using linear interpolation to find intermediate values:

TABLE 2 OF § 1065.640–

C_{fCFV} VERSUS β AND γ FOR CFV FLOW METERS

C_{fCFV}		
β	γ_{exh} = 1.385	γ_{dexh} = γ_{air} = 1.399
0.000	0.6822	0.6846
0.400	0.6857	0.6881
0.500	0.6910	0.6934
0.550	0.6953	0.6977
0.600	0.7011	0.7036
0.625	0.7047	0.7072
0.650	0.7089	0.7114
0.675	0.7137	0.7163
0.700	0.7193	0.7219
0.720	0.7245	0.7271
0.740	0.7303	0.7329
0.760	0.7368	0.7395
0.770	0.7404	0.7431
0.780	0.7442	0.7470
0.790	0.7483	0.7511
0.800	0.7527	0.7555
0.810	0.7573	0.7602
0.820	0.7624	0.7652
0.830	0.7677	0.7707
0.840	0.7735	0.7765
0.850	0.7798	0.7828

(ii) For any CFV or SSV flow meter, you may use the following equation to calculate C_f:

$$C_f = \left[\frac{2 \cdot \gamma \cdot \left(r^{\frac{\gamma-1}{\gamma}} - 1 \right)}{(\gamma - 1) \cdot \left(\beta^4 - r^{\frac{-2}{\gamma}} \right)} \right]^{\frac{1}{2}}$$

Eq. 1065.640-6

Where:
γ = isentropic exponent. For an ideal gas, this is the ratio of specific heats of the gas mixture, C_p/C_v.
r = pressure ratio, as determined in paragraph (c)(3) of this section.
β = ratio of venturi throat to inlet diameters.
(3) Calculate r as follows:
(i) For SSV systems only, calculate r_{SSV} using the following equation:

$$r_{SSV} = 1 - \frac{\Delta p_{SSV}}{p_{in}}$$

Eq. 1065.640-7

Where:
Δp_{SSV} = Differential static pressure; venturi inlet minus venturi throat.
(ii) For CFV systems only, calculate r_{CFV} iteratively using the following equation:

$$r_{CFV}^{\frac{1-\gamma}{\gamma}} + \left(\frac{\gamma - 1}{2}\right) \cdot \beta^4 \cdot r_{CFV}^{\frac{2}{\gamma}} = \frac{\gamma + 1}{2}$$

Eq. 1065.640-8

(4)You may make any of the following simplifying assumptions of the governing equations, or you may use good engineering judgment to develop more appropriate values for your testing:
(i) For emission testing over the full ranges of raw exhaust, diluted exhaust and dilution air, you may assume that the gas mixture behaves as an ideal gas: Z=1.
(ii) For the full range of raw exhaust you may assume a constant ratio of specific heats of γ=1.385.
(iii) For the full range of diluted exhaust and air (e.g., calibration air or dilution air), you may assume a constant ratio of specific heats of γ=1.399.
(iv) For the full range of diluted exhaust and air, you may assume the molar mass of the mixture is a function only of the amount of water in the dilution air or calibration air, x_{H2O}, determined as described in § 1065.645, as follows:

$$M_{mix} = M_{air} \cdot (1 - x_{H2O}) + M_{H2O} \cdot x_{H2O}$$

Eq. 1065.640-9

Example:
M_{air} = 28.96559 g/mol
x_{H2O} = 0.0169 mol/mol
M_{H2O} = 18.01528 g/mol
M_{mix} = 28.96559 · (1– 0.0169) + 18.01528 · 0.0169
M_{mix} = 28.7805 g/mol
(v) For the full range of diluted exhaust and air, you may assume a constant molar mass of the mixture, M_{mix}, for all calibration and all testing as long as your assumed molar mass differs no more than ±1 % from the estimated minimum and maximum molar mass during calibration and testing. You may assume this, using good engineering judgment, if you sufficiently control the amount of water in calibration air and in dilution air or if you remove sufficient water from both calibration air and dilution air. The following table gives examples of permissible ranges of dilution air dewpoint versus calibration air dewpoint:

TABLE 3 OF § 1065.640–
EXAMPLES OF DILUTION AIR AND CALIBRATION AIR DEWPOINTS AT WHICH YOU MAY ASSUME A CONSTANT M_{mix}

If calibration T_{dew} (°C) is...	assume the following constant M_{mix} (g/mol)...	for the following ranges of T_{dew} (°C) during emission tests[a]
dry	28.96559	dry to 18
0	28.89263	dry to 21
5	28.86148	dry to 22
10	28.81911	dry to 24
15	28.76224	dry to 26
20	28.68685	-8 to 28
25	28.58806	12 to 31
30	28.46005	23 to 34

[a]Range valid for all calibration and emission testing over the atmospheric pressure range (80.000 to 103.325) kPa.

(5) The following example illustrates the use of the governing equations to calculate the discharge coefficient, C_d of an SSV flow meter at one reference flow meter value. Note that calculating C_d for a CFV flow meter would be similar, except that C_f would be determined from Table 2 of this section or calculated iteratively using values of β and γ as described in paragraph (c)(2) of this section.

Example:

$\dot{n}_{ref} = 57.625$ mol/s

$Z = 1$

$M_{mix} = 28.7805$ g/mol = 0.0287805 kg/mol

$R = 8.314472$ J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)

$T_{in} = 298.15$ K

$A_t = 0.01824$ m^2

$p_{in} = 99.132$ kPa = 99132.0 Pa = 99132 kg/(m·s^2)

$\gamma = 1.399$

$\beta = 0.8$

$\Delta p = 2.312$ kPa

$$r_{SSV} = 1 - \frac{2.312}{99.132} = 0.977$$

$$C_f = \left[\frac{2 \cdot 1.399 \cdot \left(0.977^{\frac{1.399-1}{1.399}} - 1\right)}{(1.399-1) \cdot \left(0.8^4 - 0.977^{\frac{-2}{1.399}}\right)} \right]^{\frac{1}{2}}$$

$C_f = 0.274$

$$C_d = 57.625 \cdot \frac{\sqrt{1 \cdot 0.0287805 \cdot 8.314472 \cdot 298.15}}{0.274 \cdot 0.01824 \cdot 99132.0}$$

$C_d = 0.982$

(d) SSV calibration. Perform the following steps to calibrate an SSV flow meter:

(1) Calculate the Reynolds number, $Re^{\#}$, for each reference molar flow rate, $\dot{n}_{ref}$, using the throat diameter of the venturi, d_t. Because the dynamic viscosity, μ, is needed to compute $Re^{\#}$, you may use your own fluid viscosity model to determine μ for your calibration gas (usually air), using good engineering judgment. Alternatively, you may use the Sutherland three-coefficient viscosity model to approximate μ, as shown in the following sample calculation for $Re^{\#}$:

$$Re^{\#} = \frac{4 \cdot M_{mix} \cdot \dot{n}_{ref}}{\pi \cdot d_t \cdot \mu}$$

Eq. 1065.640-10

Where, using the Sutherland three-coefficient viscosity model:

$$\mu = \mu_0 \cdot \left(\frac{T_{in}}{T_0}\right)^{\frac{3}{2}} \cdot \left(\frac{T_0 + S}{T_{in} + S}\right)$$

Eq. 1065.640-11

Where:
μ_0 = Sutherland reference viscosity.
T_0 = Sutherland reference temperature.
S = Sutherland constant.

TABLE 4 OF § 1065.640–
SUTHERLAND THREE-COEFFICIENT VISCOSITY MODEL PARAMETERS

Gas[a]	μ_0	T_0	S	Temp range within ±2 % error[b]	Pressure limit[b]
	kg/(m·s)	K	K	K	kPa
Air	$1.716 \cdot 10^{-5}$	273	111	170 to 1900	≤ 1800
CO_2	$1.370 \cdot 10^{-5}$	273	222	190 to 1700	≤ 3600
H_2O	$1.12 \cdot 10^{-5}$	350	1064	360 to 1500	≤ 10000
O_2	$1.919 \cdot 10^{-5}$	273	139	190 to 2000	≤ 2500
N_2	$1.663 \cdot 10^{-5}$	273	107	100 to 1500	≤ 1600

[a]Use tabulated parameters only for the pure gases, as listed. Do not combine parameters in calculations to calculate viscosities of gas mixtures.
[b]The model results are valid only for ambient conditions in the specified ranges.

Example:
$\mu_0 = 1.716 \cdot 10^{-5}$ kg/(m·s)
$T_0 = 273$ K
$S = 111$ K

$$\mu = 1.716 \cdot 10^{-5} \cdot \left(\frac{298.15}{273}\right)^{\frac{3}{2}} \cdot \left(\frac{273 + 111}{298.15 + 111}\right)$$

$\mu = 1.838 \cdot 10^{-5}$ kg/(m·s)

M_{mix} = 28.7805 g/mol

$\dot{n}_{ref}$ = 57.625 mol/s

d_t = 152.4 mm = 0.1524 m

T_{in} = 298.15 K

$$Re^{\#} = \frac{4 \cdot 28.7805 \cdot 57.625}{3.14159 \cdot 0.1524 \cdot 1.838 \cdot 10^{-5}}$$

$Re^{\#} = 7.538 \cdot 10^{8}$

(2) Create an equation for C_d as a function of $Re^{\#}$, using paired values of the two quantities. The equation may involve any mathematical expression, including a polynomial or a power series. The following equation is an example of a commonly used mathematical expression for relating C_d and $Re^{\#}$:

$$C_d = a_0 - a_1 \cdot \sqrt{\frac{10^6}{Re^{\#}}}$$

Eq. 1065.640-12

(3) Perform a least-squares regression analysis to determine the best-fit coefficients for the equation and calculate the equation's regression statistic, *SEE,* according to § 1065.602.

(4) If the equation meets the criterion of $SEE \leq 0.5\ \% \cdot C_{dmax}$, you may use the equation to determine C_d for emission tests, as described in § 1065.642.

(5) If the equation does not meet the specified statistical criterion, you may use good engineering judgment to omit calibration data points; however you must use at least seven calibration data points to demonstrate that you meet the statistical criterion. This will usually involve narrowing the range of flow rates for a better curve fit.

(6) Take corrective action if the equation does not meet the specified statistical criterion even after omitting calibration data points. For example, select another mathematical expression for the C_d versus $Re^{\#}$ equation, check for leaks, or repeat the calibration process. If you must repeat the process, we recommend applying tighter tolerances to measurements and allowing more time for flows to stabilize.

(7) Once you have an equation that meets the specified statistical criterion, you may use the equation only for the corresponding range of $Re^{\#}$.

(e) CFV calibration. Some CFV flow meters consist of a single venturi and some consist of multiple venturis, where different combinations of venturis are used to meter different flow rates. For CFV flow meters that consist of multiple venturis, either calibrate each venturi independently to determine a separate discharge coefficient, C_d, for each venturi, or calibrate each combination of venturis as one venturi. In the case where you calibrate a combination of venturis, use the sum of the active venturi throat areas as A_t, the square root of the sum of the squares of the active venturi throat diameters as d_t, and the ratio of the venturi throat to inlet diameters as the ratio of the square root of the sum of the active venturi throat diameters (d_t) to the diameter of the common entrance to all the venturis (D). To determine the C_d for a single venturi or a single combination of venturis, perform the following steps:

(1) Use the data collected at each calibration set point to calculate an individual C_d for each point using Eq. 1065.640-4.

(2) Calculate the mean and standard deviation of all the C_d values according to Eqs. 1065.602-1 and 1065.602-2.

(3) If the standard deviation of all the C_d values is less than or equal to 0.3 % of the mean C_d, use

the mean C_d in Eq. 1065.642-4, and use the CFV only up to the highest r measured during calibration using the following equation:

$$r = 1 - \frac{\Delta p_{CFV}}{p_{in}}$$

Eq. 1065.640-13

Where:

Δp_{CFV} = Differential static pressure; venturi inlet minus venturi outlet.

(4) If the standard deviation of all the C_d values exceeds 0.3 % of the mean C_d, omit the C_d value corresponding to the data point collected at the highest r measured during calibration.

(5) If the number of remaining data points is less than seven, take corrective action by checking your calibration data or repeating the calibration process. If you repeat the calibration process, we recommend checking for leaks, applying tighter tolerances to measurements and allowing more time for flows to stabilize.

(6) If the number of remaining C_d values is seven or greater, recalculate the mean and standard deviation of the remaining C_d values.

(7) If the standard deviation of the remaining C_d values is less than or equal to 0.3 % of the mean of the remaining C_d, use that mean C_d in Eq. 1065.642-4, and use the CFV values only up to the highest r associated with the remaining C_d.

(8) If the standard deviation of the remaining C_d still exceeds 0.3 % of the mean of the remaining C_d values, repeat the steps in paragraph (e)(4) through (8) of this section.

§ 1065.642 SSV, CFV, and PDP molar flow rate calculations.

This section describes the equations for calculating molar flow rates from various flow meters. After you calibrate a flow meter according to § 1065.640, use the calculations described in this section to calculate flow during an emission test.

(a) PDP molar flow rate. Based upon the speed at which you operate the PDP for a test interval, select the corresponding slope, a_1, and intercept, a_0, as calculated in § 1065.640, to calculate molar flow rate, $\dot{n}$ as follows:

$$\dot{n} = f_{nPDP} \cdot \frac{p_{in} \cdot V_{rev}}{R \cdot T_{in}}$$

Eq. 1065.642-1

Where:

$$V_{rev} = \frac{a_1}{f_{nPDP}} \cdot \sqrt{\frac{p_{out} - p_{in}}{p_{out}}} + a_0$$

Eq. 1065.642-2

Example:

a_1 = 0.8405 (m^3/s)

f_{nPDP} = 12.58 r/s

p_{out} = 99.950 kPa

p_{in} = 98.575 kPa = 98575 Pa = 98575 kg/(m·s^2)

a_0 = 0.056 (m^3/r)

R = 8.314472 J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)

T_{in} = 323.5 K

$$V_{rev} = \frac{0.8405}{12.58} \cdot \sqrt{\frac{99.950 - 98.575}{99.950}} + 0.056$$

$V_{rev} = 0.06383\ m^3/r$

$$\dot{n} = 12.58 \cdot \frac{98575 \cdot 0.06383}{8.314472 \cdot 323.5}$$

$\dot{n} = 29.428$ mol/s

(b) SSV molar flow rate. Based on the C_d versus $Re^{\#}$ equation you determined according to § 1065.640, calculate SSV molar flow rate, $\dot{n}$ during an emission test as follows:

$$\dot{n} = C_d \cdot C_f \cdot \frac{A_t \cdot p_{in}}{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}$$

Eq. 1065.642-3

Example:

$A_t = 0.01824\ m^2$

$p_{in} = 99.132$ kPa = 99132 Pa = 99132 kg/(m·s^2)

$Z = 1$

$M_{mix} = 28.7805$ g/mol = 0.0287805 kg/mol

$R = 8.314472$ J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)

$T_{in} = 298.15$ K

$Re^{\#} = 7.232 \cdot 10^5$

$\gamma = 1.399$

$\beta = 0.8$

$\Delta p = 2.312$ kPa

Using Eq. 1065.640-7,

$r_{ssv} = 0.997$

Using Eq. 1065.640-6,

$C_f = 0.274$

Comment [CAL3]: Italic

Using Eq. 1065.640-5,

$C_d = 0.990$

Comment [CAL4]: Italic

$$\dot{n} = 0.990 \cdot 0.274 \cdot \frac{0.01824 \cdot 99132}{\sqrt{1 \cdot 0.0287805 \cdot 8.314472 \cdot 298.15}}$$

$\dot{n} = 58.173$ mol/s

(c) CFV molar flow rate. Some CFV flow meters consist of a single venturi and some consist of multiple venturis, where different combinations of venturis are used to meter different flow rates. If you use multiple venturis and you calibrated each venturi independently to determine a separate discharge coefficient, C_d (or calibration coefficient, K_v), for each venturi, calculate the individual molar flow rates through each venturi and sum all their flow rates to determine $\dot{n}$. If you use multiple venturis and you calibrated each combination of venturis, calculate $\dot{n}$ using the sum of the active venturi throat areas as A_t, the square root of the sum of the squares of the active venturi throat diameters as d_t, and the ratio of the venturi throat to inlet diameters as the ratio of

the square root of the sum of the active venturi throat diameters (d_t) to the diameter of the common entrance to all the venturis (D).

(1) To calculate the molar flow rate through one venturi or one combination of venturis, use its respective mean C_d and other constants you determined according to § 1065.640 and calculate its molar flow rate $\dot{n}$ during an emission test, as follows:

$$\dot{n} = C_d \cdot C_f \cdot \frac{A_t \cdot p_{in}}{\sqrt{Z \cdot M_{mix} \cdot R \cdot T_{in}}}$$

Eq. 1065.642-4

Example:

$C_d = 0.985$

$C_f = 0.7219$

$A_t = 0.00456\ m^2$

$p_{in} = 98.836\ kPa = 98836\ Pa = 98836\ kg/(m \cdot s^2)$

$Z = 1$

$M_{mix} = 28.7805\ g/mol = 0.0287805\ kg/mol$

$R = 8.314472\ J/(mol \cdot K) = 8.314472\ (m^2 \cdot kg)/(s^2 \cdot mol \cdot K)$

$T_{in} = 378.15\ K$

$$\dot{n} = 0.985 \cdot 0.7219 \cdot \frac{0.00456 \cdot 98836}{\sqrt{1 \cdot 0.0287805 \cdot 8.314472 \cdot 378.15}}$$

$\dot{n} = 33.690\ mol/s$

(2) To calculate the molar flow rate through one venturi or a combination of venturis, you may use its respective mean, K_v, and other constants you determined according to § 1065.640 and calculate its molar flow rate $\dot{n}$ during an emission test. Note that if you follow the permissible ranges of dilution air dewpoint versus calibration air dewpoint in Table 3 of § 1065.640, you may set $M_{mix\text{-}cal}$ and M_{mix} equal to 1. Calculate $\dot{n}$ as follows:

$$\dot{n} = \frac{K_v \cdot p_{in}}{\sqrt{T_{in}}} \cdot \frac{p_{std}}{T_{std} \cdot R} \cdot \frac{\sqrt{M_{mix\text{-}cal}}}{\sqrt{M_{mix}}}$$

Eq. 1065.642-5

Where:

$$K_v = \frac{V_{stdref} \cdot \sqrt{T_{in\text{-}cal}}}{p_{in\text{-}cal}}$$

Eq. 1065.642-6

V_{stdref} = volume flow rate of the standard at reference conditions of 293.15 K and 101.325 kPa.

$T_{in\text{-}cal}$ = venturi inlet temperature during calibration.

$P_{in\text{-}cal}$ = venturi inlet pressure during calibration.

$M_{mix\text{-}cal}$ = molar mass of gas mixture used during calibration.

M_{mix} = molar mass of gas mixture during the emission test calculated using Equation 1065.640-9.

Example:

$V_{stdref} = 0.4895\ m^3$

$T_{in\text{-}cal} = 302.52\ K$

$P_{in\text{-}cal} = 99.654\ kPa = 99654\ Pa = 99654\ kg/(m \cdot s^2)$

$p_{in} = 98.836\ kPa = 98836\ Pa = 98836\ kg/(m \cdot s^2)$

p_{std} = 101.325 kPa = 101325 Pa = 101325 kg/(m·s^2)
$M_{mix\text{-}cal}$ = 28.9656 g/mol = 0.0289656 kg/mol
M_{mix} = 28.7805 g/mol = 0.0287805 kg/mol
T_{in} = 353.15 K
T_{std} = 293.15 K
R = 8.314472 J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)

$$K_v = \frac{0.4895 \cdot \sqrt{302.52}}{99654} = 0.000074954 \ \mathrm{m^4 \cdot s \cdot K^{0.5}/kg}$$

$$\dot{n} = \frac{0.000074954 \cdot 98936}{\sqrt{353.15}} \cdot \frac{101325}{293.15 \cdot 8.314472} \cdot \frac{\sqrt{0.0289656}}{\sqrt{0.0287805}}$$

$\dot{n}$ = 16.457 mol/s

§ 1065.644 Vacuum-decay leak rate.

This section describes how to calculate the leak rate of a vacuum-decay leak verification, which is described in § 1065.345(e). Use the following equation to calculate the leak rate, $\dot{n}_{leak}$, and compare it to the criterion specified in § 1065.345(e):

$$\dot{n}_{leak} = \frac{V_{vac}}{R} \cdot \frac{\left(\frac{p_2}{T_2} - \frac{p_1}{T_1}\right)}{(t_2 - t_1)}$$

Eq. 1065.644-1

Where:
V_{vac} = geometric volume of the vacuum-side of the sampling system.
R = molar gas constant.
p_2 = vacuum-side absolute pressure at time t_2.
T_2 = vacuum-side absolute temperature at time t_2.
p_1 = vacuum-side absolute pressure at time t_1.
T_1 = vacuum-side absolute temperature at time t_1.
t_2 = time at completion of vacuum-decay leak verification test.
t_1 = time at start of vacuum-decay leak verification test.

Example:
V_{vac} = 2.0000 L = 0.00200 m^3
R = 8.314472 J/(mol·K) = 8.314472 (m^2·kg)/(s^2·mol·K)
p_2 = 50.600 kPa = 50600 Pa = 50600 kg/(m·s^2)
T_2 = 293.15 K
p_1 = 25.300 kPa = 25300 Pa = 25300 kg/(m·s^2)
T_1 = 293.15 K
t_2 = 10:57:35 AM
t_1 = 10:56:25 AM

$$\dot{n}_{leak} = \frac{0.0002}{8.314472} \cdot \frac{\left(\frac{50600}{293.15} - \frac{25300}{293.15}\right)}{(10:57:35 - 10:56:25)}$$

$$\dot{n}_{leak} = \frac{0.00200}{8.314472} \cdot \frac{86.304}{70}$$

$$\dot{n}_{leak} = 0.00030 \text{ mol/s}$$

§ 1065.645 Amount of water in an ideal gas.

This section describes how to determine the amount of water in an ideal gas, which you need for various performance verifications and emission calculations. Use the equation for the vapor pressure of water in paragraph (a) of this section or another appropriate equation and, depending on whether you measure dewpoint or relative humidity, perform one of the calculations in paragraph (b) or (c) of this section. Paragraph (d) of this section provides an equation for determining dewpoint from relative humidity and dry bulb temperature measurements. The equations for the vapor pressure of water as presented in this section are derived from equations in "Saturation Pressure of Water on the New Kelvin Temperature Scale" (Goff, J.A., Transactions American Society of Heating and Air-Conditioning Engineers, Vol. 63, No. 1607, pages 347 – 354). Note that the equations were originally published to derive vapor pressure in units of atmospheres and have been modified to derive results in units of kPa by converting the last term in each equation.

(a) Vapor pressure of water. Calculate the vapor pressure of water for a given saturation temperature condition, T_{sat}, as follows, or use good engineering judgment to use a different relationship of the vapor pressure of water to a given saturation temperature condition:

(1) For humidity measurements made at ambient temperatures from (0 to 100) °C, or for humidity measurements made over super-cooled water at ambient temperatures from (–50 to 0) °C, use the following equation:

$$\log_{10}(p_{H2O}) = 10.79574 \cdot \left(1 - \frac{273.16}{T_{sat}}\right) - 5.02800 \cdot \log_{10}\left(\frac{T_{sat}}{273.16}\right) + 1.50475 \cdot 10^{-4} \cdot \left(1 - 10^{-8.2969 \cdot \left(\frac{T_{sat}}{273.16} - 1\right)}\right)$$

$$+0.42873 \cdot 10^{-3} \cdot \left(10^{4.76955 \cdot \left(1 - \frac{273.16}{T_{sat}}\right)} - 1\right) - 0.2138602$$

Eq. 1065.645-1

Where:

p_{H2O} = vapor pressure of water at saturation temperature condition, kPa.

T_{sat} = saturation temperature of water at measured conditions, K.

Example:

T_{sat} = 9.5 °C = 282.65 K

$$\log_{10}(p_{H2O}) = 10.79574 \cdot \left(1 - \frac{273.16}{282.65}\right) - 5.02800 \cdot \log_{10}\left(\frac{282.65}{273.16}\right) + 1.50475 \cdot 10^{-4} \cdot \left(1 - 10^{-8.2969 \cdot \left(\frac{282.65}{273.16} - 1\right)}\right)$$

$$+0.42873 \cdot 10^{-3} \cdot \left(10^{4.76955 \cdot \left(1 - \frac{273.16}{282.65}\right)} - 1\right) - 0.2138602$$

$\log_{10}(p_{H2O})$ = 0.074297

$p_{H2O} = 10^{0.074297}$ = 1.186581 kPa

(2) For humidity measurements over ice at ambient temperatures from (–100 to 0) °C, use the following equation:

$$\log_{10}(p_{H2O}) = -9.096853 \cdot \left(\frac{273.16}{T_{sat}} - 1\right) - 3.566506 \cdot \log_{10}\left(\frac{273.16}{T_{sat}}\right)$$
$$+0.876812 \cdot \left(1 - \frac{T_{sat}}{273.16}\right) - 0.2138602$$

Eq. 1065.645-2

Example:
T_{ice} = –15.4 °C = 257.75 K

$$\log_{10}(p_{H2O}) = -9.096853 \cdot \left(\frac{273.16}{257.75} - 1\right) - 3.566506 \cdot \log_{10}\left(\frac{273.16}{257.75}\right)$$
$$+0.876812 \cdot \left(1 - \frac{257.75}{273.16}\right) - 0.2138602$$

$\log_{10}(p_{H2O})$ = –0.798207
$p_{H2O} = 10^{-0.79821}$ = 0.159145 kPa

(b) Dewpoint. If you measure humidity as a dewpoint, determine the amount of water in an ideal gas, x_{H2O}, as follows:

$$x_{H2O} = \frac{p_{H2O}}{p_{abs}}$$

Eq. 1065.645-3

Where:
x_{H2O} = amount of water in an ideal gas.
p_{H2O} = water vapor pressure at the measured dewpoint, $T_{sat} = T_{dew}$.
p_{abs} = wet static absolute pressure at the location of your dewpoint measurement.

Example:
p_{abs} = 99.980 kPa
$T_{sat} = T_{dew}$ = 9.5 °C
Using Eq. 1065.645-1,
p_{H2O} = 1.186581 kPa
x_{H2O} = 1.186581 / 99.980
x_{H2O} = 0.011868 mol/mol

(c) Relative humidity. If you measure humidity as a relative humidity, *RH* %, determine the amount of water in an ideal gas, x_{H2O}, as follows:

$$x_{H2O} = \frac{RH\,\% \cdot p_{H2O}}{p_{abs}}$$

Eq. 1065.645-4

Where:

x_{H2O} = amount of water in an ideal gas.
RH % = relative humidity.
p_{H2O} = water vapor pressure at 100 % relative humidity at the location of your relative humidity measurement, $T_{sat} = T_{amb}$.
p_{abs} = wet static absolute pressure at the location of your relative humidity measurement.

Example:
RH % = 50.77 %
p_{abs} = 99.980 kPa
$T_{sat} = T_{amb}$ = 20 °C
Using Eq. 1065.645-1,
p_{H2O} = 2.3371 kPa
x_{H2O} = (50.77 %· 2.3371) / 99.980
x_{H2O} = 0.011868 mol/mol

(d) Dewpoint determination from relative humidity and dry bulb temperature. This paragraph (d) describes how to calculate dewpoint temperature from relative humidity, RH %. This is based on "ITS-90 Formulations for Vapor Pressure, Frostpoint Temperature, Dewpoint Temperature, and Enhancement Factors in the Range –100 to +100 °C" (Hardy, B., The Proceedings of the Third International Symposium on Humidity & Moisture, Teddington, London, England, April 1998). Calculate p_{H20sat} as described in paragraph (a) of this section based on setting T_{sat} equal to T_{amb}. Calculate $p_{H20scaled}$ by multiplying p_{H20sat} by RH %. Calculate the dewpoint, T_{dew}, from p_{H20} using the following equation:

$$T_{dew} = \frac{2.0798233 \cdot 10^{2} - 2.0156028 \cdot 10^{1} \cdot \ln\left(p_{H2O}\right) + 4.6778925 \cdot 10^{-1} \cdot \ln\left(p_{H2O}\right)^{2} - 9.2288067 \cdot 10^{-6} \cdot \ln\left(p_{H2O}\right)^{3}}{1 - 1.3319669 \cdot 10^{-1} \cdot \ln\left(p_{H2O}\right) + 5.6577518 \cdot 10^{-3} \cdot \ln\left(p_{H2O}\right)^{2} - 7.5172865 \cdot 10^{-5} \cdot \ln\left(p_{H2O}\right)^{3}}$$

Eq. 1065.645-5

Where:
$\ln(p_{H2O})$ = the natural log of $p_{H2Oscaled}$, which is the water vapor pressure scaled to the relative humidity at the location of the relative humidity measurement, $T_{sat} = T_{amb}$.

Example:
RH % = 39.61 %
$T_{sat} = T_{amb}$ = 20.00 °C = 293.15K
Using Eq. 1065.645-1,
p_{H2Osat} = 2.3371 kPa
$p_{H2Oscaled}$ = (39.61 %·2.3371) = 0.925717 kPa = 925.717 Pa

$$T_{dew} = \frac{2.0798233 \cdot 10^{2} - 2.0156028 \cdot 10^{1} \cdot \ln\left(925.717\right) + 4.6778925 \cdot 10^{-1} \cdot \ln\left(925.717\right)^{2} - 9.2288067 \cdot 10^{-6} \cdot \ln\left(925.717\right)^{3}}{1 - 1.3319669 \cdot 10^{-1} \cdot \ln\left(925.717\right) + 5.6577518 \cdot 10^{-3} \cdot \ln\left(925.717\right)^{2} - 7.5172865 \cdot 10^{-5} \cdot \ln\left(925.717\right)^{3}}$$

T_{dew} = 279.00 K = 5.85 °C

§ 1065.650 Emission calculations.

(a) General. Calculate brake-specific emissions over each applicable duty cycle or test interval. For test intervals with zero work (or power), calculate the emission mass (or mass rate), but do not calculate brake-specific emissions. For duty cycles with multiple test intervals, refer to the standard-setting part for calculations you need to determine a composite result, such as a

calculation that weights and sums the results of individual test intervals in a duty cycle. If the standard-setting part does not include those calculations, use the equations in paragraph (g) of this section. This section is written based on rectangular integration, where each indexed value (i.e., "$_i$") represents (or approximates) the mean value of the parameter for its respective time interval, delta-t. You may also integrate continuous signals using trapezoidal integration consistent with good engineering judgment.

(b) Brake-specific emissions over a test interval. We specify three alternative ways to calculate brake-specific emissions over a test interval, as follows:

(1) For any testing, you may calculate the total mass of emissions, as described in paragraph (c) of this section, and divide it by the total work generated over the test interval, as described in paragraph (d) of this section, using the following equation:

$$e = \frac{m}{W}$$

Eq. 1065.650-1

Example:

$m_{NOx} = 64.975$ g

$W = 25.783$ kW·hr

$e_{NOx} = 64.975/25.783$

$e_{NOx} = 2.520$ g/(kW·hr)

(2) For discrete-mode steady-state testing, you may calculate the brake-specific emissions over a test interval using the ratio of emission mass rate to power, as described in paragraph (e) of this section, using the following equation:

$$e = \frac{\overline{m}}{\overline{P}}$$

Eq. 1065.650-2

(3) For field testing, you may calculate the ratio of total mass to total work, where these individual values are determined as described in paragraph (f) of this section. You may also use this approach for laboratory testing, consistent with good engineering judgment. Good engineering judgment dictates that this method not be used if there are any work flow paths described in § 1065.210 that cross the system boundary, other than the primary output shaft (crankshaft). This is a special case in which you use a signal linearly proportional to raw exhaust molar flow rate to determine a value proportional to total emissions. You then use the same linearly proportional signal to determine total work using a chemical balance of fuel, intake air, and exhaust as described in § 1065.655, plus information about your engine's brake-specific fuel consumption. Under this method, flow meters need not meet accuracy specifications, but they must meet the applicable linearity and repeatability specifications in subpart D or subpart J of this part. The result is a brake-specific emission value calculated as follows:

$$e = \frac{\tilde{m}}{\tilde{W}}$$

Eq. 1065.650-3

Example:

$\tilde{m} = 805.5$ g

$\tilde{W} = 52.102$ kW·hr

$e_{CO} = 805.5/52.102$

$e_{CO} = 2.520$ g/(kW·hr)

(c) Total mass of emissions over a test interval. To calculate the total mass of an emission, multiply a concentration by its respective flow. For all systems, make preliminary calculations as described in paragraph (c)(1) of this section to correct concentrations. Next, use the method in paragraphs (c)(2) through (4) of this section that is appropriate for your system. Finally, if necessary, calculate the mass of NMHC as described in paragraph (c)(5) of this section for all systems. Calculate the total mass of emissions as follows:

(1) Concentration corrections. Perform the following sequence of preliminary calculations on recorded concentrations:

(i) Correct all gaseous emission analyzer concentration readings, including continuous readings, sample bag readings, and dilution air background readings, for drift as described in § 1065.672. Note that you must omit this step where brake-specific emissions are calculated without the drift correction for performing the drift validation according to § 1065.550(b). When applying the initial THC and CH_4 contamination readings according to § 1065.520(f), use the same values for both sets of calculations. You may also use as-measured values in the initial set of calculations and corrected values in the drift-corrected set of calculations as described in § 1065.520(f)(7).

(ii) Correct all THC and CH_4 concentrations for initial contamination as described in § 1065.660(a), including continuous readings, sample bags readings, and dilution air background readings.

(iii) Correct all concentrations measured on a "dry" basis to a "wet" basis, including dilution air background concentrations, as described in § 1065.659.

(iv) Calculate all NMHC and CH_4 concentrations, including dilution air background concentrations, as described in § 1065.660.

(v) For emission testing with an oxygenated fuel, calculate any HC concentrations, including dilution air background concentrations, as described in § 1065.665. See subpart I of this part for testing with oxygenated fuels.

(vi) Correct all the NO_x concentrations, including dilution air background concentrations, for intake-air humidity as described in § 1065.670.

Comment [CAL5]: Intake-air humidity correction should only be applied to the final mass value, post background correction. This currently accounts for about a 5% NOx error, but the error will grow as emission levels decrease. Note most labs are controlling the correction factor very close to 1. The error will increase as you move away from 1.

Is this really needed? A calculation check says no.

(2) Continuous sampling. For continuous sampling, you must frequently record a continuously updated concentration signal. You may measure this concentration from a changing flow rate or a constant flow rate (including discrete-mode steady-state testing), as follows:

(i) Varying flow rate. If you continuously sample from a changing exhaust flow rate, time align and then multiply concentration measurements by the flow rate from which you extracted it. Use good engineering judgment to time-align flow and concentration data to match transformation time, t_{50}, to within ±1 s. We consider the following to be examples of changing flows that require a continuous multiplication of concentration times molar flow rate: raw exhaust, exhaust diluted with a constant flow rate of dilution air, and CVS dilution with a CVS flow meter that does not have an upstream heat exchanger or electronic flow control. This multiplication results in the flow rate of the emission itself. Integrate the emission flow rate over a test interval to determine the total emission. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass, M. The result is the mass of the emission, m. Calculate m for continuous sampling with variable flow using the following equations:

$$m = M \cdot \sum_{i=1}^{N} x_i \cdot \dot{n}_i \cdot \Delta t$$

Eq. 1065.650-4

Where:
$\Delta t = 1/f_{record}$ Eq. 1065.650-5

Example:
$M_{NMHC} = 13.875389$ g/mol
$N = 1200$
$x_{NMHC1} = 84.5$ µmol/mol $= 84.5 \cdot 10^{-6}$ mol/mol
$x_{NMHC2} = 86.0$ µmol/mol $= 86.0 \cdot 10^{-6}$ mol/mol
$\dot{n}_{exh1} = 2.876$ mol/s
$\dot{n}_{exh2} = 2.224$ mol/s
$f_{record} = 1$ Hz
Using Eq. 1065.650-5,
$\Delta t = 1/1 = 1$ s
$m_{NMHC} = 13.875389 \cdot (84.5 \cdot 10^{-6} \cdot 2.876 + 86.0 \cdot 10^{-6} \cdot 2.224 + \ldots + x_{NMHC1200} \cdot \dot{n}_{exh}) \cdot 1$
$m_{NMHC} = 25.23$ g

(ii) Constant flow rate. If you continuously sample from a constant exhaust flow rate, use the same emission calculations described in paragraph (c)(2)(i) of this section or calculate the mean or flow-weighted concentration recorded over the test interval and treat the mean as a batch sample, as described in paragraph (c)(3)(ii) of this section. We consider the following to be examples of constant exhaust flows: CVS diluted exhaust with a CVS flow meter that has either an upstream heat exchanger, electronic flow control, or both.

(3) Batch sampling. For batch sampling, the concentration is a single value from a proportionally extracted batch sample (such as a bag, filter, impinger, or cartridge). In this case, multiply the mean concentration of the batch sample by the total flow from which the sample was extracted. You may calculate total flow by integrating a changing flow rate or by determining the mean of a constant flow rate, as follows:

(i) Varying flow rate. If you collect a batch sample from a changing exhaust flow rate, extract a sample proportional to the changing exhaust flow rate. We consider the following to be examples of changing flows that require proportional sampling: raw exhaust, exhaust diluted with a constant flow rate of dilution air, and CVS dilution with a CVS flow meter that does not have an upstream heat exchanger or electronic flow control. Integrate the flow rate over a test interval to determine the total flow from which you extracted the proportional sample. Multiply the mean concentration of the batch sample by the total flow from which the sample was extracted. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass, M. The result is the mass of the emission, m. In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample, $\overline{M}_{PM}$, simply multiply it by the total flow. The result is the total mass of PM, m_{PM}. Calculate m for batch sampling with variable flow using the following equation:

$$m = M \cdot \overline{x} \cdot \sum_{i=1}^{N} \dot{n}_i \cdot \Delta t$$

Eq. 1065.650-6

Example:
$M_{NOx} = 46.0055$ g/mol

$N = 9000$
$\bar{x}_{NOx} = 85.6$ μmol/mol $= 85.6 \cdot 10^{-6}$ mol/mol
$\dot{n}_{dexh1} = 25.534$ mol/s
$\dot{n}_{dexh2} = 26.950$ mol/s
$f_{record} = 5$ Hz
Using Eq. 1065.650-5,
$\Delta t = 1/5 = 0.2$
$m_{NOx} = 46.0055 \cdot 85.6 \cdot 10^{-6} \cdot (25.534 + 26.950 + ... + \dot{n}_{exh9000}) \cdot 0.2$
$m_{NOx} = 4.201$ g
(ii) Constant flow rate. If you batch sample from a constant exhaust flow rate, extract a sample at a proportional or constant flow rate. We consider the following to be examples of constant exhaust flows: CVS diluted exhaust with a CVS flow meter that has either an upstream heat exchanger, electronic flow control, or both. Determine the mean molar flow rate from which you extracted the constant flow rate sample. Multiply the mean concentration of the batch sample by the mean molar flow rate of the exhaust from which the sample was extracted, and multiply the result by the time of the test interval. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass, M. The result is the mass of the emission, m. In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample, $\bar{M}_{PM}$, simply multiply it by the total flow, and the result is the total mass of PM, m_{PM}. Calculate m for sampling with constant flow using the following equations:

$$m = M \cdot \bar{x} \cdot \bar{\dot{n}} \cdot \Delta t$$

Eq. 1065.650-7

and for PM or any other analysis of a batch sample that yields a mass per mole of sample,

$$\bar{M} = M \cdot \bar{x}$$

Eq. 1065.650-8

Example:
$\bar{M}_{PM} = 144.0$ μg/mol $= 144.0 \cdot 10^{-6}$ g/mol
$\bar{\dot{n}}_{dexh} = 57.692$ mol/s
$\Delta t = 1200$ s
$m_{PM} = 144.0 \cdot 10^{-6} \cdot 57.692 \cdot 1200$
$m_{PM} = 9.9692$ g
(4) Additional provisions for diluted exhaust sampling; continuous or batch. The following additional provisions apply for sampling emissions from diluted exhaust:
(i) For sampling with a constant dilution ratio, DR, of diluted exhaust versus exhaust flow (e.g., secondary dilution for PM sampling), calculate m using the following equation:

$$m_{PM} = m_{PMdil} \cdot DR$$

Eq. 1065.650-9

Example:
$m_{PMdil} = 6.853$ g
$DR = 6:1$
$m_{PM} = 6.853 \cdot 6$
$m_{PM} = 41.118$ g
(ii) For continuous or batch sampling, you may measure background emissions in the dilution

air. You may then subtract the measured background emissions, as described in § 1065.667.
(5) Mass of NMHC. Compare the corrected mass of NMHC to corrected mass of THC. If the corrected mass of NMHC is greater than 0.98 times the corrected mass of THC, take the corrected mass of NMHC to be 0.98 times the corrected mass of THC. If you omit the NMHC calculations as described in § 1065.660(b)(1), take the corrected mass of NMHC to be 0.98 times the corrected mass of THC.
(d) Total work over a test interval. To calculate the total work from the engine over a test interval, add the total work from all the work paths described in § 1065.210 that cross the system boundary including electrical energy/work, mechanical shaft work, and fluid pumping work. For all work paths, except the engine's primary output shaft (crankshaft), the total work for the path over the test interval is the integration of the net work flow rate (power) out of the system boundary. When energy/work flows into the system boundary, this work flow rate signal becomes negative; in this case, include these negative work rate values in the integration to calculate total work from that work path. Some work paths may result in a negative total work. Include negative total work values from any work path in the calculated total work from the engine rather than setting the values to zero. The rest of this paragraph (d) describes how to calculate total work from the engine's primary output shaft over a test interval. Before integrating power on the engine's primary output shaft, adjust the speed and torque data for the time alignment used in § 1065.514(c). Any advance or delay used on the feedback signals for cycle validation must also be used for calculating work. Account for work of accessories according to § 1065.110. Exclude any work during cranking and starting. Exclude work during actual motoring operation (negative feedback torques), unless the engine was connected to one or more energy storage devices. Examples of such energy storage devices include hybrid powertrain batteries and hydraulic accumulators, like the ones illustrated in Figure 1 of § 1065.210. Exclude any work during reference zero-load idle periods (0 % speed or idle speed with 0 N·m reference torque). Note, that there must be two consecutive reference zero load idle points to establish a period where this applies. Include work during idle points with simulated minimum torque such as Curb Idle Transmissions Torque (CITT) for automatic transmissions in "drive". The work calculation method described in paragraphs (b)(1) though (7) of this section meets these requirements using rectangular integration. You may use other logic that gives equivalent results. For example, you may use a trapezoidal integration method as described in paragraph (b)(8) of this section.
(1) Time align the recorded feedback speed and torque values by the amount used in § 1065.514(c).
(2) Calculate shaft power at each point during the test interval by multiplying all the recorded feedback engine speeds by their respective feedback torques.
(3) Adjust (reduce) the shaft power values for accessories according to § 1065.110.
(4) Set all power values during any cranking or starting period to zero. See § 1065.525 for more information about engine cranking.
(5) Set all negative power values to zero, unless the engine was connected to one or more energy storage devices. If the engine was tested with an energy storage device, leave negative power values unaltered.
(6) Set all power values to zero during idle periods with a corresponding reference torque of 0 N·m.
(7) Integrate the resulting values for power over the test interval. Calculate total work as follows:

$$W = \sum_{i=1}^{N} P_i \cdot \Delta t$$

Eq. 1065.650-10

Where:
W = total work from the primary output shaft
P_i = instantaneous power from the primary output shaft over an interval i.
$P_i = f_{ni} \cdot T_i$

Eq. 1065.650-11

Example:
$N = 9000$
$f_{n1} = 1800.2$ r/min
$f_{n2} = 1805.8$ r/min
$T_1 = 177.23$ N·m
$T_2 = 175.00$ N·m
$C_{rev} = 2 \cdot \pi$ rad/r
$C_{t1} = 60$ s/min
$C_p = 1000$ (N·m·rad/s)/kW
$f_{record} = 5$ Hz
$C_{t2} = 3600$ s/hr

$$P_1 = \frac{1800.2 \cdot 177.23 \cdot 2 \cdot 3.14159}{60 \cdot 1000}$$

$P_1 = 33.41$ kW
$P_2 = 33.09$ kW
Using Eq. 1065.650-5,
$\Delta t = 1/5 = 0.2$ s

$$W = \frac{(33.41 + 33.09 + \ldots + P_{9000}) \cdot 0.2}{3600}$$

$W = 16.875$ kW·hr

(8) You may use a trapezoidal integration method instead of the rectangular integration described in this paragraph (d). To do this, you must integrate the fraction of work between points where the torque is positive. You may assume that speed and torque are linear between data points. You may not set negative values to zero before running the integration.

(e) Steady-state mass rate divided by power. To determine steady-state brake-specific emissions for a test interval as described in paragraph (b)(2) of this section, calculate the mean steady-state mass rate of the emission, $\overline{\dot{m}}$, and the mean steady-state power, $\overline{P}$, as follows:

(1) To calculate $\overline{\dot{m}}$, multiply its mean concentration, $\overline{x}$, by its corresponding mean molar flow rate, $\overline{\dot{n}}$. If the result is a molar flow rate, convert this quantity to a mass rate by multiplying it by its molar mass, M. The result is the mean mass rate of the emission, $\overline{\dot{m}}$. In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample, $\overline{M}_{PM}$, simply multiply it by the mean molar flow rate, $\overline{\dot{n}}$. The result is the mass rate of PM,

$\dot{m}_{PM}$. Calculate $\overline{\dot{m}}$ using the following equation:

$$\overline{\dot{m}} = M \cdot \overline{x} \cdot \overline{\dot{n}}$$

Eq. 1065.650-12

(2) To calculate an engine's mean steady-state total power, $\overline{P}$, add the mean steady-state power from all the work paths described in § 1065.210 that cross the system boundary including electrical power, mechanical shaft power, and fluid pumping power. For all work paths, except the engine's primary output shaft (crankshaft), the mean steady-state power over the test interval is the integration of the net work flow rate (power) out of the system boundary divided by the period of the test interval. When power flows into the system boundary, the power/work flow rate signal becomes negative; in this case, include these negative power/work rate values in the integration to calculate the mean power from that work path. Some work paths may result in a negative mean power. Include negative mean power values from any work path in the mean total power from the engine rather than setting these values to zero. The rest of this paragraph (e)(2) describes how to calculate the mean power from the engine's primary output shaft. Calculate $\overline{P}$ using Equation 1065.650-13, noting that $\overline{P}$, $\overline{f}_n$ and $\overline{T}$ refer to mean power, mean rotational shaft frequency, and mean torque from the primary output shaft. Account for the power of simulated accessories according to § 1065.110 (reducing the mean primary output shaft power or torque by the accessory power or torque). Set the power to zero during actual motoring operation (negative feedback torques), unless the engine was connected to one or more energy storage devices. Examples of such energy storage devices include hybrid powertrain batteries and hydraulic accumulators, like the ones illustrated in Figure 1 of § 1065.210. Set the power to zero for modes with a zero reference load (0 N·m reference torque or 0 kW reference power). Include power during idle modes with simulated minimum torque or power.

$$\overline{P} = \overline{f}_n \cdot \overline{T}$$

Eq. 1065.650-13

(3) Divide emission mass rate by power to calculate a brake-specific emission result as described in paragraph (b)(2) of this section.

(4) The following example shows how to calculate mass of emissions using mean mass rate and mean power:

M_{CO} = 28.0101 g/mol

$\overline{x}_{CO}$ = 12.00 mmol/mol = 0.01200 mol/mol

$\overline{\dot{n}}$ = 1.530 mol/s

$\overline{f}_n$ = 3584.5 r/min = 375.37 rad/s

$\overline{T}$ = 121.50 N·m

$\overline{\dot{m}} = 28.0101 \cdot 0.01200 \cdot 1.530$

$\overline{\dot{m}}$ = 0.514 g/s = 1850.4 g/hr

$\overline{P} = 121.5 \cdot 375.37$

$\overline{P}$ = 45607 W

$\overline{P}$ = 45.607 kW

e_{CO} = 1850.4/45.61

e_{CO} = 40.57 g/(kW·hr)

(f) Ratio of total mass of emissions to total work. To determine brake-specific emissions for a

test interval as described in paragraph (b)(3) of this section, calculate a value proportional to the total mass of each emission. Divide each proportional value by a value that is similarly proportional to total work.

(1) Total mass. To determine a value proportional to the total mass of an emission, determine total mass as described in paragraph (c) of this section, except substitute for the molar flow rate, $\dot{n}$, or the total flow, n, with a signal that is linearly proportional to molar flow rate, $\tilde{\dot{n}}$, or linearly proportional to total flow, $\tilde{n}$, as follows:

$$\tilde{\dot{m}}_{\text{fueli}} = \frac{1}{w_{\text{fuel}}} \cdot \frac{M_C \cdot \tilde{\dot{n}}_i \cdot x_{\text{Ccombdryi}}}{1 + x_{\text{H2Oexhdryi}}}$$

Eq. 1065.650-14

(2) Total work. To calculate a value proportional to total work over a test interval, integrate a value that is proportional to power. Use information about the brake-specific fuel consumption of your engine, e_{fuel}, to convert a signal proportional to fuel flow rate to a signal proportional to power. To determine a signal proportional to fuel flow rate, divide a signal that is proportional to the mass rate of carbon products by the fraction of carbon in your fuel, w_C. You may use a measured w_C or you may use default values for a given fuel as described in § 1065.655(d). Calculate the mass rate of carbon from the amount of carbon and water in the exhaust, which you determine with a chemical balance of fuel, intake air, and exhaust as described in § 1065.655. In the chemical balance, you must use concentrations from the flow that generated the signal proportional to molar flow rate, $\tilde{\dot{n}}$, in paragraph (e)(1) of this section. Calculate a value proportional to total work as follows:

Deleted: w_c

Deleted: w_c

$$W = \sum_{i=1}^{N} \tilde{P}_i \cdot \Delta t$$

Eq. 1065.650-15

Where:

$$\tilde{P}_i = \frac{\tilde{\dot{m}}_{\text{fueli}}}{e_{\text{fuel}}}$$

Eq. 1065.650-16

(3) Brake-specific emissions. Divide the value proportional to total mass by the value proportional to total work to determine brake-specific emissions, as described in paragraph (b)(3) of this section.

(4) Example. The following example shows how to calculate mass of emissions using proportional values:

$N = 3000$

$f_{\text{record}} = 5$ Hz

$e_{\text{fuel}} = 285$ g/(kW·hr)

$w_{\text{fuel}} = 0.869$ g/g

$M_C = 12.0107$ g/mol

Deleted: M_c

$\tilde{\dot{n}}_1 = 3.922$ mol/s = 14119.2 mol/hr

$x_{\text{Ccombdry1}} = 91.634$ mmol/mol = 0.091634 mol/mol

$x_{\text{H2Oexh1}} = 27.21$ mmol/mol = 0.02721 mol/mol

Using Eq. 1065.650-5,

$\Delta t = 0.2$ s

$$\tilde{W} = \frac{12.0107\left(\frac{3.922 \cdot 0.091634}{1+0.02721} + \frac{\tilde{n}_2 \cdot x_{\text{Ccombdry2}}}{1+x_{\text{H2Oexh2}}} + \ldots + \frac{\tilde{n}_{3000} \cdot x_{\text{Ccombdry3000}}}{1+x_{\text{H2Oexh3000}}}\right) \cdot 0.2}{285 \cdot 0.869}$$

$\tilde{W}$ = 5.09 (kW·hr)

(g) Brake-specific emissions over a duty cycle with multiple test intervals. The standard-setting part may specify a duty cycle with multiple test intervals, such as with discrete-mode steady-state testing. Unless we specify otherwise, calculate composite brake-specific emissions over the duty cycle as described in this paragraph (g). If a measured mass (or mass rate) is negative, set it to zero for calculating composite brake-specific emissions, but leave it unchanged for drift validation. In the case of calculating composite brake-specific emissions relative to a combined emission standard (such as a NO_x + NMHC standard), change any negative mass (or mass rate) values to zero for a particular pollutant before combining the values for the different pollutants.

(1) Use the following equation to calculate composite brake-specific emissions for duty cycles with multiple test intervals all with prescribed durations, such as cold-start and hot-start transient cycles:

$$e_{\text{composite}} = \frac{\sum_{i=1}^{N} WF_i \cdot m_i}{\sum_{i=1}^{N} WF_i \cdot W_i}$$

Eq. 1065.650-17

Where

i = test interval number.

N = number of test intervals.

WF = weighting factor for the test interval as defined in the standard-setting part.

m = mass of emissions over the test interval as determined in paragraph (c) of this section.

W = total work from the engine over the test interval as determined in paragraph (d) of this section.

Example:

$N = 2$

$WF_1 = 0.1428$

$WF_2 = 0.8572$

$m_1 = 70.125$ g

$m_2 = 64.975$ g

$W_1 = 25.783$ kW·hr

$W_2 = 25.783$ kW·hr

$$e_{\text{NO}_x\text{composite}} = \frac{(0.1428 \cdot 70.125) + (0.8572 \cdot 64.975)}{(0.1428 \cdot 25.783) + (0.8572 \cdot 25.783)}$$

$e_{\text{NOxcomposite}}$ = 2.548 g/kW·hr

(2) Calculate composite brake-specific emissions for duty cycles with multiple test intervals that allow use of varying duration, such as discrete-mode steady-state duty cycles, as follows:

(i) Use the following equation if you calculate brake-specific emissions over test intervals based on total mass and total work as described in paragraph (b)(1) of this section:

$$e_{\text{composite}} = \frac{\sum_{i=1}^{N} WF_i \cdot \frac{m_i}{t_i}}{\sum_{i=1}^{N} WF_i \cdot \frac{W_i}{t_i}}$$

Eq. 1065.650-18

Where
i = test interval number.
N = number of test intervals.
WF = weighting factor for the test interval as defined in the standard-setting part.
m = mass of emissions over the test interval as determined in paragraph (c) of this section.
W = total work from the engine over the test interval as determined in paragraph (d) of this section.
t = duration of the test interval.

Example:
$N = 2$
$WF_1 = 0.85$
$WF_2 = 0.15$
$m_1 = 1.3753$ g
$m_2 = 0.4135$ g
$t_1 = 120$ s
$t_2 = 200$ s
$W_1 = 2.8375$ kW·hr
$W_2 = 0.0$ kW·hr

$$e_{\text{NO}_x\text{composite}} = \frac{\left(0.85 \cdot \frac{1.3753}{120}\right) + \left(0.15 \cdot \frac{0.4135}{200}\right)}{\left(0.85 \cdot \frac{2.8375}{120}\right) + \left(0.15 \cdot \frac{0.0}{200}\right)}$$

$e_{\text{NOxcomposite}} = 0.5001$ g/kW·hr

(ii) Use the following equation if you calculate brake-specific emissions over test intervals based on the ratio of mass rate to power as described in paragraph (b)(2) of this section:

$$e_{\text{composite}} = \frac{\sum_{i=1}^{N} WF_i \cdot \overline{\dot{m}}_i}{\sum_{i=1}^{N} WF_i \cdot \overline{P}_i}$$

Eq. 1065.650-19

Where
i = test interval number.
N = number of test intervals.
WF = weighting factor for the test interval as defined in the standard-setting part.
$\overline{\dot{m}}$ = mean steady-state mass rate of emissions over the test interval as determined in paragraph (e) of this section.

$\overline{P}$ is the mean steady-state power over the test interval as described in paragraph (e) of this section.

Example:
$N = 2$
$WF_1 = 0.85$
$WF_2 = 0.15$
$\overline{m}_1 = 2.25842$ g/hr
$\overline{m}_2 = 0.063443$ g/hr
$\overline{P}_1 = 4.5383$ kW
$\overline{P}_2 = 0.0$ kW

$$e_{NO_x composite} = \frac{(0.85 \cdot 2.25842) + (0.15 \cdot 0.063443)}{(0.85 \cdot 4.5383) + (0.15 \cdot 0.0)}$$

$e_{NOxcomposite} = 0.5001$ g/kW·hr

(h) Rounding. Round the final brake-specific emission values to be compared to the applicable standard only after all calculations are complete (including any drift correction, applicable deterioration factors, adjustment factors, and allowances) and the result is in g/(kW·hr) or units equivalent to the units of the standard, such as g/(hp·hr). See the definition of "Round" in § 1065.1001.

§ 1065.655 Chemical balances of fuel, intake air, and exhaust.

(a) General. Chemical balances of fuel, intake air, and exhaust may be used to calculate flows, the amount of water in their flows, and the wet concentration of constituents in their flows. With one flow rate of either fuel, intake air, or exhaust, you may use chemical balances to determine the flows of the other two. For example, you may use chemical balances along with either intake air or fuel flow to determine raw exhaust flow.

(b) Procedures that require chemical balances. We require chemical balances when you determine the following:

(1) A value proportional to total work, $\tilde{W}$ when you choose to determine brake-specific emissions as described in § 1065.650(f).

(2) The amount of water in a raw or diluted exhaust flow, x_{H2Oexh}, when you do not measure the amount of water to correct for the amount of water removed by a sampling system. Correct for removed water according to § 1065.659.

(3) The calculated total dilution air flow when you do not measure dilution air flow to correct for background emissions as described in § 1065.667(c) and (d).

(c) Chemical balance procedure. The calculations for a chemical balance involve a system of equations that require iteration. We recommend using a computer to solve this system of equations. You must guess the initial values of up to three quantities: the amount of water in the measured flow, x_{H2Oexh}, fraction of dilution air in diluted exhaust, $x_{dil/exh}$, and the amount of products on a C_1 basis per dry mole of dry measured flow, $x_{Ccombdry}$. You may use time-weighted mean values of combustion air humidity and dilution air humidity in the chemical balance; as long as your combustion air and dilution air humidities remain within tolerances of ±0.0025 mol/mol of their respective mean values over the test interval. For each emission concentration, x, and amount of water, x_{H2Oexh}, you must determine their completely dry concentrations, x_{dry} and

$x_{H2Oexhdry}$. You must also use your fuel's atomic hydrogen-to-carbon ratio, α, oxygen-to-carbon ratio, β, sulfur-to-carbon ratio, γ, and nitrogen-to-carbon ratio, δ. You may calculate α, β, γ, and δ based on measured fuel composition as described in paragraph (d)(1) or (d)(2) of this section, or you may use default values for a given fuel as described in paragraph (d)(3) of this section. Use the following steps to complete a chemical balance:

(1) Convert your measured concentrations such as, $x_{CO2meas}$, x_{NOmeas}, and x_{H2Oint}, to dry concentrations by dividing them by one minus the amount of water present during their respective measurements; for example: $x_{H2OxCO2meas}$, $x_{H2OxNOmeas}$, and x_{H2Oint}. If the amount of water present during a "wet" measurement is the same as the unknown amount of water in the exhaust flow, x_{H2Oexh}, iteratively solve for that value in the system of equations. If you measure only total NO_x and not NO and NO_2 separately, use good engineering judgment to estimate a split in your total NO_x concentration between NO and NO_2 for the chemical balances. For example, if you measure emissions from a stoichiometric spark-ignition engine, you may assume all NO_x is NO. For a compression-ignition engine, you may assume that your molar concentration of NO_x, x_{NOx}, is 75 % NO and 25 % NO_2. For NO_2 storage aftertreatment systems, you may assume x_{NOx} is 25 % NO and 75 % NO_2. Note that for calculating the mass of NO_x emissions, you must use the molar mass of NO_2 for the effective molar mass of all NO_x species, regardless of the actual NO_2 fraction of NO_x.

(2) Enter the equations in paragraph (c)(4) of this section into a computer program to iteratively solve for x_{H2Oexh}, $x_{Ccombdry}$, and $x_{dil/exh}$. Use good engineering judgment to guess initial values for x_{H2Oexh}, $x_{Ccombdry}$, and $x_{dil/exh}$. We recommend guessing an initial amount of water that is about twice the amount of water in your intake or dilution air. We recommend guessing an initial value of $x_{Ccombdry}$ as the sum of your measured CO_2, CO, and THC values. We also recommend guessing an initial $x_{dil/exh}$ between 0.75 and 0.95, such as 0.8. Iterate values in the system of equations until the most recently updated guesses are all within ±1 % of their respective most recently calculated values.

(3) Use the following symbols and subscripts in the equations for this paragraph (c):

$x_{dil/exh}$ = amount of dilution gas or excess air per mole of exhaust.

x_{H2Oexh} = amount of H_2O in exhaust per mole of exhaust.

$x_{Ccombdry}$ = amount of carbon from fuel in the exhaust per mole of dry exhaust.

x_{H2dry} = amount of H_2 in exhaust per amount of dry exhaust.

K_{H2Ogas} = water-gas reaction equilibrium coefficient. You may use 3.5 or calculate your own value using good engineering judgment.

$x_{H2Oexhdry}$ = amount of H_2O in exhaust per dry mole of dry exhaust.

$x_{prod/intdry}$ = amount of dry stoichiometric products per dry mole of intake air.

$x_{dil/exhdry}$ = amount of dilution gas and/or excess air per mole of dry exhaust.

$x_{int/exhdry}$ = amount of intake air required to produce actual combustion products per mole of dry (raw or diluted) exhaust.

$x_{raw/exhdry}$ = amount of undiluted exhaust, without excess air, per mole of dry (raw or diluted) exhaust.

x_{O2int} = amount of intake air O_2 per mole of intake air.

$x_{CO2intdry}$ = amount of intake air CO_2 per mole of dry intake air. You may use $x_{CO2intdry}$ = 375 μmol/mol, but we recommend measuring the actual concentration in the intake air.

$x_{H2Ointdry}$ = amount of intake air H_2O per mole of dry intake air.

x_{CO2int} = amount of intake air CO_2 per mole of intake air.

x_{CO2dil} = amount of dilution gas CO_2 per mole of dilution gas.

$x_{CO2dildry}$ = amount of dilution gas CO_2 per mole of dry dilution gas. If you use air as diluent, you may use $x_{CO2dildry}$ = 375 μmol/mol, but we recommend measuring the actual concentration in the intake air.
$x_{H2Odildry}$ = amount of dilution gas H_2O per mole of dry dilution gas.
x_{H2Odil} = amount of dilution gas H_2O per mole of dilution gas.
$x_{[emission]meas}$ = amount of measured emission in the sample at the respective gas analyzer.
$x_{[emission]dry}$ = amount of emission per dry mole of dry sample.
$x_{H2O[emission]meas}$ = amount of H_2O in sample at emission-detection location. Measure or estimate these values according to § 1065.145(e)(2).
x_{H2Oint} = amount of H_2O in the intake air, based on a humidity measurement of intake air.
α = atomic hydrogen-to-carbon ratio of the mixture of fuel(s) being combusted, weighted by molar consumption.
β = atomic oxygen-to-carbon ratio of the mixture of fuel(s) being combusted, weighted by molar consumption.
γ = atomic sulfur-to-carbon ratio of the mixture of fuel(s) being combusted, weighted by molar consumption.
δ = atomic nitrogen-to-carbon ratio of the mixture of fuel(s) being combusted, weighted by molar consumption.
(4) Use the following equations to iteratively solve for $x_{dil/exh}$, x_{H2Oexh}, and $x_{Ccombdry}$:

$$x_{dil/exh} = 1 - \frac{x_{raw/exhdry}}{1 + x_{H2Oexhdry}}$$

Eq. 1065.655-1

$$x_{H2Oexh} = \frac{x_{H2Oexhdry}}{1 + x_{H2Oexhdry}}$$

Eq. 1065.655-2

$$x_{Ccombdry} = x_{CO2dry} + x_{COdry} + x_{THCdry} - x_{CO2dil} \cdot x_{dil/exhdry} - x_{CO2int} \cdot x_{int/exhdry}$$

Eq. 1065.655-3

$$x_{H2dry} = \frac{x_{COdry} \cdot \left(x_{H2Oexhdry} - x_{H2Odil} \cdot x_{dil/exhdry}\right)}{K_{H2O\text{-}gas} \cdot \left(x_{CO2dry} - x_{CO2dil} \cdot x_{dil/exhdry}\right)}$$

Eq. 1065.655-4

$$x_{H2Oexhdry} = \frac{\alpha}{2}\left(x_{Ccombdry} - x_{THCdry}\right) + x_{H2Odil} \cdot x_{dil/exhdry} + x_{H2Oint} \cdot x_{int/exhdry} - x_{H2dry}$$

Eq. 1065.655-5

$$x_{dil/exhdry} = \frac{x_{dil/exh}}{1 - x_{H2Oexh}}$$

Eq. 1065.655-6

$$x_{int/exhdry} = \frac{1}{2 \cdot x_{O2int}}\left(\left(\frac{\alpha}{2} - \beta + 2 + 2\gamma\right)\left(x_{Ccombdry} - x_{THCdry}\right) - \left(x_{COdry} - x_{NOdry} - 2x_{NO2dry} + x_{H2dry}\right)\right)$$

Eq. 1065.655-7

$$x_{raw/exhdry} = \frac{1}{2}\left(\left(\frac{\alpha}{2} + \beta + \delta\right)\left(x_{Ccombdry} - x_{THCdry}\right) + \left(2x_{THCdry} + x_{COdry} - x_{NO2dry} + x_{H2dry}\right)\right) + x_{int/exhdry}$$

Eq. 1065.655-8

$$x_{O2int} = \frac{0.209820 - x_{CO2intdry}}{1 + x_{H2Ointdry}}$$

Eq. 1065.655-9

$$x_{CO2int} = \frac{x_{CO2intdry}}{1 + x_{H2Ointdry}}$$

Eq. 1065.655-10

$$x_{H2Ointdry} = \frac{x_{H2Oint}}{1 - x_{H2Oint}}$$

Eq. 1065.655-11

$$x_{CO2dil} = \frac{x_{CO2dildry}}{1 + x_{H2Odildry}}$$

Eq. 1065.655-12

$$x_{H2Odildry} = \frac{x_{H2Odil}}{1 - x_{H2Odil}}$$

Eq. 1065.655-13

$$x_{COdry} = \frac{x_{COmeas}}{1 - x_{H2OCOmeas}}$$

Eq. 1065.655-14

$$x_{CO2dry} = \frac{x_{CO2meas}}{1 - x_{H2OCO2meas}}$$

Eq. 1065.655-15

$$x_{NOdry} = \frac{x_{NOmeas}}{1 - x_{H2ONOmeas}}$$

Eq. 1065.655-16

$$x_{NO2dry} = \frac{x_{NO2meas}}{1 - x_{H2ONO2meas}}$$

Eq. 1065.655-17

$$x_{THCdry} = \frac{x_{THCmeas}}{1 - x_{H2OTHCmeas}}$$

Eq. 1065.655-18

(5) The following example is a solution for $x_{dil/exh}$, x_{H2Oexh}, and $x_{Ccombdry}$ using the equations in paragraph (c)(4) of this section:

$$x_{dil/exh} = 1 - \frac{0.184}{1 + \frac{35.37}{1000}} = 0.822\, mol/mol$$

$$x_{H2Oexh} = \frac{35.37}{1 + \frac{35.37}{1000}} = 34.16\, mmol/mol$$

$$x_{Ccombdry} = 0.0252 + \frac{29.3}{1000000} + \frac{47.6}{1000000} - \frac{0.371}{1000} \cdot 0.851 - \frac{0.369}{1000} \cdot 0.172 = 0.0249\, mol/mol$$

$$x_{H2dry} = \frac{29.3 \cdot (0.034 - 0.012 \cdot 0.851)}{3.5 \cdot \left(\frac{25.2}{1000} - \frac{0.371}{1000} \cdot 0.851 \right)} = 8.5\, \mu mol/mol$$

$$x_{H2Oexhdry} = \frac{1.8}{2} \left(0.0249 - \frac{47.6}{1000000} \right) + 0.012 \cdot 0.851 + 0.017 \cdot 0.172 - \frac{8.5}{1000000} = 0.0353\, mol/mol$$

$$x_{dil/exhdry} = \frac{0.822}{1\text{-}0.034} = 0.851\, mol/mol$$

$$x_{int/exhdry} = \frac{1}{2 \cdot 0.206} \left(\begin{array}{l} \left(\frac{1.8}{2} - 0.050 + 2 + 2 \cdot 0.0003 \right) \left(0.0249 - \frac{47.6}{1000000} \right) - \\ \left(\frac{29.3}{1000000} - \frac{50.4}{1000000} - 2 \cdot \frac{12.1}{1000000} + \frac{8.5}{1000000} \right) \end{array} \right) = 0.172\, mol/mol$$

$$x_{raw/exhdry} = \frac{1}{2} \left(\begin{array}{l} \left(\frac{1.8}{2} + 0.050 + 0.0001 \right) \left(0.0249 - \frac{47.6}{1000000} \right) + \\ \left(2 \cdot \frac{47.6}{1000000} + \frac{29.3}{1000000} - \frac{12.1}{1000000} + \frac{8.5}{1000000} \right) \end{array} \right) + 0.172 = 0.184\, mol/mol$$

$$x_{O2int} = \frac{0.209820 - 0.000375}{1 + \frac{17.22}{1000}} = 0.206\, mol/mol$$

$$x_{CO2int} = \frac{0.000375 \cdot 1000}{1 + \frac{17.22}{1000}} = 0.369\, mmol/mol$$

$$x_{H2Ointdry} = \frac{16.93}{1 - \frac{16.93}{1000}} = 17.22\, mmol/mol$$

$$x_{\mathrm{CO2dil}} = \frac{0.375}{1+\frac{12.01}{1000}} = 0.371\,mmol/mol$$

$$x_{\mathrm{H2Odildry}} = \frac{11.87}{1-\frac{11.87}{1000}} = 12.01\,mmol/mol$$

$$x_{\mathrm{COdry}} = \frac{29.0}{1-\frac{8.601}{1000}} = 29.3\,\mu mol/mol$$

$$x_{\mathrm{CO2dry}} = \frac{24.98}{1-\frac{8.601}{1000}} = 25.2\,mmol/mol$$

$$x_{\mathrm{NOdry}} = \frac{50.0}{1-\frac{8.601}{1000}} = 50.4\,\mu mol/mol$$

$$x_{\mathrm{NO2dry}} = \frac{12.0}{1-\frac{8.601}{1000}} = 12.1\,\mu mol/mol$$

$$x_{\mathrm{THCdry}} = \frac{46}{1-\frac{34.16}{1000}} = 47.6\,\mu mol/mol$$

$\alpha = 1.8$
$\beta = 0.05$
$\gamma = 0.0003$
$\delta = 0.0001$

(d) Carbon mass fraction and fuel composition. Determine carbon mass fraction of fuel, w_C, and fuel composition represented by α, β, γ, and δ using one of the following methods:

(1) You may calculate w_C as described in this paragraph (d)(1) based on measured fuel properties. To do so, you must determine values for α and β in all cases, but you may set γ and δ to zero if the default value listed in Table 1 of this section is zero. Calculate w_C using the following equation:

$$w_C = \frac{1 \cdot M_C}{1 \cdot M_C + \alpha \cdot M_H + \beta \cdot M_O + \gamma \cdot M_S + \delta \cdot M_N}$$

Deleted: w_c

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Comment [CAL6]: Equation updated.

Eq. 1065.655-19

Where:

w_C = carbon mass fraction of fuel.

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M_C = molar mass of carbon.

α = atomic hydrogen-to-carbon ratio of the mixture of fuel(s) being combusted.

Deleted: , weighted by molar consumption

M_H = molar mass of hydrogen.

β = atomic oxygen-to-carbon ratio of the mixture of fuel(s) being combusted.

Deleted: , weighted by molar consumption

M_O = molar mass of oxygen.

γ = atomic sulfur-to-carbon ratio of the mixture of fuel(s) being combusted.

Deleted: , weighted by molar consumption

M_S = molar mass of sulfur.

δ = atomic nitrogen-to-carbon ratio of the mixture of fuel(s) being combusted.

Deleted: , weighted by molar consumption

M_N = molar mass of nitrogen.

Example:

$\alpha = 1.8$

$\beta = 0.05$

$\gamma = 0.0003$

$\delta = 0.0001$

$M_C = 12.0107$

$M_H = 1.00794$

$M_O = 15.9994$

$M_S = 32.065$

$M_N = 14.0067$

$$w_C = \frac{1 \cdot 12.0107}{1 \cdot 12.0107 + 1.8 \cdot 1.00794 + 0.05 \cdot 15.9994 + 0.0003 \cdot 32.065 + 0.0001 \cdot 14.0067}$$

$w_C = 0.8206$

Comment [CAL7]: Example updated.

Deleted: w_c

(2) Determine a fuel's elemental mass fractions and values for α, β, γ, and δ as follows:

(i) For gaseous fuels, use the default values for α, β, γ, and δ in Table 1 of this section or use good engineering judgment to determine those values based on measurement.

(ii) Determine mass fractions of liquid fuels as follows:

(A) You may determine the carbon and hydrogen mass fractions according to ASTM D5291 (incorporated by reference in § 1065.1010). When using ASTM D5291 to determine carbon and hydrogen mass fractions of gasoline (with or without blended ethanol), use good engineering judgment to adapt the method as appropriate.

(B) Determine oxygen mass fraction of gasoline (with or without blended ethanol) according to ASTM D5599 (incorporated by reference in § 1065.1010). For all other liquid fuels, determine the oxygen mass fraction using good engineering judgment.

(C) Determine the nitrogen mass fraction according to ASTM D4629 or ASTM D5762 (incorporated by reference in § 1065.1010) for all liquid fuels. Select the correct method based on the expected nitrogen content.

(D) Determine the sulfur mass fraction according to subpart H of this part.
(iii) For liquid fuels, use the default values for α, β, γ, and δ in Table 1 of this section, or you may determine the value for any of these parameters based on measurement. Calculate these values using the following equations:

$$\alpha = \frac{w_H \cdot M_C}{w_C \cdot M_H}$$

Eq. 1065.655-20

$$\beta = \frac{w_O \cdot M_C}{w_C \cdot M_O}$$

Eq. 1065.655-21

$$\gamma = \frac{w_S \cdot M_C}{w_C \cdot M_S}$$

Eq. 1065.655-22

$$\delta = \frac{w_N \cdot M_C}{w_C \cdot M_N}$$

Eq. 1065.655-23

Where:
w_C = carbon mass fraction of fuel.
w_H = hydrogen mass fraction of fuel.
w_O = oxygen mass fraction of fuel.
w_S = sulfur mass fraction of fuel.
w_N = nitrogen mass fraction of fuel.

Example:
$w_C = 0.8206$
$w_H = 0.1239$
$w_O = 0.0547$
$w_S = 0.00066$
$w_N = 0.000095$
$M_C = 12.0107$
$M_H = 1.00794$
$M_O = 15.9994$
$M_S = 32.065$
$M_N = 14.0067$

$$\alpha = \frac{0.1239 \cdot 12.0107}{0.8206 \cdot 1.00794}$$

$$\beta = \frac{0.0547 \cdot 12.0107}{0.8206 \cdot 15.9994}$$

$$\gamma = \frac{0.00066 \cdot 12.0107}{0.8206 \cdot 32.065}$$

$$\delta = \frac{0.000095 \cdot 12.0107}{0.8206 \cdot 14.0067}$$

$\alpha = 1.8$
$\beta = 0.05$

$\gamma = 0.0003$
$\delta = 0.0001$

TABLE 1 OF § 1065.655–DEFAULT VALUES OF α, β, γ, δ, AND w_C FOR VARIOUS FUELS

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Fuel	Atomic hydrogen, oxygen, sulfur, and nitrogen-to-carbon ratios $CH_\alpha O_\beta S_\gamma N_\delta$	Carbon mass fraction, w_C g/g
Gasoline	$CH_{1.85}O_0S_0N_0$	0.866
E10 Gasoline	$CH_{1.92}O_{0.03}S_0N_0$	0.833
E15 Gasoline	$CH_{1.95}O_{0.05}S_0N_0$	0.817
E85 Gasoline	$CH_{2.73}O_{0.38}S_0N_0$	0.576
#1 Diesel	$CH_{1.93}O_0S_0N_0$	0.861
#2 Diesel	$CH_{1.80}O_0S_0N_0$	0.869
Liquefied petroleum gas	$CH_{2.64}O_0S_0N_0$	0.819
Natural gas	$CH_{3.78}O_{0.016}S_0N_0$	0.747
E100 Ethanol	$CH_3O_{0.5}S_0N_0$	0.521
M100 Methanol	$CH_4O_1S_0N_0$	0.375
Residual fuel blends	Must be determined by measured fuel properties as described in paragraph (d)(1) of this section.	

(e) Calculated raw exhaust molar flow rate from measured intake air molar flow rate or fuel mass flow rate. You may calculate the raw exhaust molar flow rate from which you sampled emissions, $\dot{n}_{exh}$, based on the measured intake air molar flow rate, $\dot{n}_{int}$, or the measured fuel mass flow rate, $\dot{m}_{fuel}$, and the values calculated using the chemical balance in paragraph (c) of this section. The chemical balance must be based on raw exhaust gas concentrations. Solve for the chemical balance in paragraph (c) of this section at the same frequency that you update and record $\dot{n}_{int}$ or $\dot{m}_{fuel}$. For laboratory tests, calculating raw exhaust molar flow rate using measured fuel mass flow rate is valid only for steady-state testing. See § 1065.915(d)(5)(iv) for application to field testing.

(1) Crankcase flow rate. If engines are not subject to crankcase controls under the standard-setting part, you may calculate raw exhaust flow based on $\dot{n}_{int}$ or $\dot{m}_{fuel}$ using one of the following:

(i) You may measure flow rate through the crankcase vent and subtract it from the calculated exhaust flow.

(ii) You may estimate flow rate through the crankcase vent by engineering analysis as long as the uncertainty in your calculation does not adversely affect your ability to show that your engines comply with applicable emission standards.

(iii) You may assume your crankcase vent flow rate is zero.

(2) Intake air molar flow rate calculation. Calculate $\dot{n}_{exh}$ based on $\dot{n}_{int}$ using the following equation:

$$\dot{n}_{exh} = \frac{\dot{n}_{int}}{\left(1 + \frac{\left(x_{int/exhdry} - x_{raw/exhdry}\right)}{\left(1 + x_{H2Oexhdry}\right)}\right)}$$

Eq. 1065.655-24

Where:

$\dot{n}_{exh}$ = raw exhaust molar flow rate from which you measured emissions.

$\dot{n}_{int}$ = intake air molar flow rate including humidity in intake air.

Example:

$\dot{n}_{int}$ = 3.780 mol/s
$x_{int/exhdry}$ = 0.69021 mol/mol
$x_{raw/exhdry}$ = 1.10764 mol/mol
$x_{H2Oexhdry}$ = 107.64 mmol/mol = 0.10764 mol/mol

$$\dot{n}_{exh} = \frac{3.780}{\left(1 + \frac{\left(0.69021 - 1.10764\right)}{\left(1 + 0.10764\right)}\right)}$$

$\dot{n}_{exh}$ = 6.066 mol/s

(3) Fuel mass flow rate calculation. This calculation may be used only for steady-state laboratory testing. See § 1065.915(d)(5)(iv) for application to field testing. Calculate $\dot{n}_{exh}$ based on $\dot{m}_{fuel}$ using the following equation:

$$\dot{n}_{exh} = \frac{\dot{m}_{fuel} \cdot w_c \cdot \left(1 + x_{H2Oexhdry}\right)}{M_c \cdot x_{Ccombdry}}$$

Eq. 1065.655-25

Where:

$\dot{n}_{exh}$ = raw exhaust molar flow rate from which you measured emissions.

$\dot{m}_{fuel}$ = fuel mass flow rate.

Example:

$\dot{m}_{fuel}$ = 7.559 g/s
w_C = 0.869 g/g

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M_C = 12.0107 g/mol
$x_{Ccombdry}$ = 99.87 mmol/mol = 0.09987 mol/mol
$x_{H2Oexhdry}$ = 107.64 mmol/mol = 0.10764 mol/mol

$$\dot{n}_{exh} = \frac{7.559 \cdot 0.869 \cdot \left(1 + 0.10764\right)}{12.0107 \cdot 0.09987}$$

$\dot{n}_{exh}$ = 6.066 mol/s

(f) Calculated raw exhaust molar flow rate from measured intake air molar flow rate, dilute exhaust molar flow rate, and dilute chemical balance. You may calculate the raw exhaust molar flow rate, $\dot{n}_{exh}$, based on the measured intake air molar flow rate, $\dot{n}_{int}$, the measured dilute exhaust molar flow rate, $\dot{n}_{dexh}$, and the values calculated using the chemical balance in paragraph (c) of this section. Note that the chemical balance must be based on dilute exhaust gas concentrations. For continuous-flow calculations, solve for the chemical balance in paragraph (c) of this section at the same frequency that you update and record $\dot{n}_{int}$ and $\dot{n}_{dexh}$. This calculated $\dot{n}_{dexh}$ may be used for the PM dilution ratio verification in § 1065.546; the calculation of dilution air molar flow rate in the background correction in § 1065.667; and the calculation of mass of emissions in § 1065.650(c) for species that are measured in the raw exhaust.

(1) Crankcase flow rate. If engines are not subject to crankcase controls under the standard-setting part, calculate raw exhaust flow as described in paragraph (e)(1) of this section.

(2) Dilute exhaust and intake air molar flow rate calculation. Calculate $\dot{n}_{exh}$ as follows:

$$\dot{n}_{exh} = \left(x_{raw/exhdry} - x_{int/exhdry}\right) \cdot \left(1 - x_{H2Oexh}\right) \cdot \dot{n}_{dexh} + \dot{n}_{int}$$

Eq. 1065.655-26

Example:

$\dot{n}_{int} = 7.930$ mol/s

$x_{raw/exhdry} = 0.1544$ mol/mol

$x_{int/exhdry} = 0.1451$ mol/mol

$x_{H2Oexh} = 32.46$ mmol/mol $= 0.03246$ mol/mol

$\dot{n}_{dexh} = 49.02$ mol/s

$\dot{n}_{exh} = (0.1544 - 0.1451) \cdot (1 - 0.03246) \cdot 49.02 + 7.930 = 0.4411 + 7.930 = 8.371$ mol/s

(g) Calculated brake torque from fuel mass flow rate determined by a chemical balance of exhaust, measured engine speed, and brake-specific fuel consumption. If the standard-setting part allows it, you may calculate brake torque from fuel mass flow rate, as determined by a chemical balance of exhaust and measured exhaust flow rate, along with measured engine speed, and a brake-specific fuel consumption, as follows:

(1) Use the following equation to calculate brake torque, T:

$$T = \frac{\dot{m}_{fuel}}{f_n \cdot e_{fuel}}$$

Eq. 1065.655-27

Where:

$\dot{m}_{fuel}$ = mass rate of fuel

f_n = engine speed

e_{fuel} = brake-specific fuel consumption

Comment [CAL8]: How is this determined?

Example:

$\dot{m}_{fuel} = 3.32$ g/s

$f_n = 3600$ r/min

$e_{fuel} = 253.61$ g/(kW·hr)

$C_p = 1000$ (N·m·rad /s)/kW
$C_{t1} = 60$ s/min
$C_{t2} = 3600$ s/hr
$C_{rev} = 2 \cdot \pi$ rad/r

$$T = \frac{3.320 \cdot 1000 \cdot 60 \cdot 3600}{3600 \cdot 253.61 \cdot 2 \cdot 3.14159}$$

$$T = 125.0 \text{ N} \cdot \text{m}$$

(2) Use the following equation to calculate flow mass flow rate, $\dot{m}_{fuel}$, from a chemical balance of exhaust and measured exhaust flow rate:

$$\dot{m}_{fuel} = \frac{M_C \cdot x_{Ccombdry} \cdot \dot{n}_{exh}}{w_C \cdot \left(1 + x_{H20exhdry}\right)}$$

Eq. 1065.655-28

Example:
$M_C = 12.0107$ g/mol
$x_{Ccombdry} = 99.87$ mmol/mol = 0.09987 mol/mol
$\dot{n}_{exh} = 2.665$ mol/s
$w_C = 0.869$ g/g
$x_{H20exhdry} = 107.64$ mmol/mol = 0.10764 mol/mol

$$\dot{m}_{fuel} = \frac{12.0107 \cdot 0.09987 \cdot 2.665}{0.869 \cdot (1 + 0.10764)}$$

$$\dot{m}_{fuel} = 3.32 \text{ g/s}$$

§ 1065.659 Removed water correction.

(a) If you remove water upstream of a concentration measurement, x, correct for the removed water. Perform this correction based on the amount of water at the concentration measurement, $x_{H2O[emission]meas}$, and at the flow meter, x_{H2Oexh}, whose flow is used to determine the mass emission rate or total mass over a test interval. For continuous analyzers downstream of a sample dryer for transient and ramped-modal cycles, you must apply this correction on a continuous basis over the test interval, even if you use one of the options in § 1065.145(e)(2) that results in a constant value for $x_{H2O[emission]meas}$ because x_{H2Oexh} varies over the test interval. For batch analyzers, determine the flow-weighted average based on the continuous x_{H2Oexh} values determined as described in paragraph (c) of this section. For batch analyzers, you may determine the flow-weighted average x_{H2Oexh} based on a single value of x_{H2Oexh} determined as described in paragraphs (c)(2) and (3) of this section, using flow-weighted average or batch concentration inputs.

(b) Determine the amount of water remaining downstream of a sample dryer and at the concentration measurement using one of the methods described in § 1065.145(e)(2). If you use a sample dryer upstream of an analyzer and if the calculated amount of water remaining downstream of the sample dryer and at the concentration measurement, $x_{H2O[emission]meas}$, is higher than the amount of water at the flow meter, x_{H2Oexh}, set $x_{H2O[emission]meas}$ equal to x_{H2Oexh}. If you use a sample dryer upstream of storage media, you must be able to demonstrate that the sample dryer is removing water continuously (i.e., x_{H2Oexh} is higher than $x_{H2O[emission]meas}$ throughout the

test interval).
(c) For a concentration measurement where you did not remove water, you may set $x_{H2O[emission]meas}$ equal to x_{H2Oexh}. You may determine the amount of water at the flow meter, x_{H2Oexh}, using any of the following methods:
(1) Measure the dewpoint and absolute pressure and calculate the amount of water as described in § 1065.645.
(2) If the measurement comes from raw exhaust, you may determine the amount of water based on intake-air humidity, plus a chemical balance of fuel, intake air, and exhaust as described in § 1065.655.
(3) If the measurement comes from diluted exhaust, you may determine the amount of water based on intake-air humidity, dilution air humidity, and a chemical balance of fuel, intake air, and exhaust as described in § 1065.655.
(d) Perform a removed water correction to the concentration measurement using the following equation:

$$x = x_{[emission]meas} \cdot \left(\frac{1 - x_{H2Oexh}}{1 - x_{H2O[emission]meas}} \right)$$

Eq. 1065.659-1

Example:
x_{COmeas} = 29.0 μmol/mol
$x_{H2OCOmeas}$ = 8.601 mmol/mol = 0.008601 mol/mol
x_{H2Oexh} = 34.04 mmol/mol = 0.03404 mol/mol

$$x_{CO} = 29.0 \cdot \left(\frac{1 - 0.03404}{1 - 0.008601} \right)$$

x_{CO} = 28.3 μmol/mol

§ 1065.660 THC, NMHC, and CH_4 determination.
(a) THC determination and initial THC/CH_4 contamination corrections. (1) If we require you to determine THC emissions, calculate $x_{THC[THC-FID]cor}$ using the initial THC contamination concentration $x_{THC[THC-FID]init}$ from § 1065.520 as follows:

$$x_{THC[THC-FID]cor} = x_{THC[THC-FID]uncor} - x_{THC[THC-FID]init}$$

Eq. 1065.660-1

Example:
$x_{THCuncor}$ = 150.3 μmol/mol
$x_{THCinit}$ = 1.1 μmol/mol
x_{THCcor} = 150.3 – 1.1
x_{THCcor} = 149.2 μmol/mol

(2) For the NMHC determination described in paragraph (b) of this section, correct $x_{THC[THC-FID]}$ for initial THC contamination using Equation 1065.660-1. You may correct $x_{THC[NMC-FID]}$ for initial contamination of the CH_4 sample train using Equation. 1065.660-1, substituting in CH_4 concentrations for THC.
(3) For the CH_4 determination described in paragraph (c) of this section, you may correct $x_{THC[NMC-FID]}$ for initial THC contamination of the CH_4 sample train using Equation 1065.660-1, substituting in CH_4 concentrations for THC.
(b) NMHC determination. Use one of the following to determine NMHC concentration, x_{NMHC}:

(1) If you do not measure CH_4, you may omit the calculation of NMHC concentrations and calculate the mass of NMHC as described in § 1065.650(c)(5).
(2) For nonmethane cutters, calculate x_{NMHC} using the nonmethane cutter's penetration fraction (*PF*) of CH_4 and the response factor penetration fraction (*RFPF*) of C_2H_6 from § 1065.365, the response factor (*RF*) of the THC FID to CH_4 from § 1065.360, the initial THC contamination and dry-to-wet corrected THC concentration $x_{THC[THC\text{-}FID]cor}$ as determined in paragraph (a) of this section, and the dry-to-wet corrected CH_4 concentration $x_{THC[NMC\text{-}FID]cor}$ optionally corrected for initial THC contamination as determined in paragraph (a) of this section.
(i) Use the following equation for penetration fractions determined using an NMC configuration as outlined in § 1065.365(d):

$$x_{NMHC} = \frac{x_{THC[THC\text{-}FID]cor} - x_{THC[NMC\text{-}FID]cor} \cdot RF_{CH4[THC\text{-}FID]}}{1 - RFPF_{C2H6[NMC\text{-}FID]} \cdot RF_{CH4[THC\text{-}FID]}}$$

Eq. 1065.660-2

Where:
x_{NMHC} = concentration of NMHC.
$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.
$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the NMC FID during sampling through the NMC.
$RF_{CH4[THC\text{-}FID]}$ = response factor of THC FID to CH_4, according to § 1065.360(d).
$RFPF_{C2H6[NMC\text{-}FID]}$ = nonmethane cutter combined ethane response factor and penetration fraction, according to § 1065.365(d).

Example:
$x_{THC[THC\text{-}FID]cor}$ = 150.3 μmol/mol
$x_{THC[NMC\text{-}FID]cor}$ = 20.5 μmol/mol
$RFPF_{C2H6[NMC\text{-}FID]}$ = 0.019
$RF_{CH4[THC\text{-}FID]}$ = 1.05

$$x_{NMHC} = \frac{150.3 - 20.5 \cdot 1.05}{1 - 0.019 \cdot 1.05}$$

x_{NMHC} = 131.4 μmol/mol

(ii) For penetration fractions determined using an NMC configuration as outlined in section § 1065.365(e), use the following equation:

$$x_{NMHC} = \frac{x_{THC[THC\text{-}FID]cor} \cdot PF_{CH4[NMC\text{-}FID]} - x_{THC[NMC\text{-}FID]cor}}{PF_{CH4[NMC\text{-}FID]} - PF_{C2H6[NMC\text{-}FID]}}$$

Eq. 1065.660-3

Where:
x_{NMHC} = concentration of NMHC.
$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.
$PF_{CH4[NMC\text{-}FID]}$ = nonmethane cutter CH_4 penetration fraction, according to § 1065.365(e).
$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the THC FID during sampling through the NMC.
$PF_{C2H6[NMC\text{-}FID]}$ = nonmethane cutter ethane penetration fraction, according to § 1065.365(e).

Example:
$x_{THC[THC\text{-}FID]cor}$ = 150.3 μmol/mol
$PF_{CH4[NMC\text{-}FID]}$ = 0.990
$x_{THC[NMC\text{-}FID]cor}$ = 20.5 μmol/mol
$PF_{C2H6[NMC\text{-}FID]}$ = 0.020

$$x_{NMHC} = \frac{150.3 \cdot 0.990 - 20.5}{0.990 - 0.020}$$

x_{NMHC} = 132.3 μmol/mol

(iii) For penetration fractions determined using an NMC configuration as outlined in section § 1065.365(f), use the following equation:

$$x_{NMHC} = \frac{x_{THC[THC\text{-}FID]cor} \cdot PF_{CH4[NMC\text{-}FID]} - x_{THC[NMC\text{-}FID]cor} \cdot RF_{CH4[THC\text{-}FID]}}{PF_{CH4[NMC\text{-}FID]} - RFPF_{C2H6[NMC\text{-}FID]} \cdot RF_{CH4[THC\text{-}FID]}}$$

Eq. 1065.660-4

Where:
x_{NMHC} = concentration of NMHC.
$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.
$PF_{CH4[NMC\text{-}FID]}$ = nonmethane cutter CH_4 penetration fraction, according to § 1065.365(f).
$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the THC FID during sampling through the NMC.
$RFPF_{C2H6[NMC\text{-}FID]}$ = nonmethane cutter CH_4 combined ethane response factor and penetration fraction, according to § 1065.365(f).
$RF_{CH4[THC\text{-}FID]}$ = response factor of THC FID to CH_4, according to § 1065.360(d).

Example:
$x_{THC[THC\text{-}FID]cor}$ = 150.3 μmol/mol
$PF_{CH4[NMC\text{-}FID]}$ = 0.990
$x_{THC[NMC\text{-}FID]cor}$ = 20.5 μmol/mol
$RFPF_{C2H6[NMC\text{-}FID]}$ = 0.019
$RF_{CH4[THC\text{-}FID]}$ = 0.980

$$x_{NMHC} = \frac{150.3 \cdot 0.990 - 20.5 \cdot 0.980}{0.990 - 0.019 \cdot 0.980}$$

x_{NMHC} = 132.5 μmol/mol

(3) For a GC-FID, calculate x_{NMHC} using the THC analyzer's response factor (*RF*) for CH_4, from § 1065.360, and the initial THC contamination and dry-to-wet corrected THC concentration $x_{THC[THC\text{-}FID]cor}$ as determined in paragraph (a) of this section as follows:

$$x_{NMHC} = x_{THC[THC\text{-}FID]cor} - RF_{CH4[THC\text{-}FID]} \cdot x_{CH4}$$

Eq. 1065.660-5

Where:
x_{NMHC} = concentration of NMHC.
$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID.
x_{CH4}= concentration of CH_4, dry-to-wet corrected, as measured by the GC-FID.

$RF_{CH4[THC\text{-}FID]}$ = response factor of THC-FID to CH_4.

Example:
$x_{THC[THC\text{-}FID[cor}$ = 145.6 µmol/mol
$RF_{CH4[THC\text{-}FID]}$ = 0.970
x_{CH4} = 18.9 µmol/mol
x_{NMHC} = 145.6 – 0.970 · 18.9
x_{NMHC} = 127.3 µmol/mol

(c) CH_4 determination. Use one of the following methods to determine CH_4 concentration, x_{CH4}:
(1) For nonmethane cutters, calculate x_{CH4} using the nonmethane cutter's penetration fraction (*PF*) of CH_4 and the response factor penetration fraction (*RFPF*) of C_2H_6 from § 1065.365, the response factor (*RF*) of the THC FID to CH_4 from § 1065.360, the initial THC contamination and dry-to-wet corrected THC concentration $x_{THC[THC\text{-}FID]cor}$ as determined in paragraph (a) of this section, and the dry-to-wet corrected CH_4 concentration $x_{THC[NMC\text{-}FID]cor}$ optionally corrected for initial THC contamination as determined in paragraph (a) of this section.
(i) Use the following equation for penetration fractions determined using an NMC configuration as outlined in § 1065.365(d):

$$x_{CH4} = \frac{x_{THC[NMC\text{-}FID]cor} - x_{THC[THC\text{-}FID]cor} \cdot RFPF_{C2H6[NMC\text{-}FID]}}{1 - RFPF_{C2H6[NMC\text{-}FID]} \cdot RF_{CH4[THC\text{-}FID]}}$$

Eq. 1065.660-6

Where:
x_{CH4} = concentration of CH_4.
$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the NMC FID during sampling through the NMC.
$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.
$RFPF_{C2H6[NMC\text{-}FID]}$ = the combined ethane response factor and penetration fraction of the nonmethane cutter, according to § 1065.365(d).
$RF_{CH4[THC\text{-}FID]}$ = response factor of THC FID to CH_4, according to § 1065.360(d).

Example:
$x_{THC[NMC\text{-}FID]cor}$ = 10.4 µmol/mol
$x_{THC[THC\text{-}FID]cor}$ = 150.3 µmol/mol
$RFPF_{C2H6[NMC\text{-}FID]}$ = 0.019
$RF_{CH4[THC\text{-}FID]}$ = 1.05

$$x_{CH4} = \frac{10.4 - 150.3 \cdot 0.019}{1 - 0.019 \cdot 1.05}$$

x_{CH4} = 7.69 µmol/mol

(ii) For penetration fractions determined using an NMC configuration as outlined in § 1065.365(e), use the following equation:

$$x_{CH4} = \frac{x_{THC[NMC\text{-}FID]cor} - x_{THC[THC\text{-}FID]cor} \cdot PF_{C2H6[NMC\text{-}FID]}}{RF_{CH4[THC\text{-}FID]} \cdot \left(PF_{CH4[NMC\text{-}FID]} - PF_{C2H6[NMC\text{-}FID]}\right)}$$

Eq. 1065.660-7

Where:

x_{CH4} = concentration of CH_4.

$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the NMC FID during sampling through the NMC.

$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.

$PF_{C2H6[NMC\text{-}FID]}$ = nonmethane cutter ethane penetration fraction, according to § 1065.365(e).

$RF_{CH4[THC\text{-}FID]}$ = response factor of THC FID to CH_4, according to § 1065.360(d).

$PF_{CH4[NMC\text{-}FID]}$ = nonmethane cutter CH_4 penetration fraction, according to § 1065.365(e).

Example:

$x_{THC[NMC\text{-}FID]cor}$ = 10.4 μmol/mol

$x_{THC[THC\text{-}FID]cor}$ = 150.3 μmol/mol

$PF_{C2H6[NMC\text{-}FID]}$ = 0.020

$RF_{CH4[THC\text{-}FID]}$ = 1.05

$PF_{CH4[NMC\text{-}FID]}$ = 0.990

$$x_{CH4} = \frac{10.4 - 150.3 \cdot 0.020}{1.05 \cdot (0.990 - 0.020)}$$

x_{CH4} = 7.25 μmol/mol

(iii) For penetration fractions determined using an NMC configuration as outlined in § 1065.365(f), use the following equation:

$$x_{CH4} = \frac{x_{THC[NMC\text{-}FID]cor} - x_{THC[THC\text{-}FID]cor} \cdot RFPF_{C2H6[NMC\text{-}FID]}}{PF_{CH4[NMC\text{-}FID]} - RFPF_{C2H6[NMC\text{-}FID]} \cdot RF_{CH4[THC\text{-}FID]}}$$

Eq. 1065.660-8

Where:

x_{CH4} = concentration of CH_4.

$x_{THC[NMC\text{-}FID]cor}$ = concentration of THC, initial THC contamination (optional) and dry-to-wet corrected, as measured by the NMC FID during sampling through the NMC.

$x_{THC[THC\text{-}FID]cor}$ = concentration of THC, initial THC contamination and dry-to-wet corrected, as measured by the THC FID during sampling while bypassing the NMC.

$RFPF_{C2H6[NMC\text{-}FID]}$ = the combined ethane response factor and penetration fraction of the nonmethane cutter, according to § 1065.365(f).

$PF_{CH4[NMC\text{-}FID]}$ = nonmethane cutter CH_4 penetration fraction, according to § 1065.365(f).

$RF_{CH4[THC\text{-}FID]}$ = response factor of THC FID to CH_4, according to § 1065.360(d).

Example:

$x_{THC[NMC\text{-}FID]cor}$ = 10.4 μmol/mol

$x_{THC[THC\text{-}FID]cor}$ = 150.3 μmol/mol

$RFPF_{C2H6[NMC\text{-}FID]}$ = 0.019

$PF_{CH4[NMC\text{-}FID]}$ = 0.990

$RF_{CH4[THC\text{-}FID]}$ = 1.05

$$x_{CH4} = \frac{10.4 - 150.3 \cdot 0.019}{0.990 - 0.019 \cdot 1.05}$$

x_{CH4} = 7.78 μmol/mol
(2) For a GC-FID, x_{CH4} is the actual dry-to-wet corrected CH_4 concentration as measured by the analyzer.

§ 1065.665 THCE and NMHCE determination.
(a) If you measured an oxygenated hydrocarbon's mass concentration, first calculate its molar concentration in the exhaust sample stream from which the sample was taken (raw or diluted exhaust), and convert this into a C_1-equivalent molar concentration. Add these C_1-equivalent molar concentrations to the molar concentration of non-oxygenated total hydrocarbon (NOTHC). The result is the molar concentration of total hydrocarbon equivalent (THCE). Calculate THCE concentration using the following equations, noting that Eq. 1065.665-3 is required only if you need to convert your oxygenated hydrocarbon (OHC) concentration from mass to moles:

$$x_{THCE} = x_{NOTHC} + \sum_{i=1}^{N}\left(x_{OHCi} - x_{OHCi\text{-}init}\right)$$

Eq. 1065.665-1

$$x_{NOTHC} = x_{THC[THC\text{-}FID]cor} - \sum_{i=1}^{N}\left(\left(x_{OHCi} - x_{OHCi\text{-}init}\right)\cdot RF_{OHCi[THC\text{-}FID]}\right)$$

Eq. 1065.665-2

$$x_{OHCi} = \frac{\dfrac{m_{dexhOHCi}}{M_{OHCi}}}{\dfrac{m_{dexh}}{M_{dexh}}} = \frac{n_{dexhOHCi}}{n_{dexh}}$$

Eq. 1065.665-3

Where:
x_{THCE} = The sum of the C_1-equivalent concentrations of non-oxygenated hydrocarbons, alcohols, and aldehydes.
x_{NOTHC} = The sum of the C_1-equivalent concentrations of NOTHC.
x_{OHCi} = The C_1-equivalent concentration of oxygenated species *i* in diluted exhaust, not corrected for initial contamination.
$x_{OHCi\text{-}init}$ = The C_1-equivalent concentration of the initial system contamination (optional) of oxygenated species *i*, dry-to-wet corrected.
$x_{THC[THC\text{-}FID]cor}$ = The C_1-equivalent response to NOTHC and all OHC in diluted exhaust, HC contamination and dry-to-wet corrected, as measured by the THC-FID.
$RF_{OHCi[THC\text{-}FID]}$ = The response factor of the FID to species *i* relative to propane on a C_1-equivalent basis.
$C^{\#}$ = the mean number of carbon atoms in the particular compound.
M_{dexh} = The molar mass of diluted exhaust as determine in § 1065.340.
$m_{dexhOHCi}$ = The mass of oxygenated species *i* in dilute exhaust.
M_{OHCi} = The C_1-equivalent molecular weight of oxygenated species *i*.
m_{dexh} = The mass of diluted exhaust
$n_{dexhOHCi}$ = The number of moles of oxygenated species *i* in total diluted exhaust flow.
n_{dexh} = The total diluted exhaust flow.
(b) If we require you to determine nonmethane hydrocarbon equivalent (NMHCE), use the following equation:

$$x_{NMHCE} = x_{THCE} - RF_{CH4[THC\text{-}FID]} \cdot x_{CH4}$$

Eq. 1065.665-4

Where:

x_{NMHCE} = The sum of the C_1-equivalent concentrations of nonoxygenated nonmethane hydrocarbon (NONMHC), alcohols, and aldehydes.

$RF_{CH4[THC\text{-}FID]}$ = response factor of THC-FID to CH_4.

x_{CH4} = concentration of CH_4, HC contamination (optional) and dry-to-wet corrected, as measured by the gas chromatograph FID.

(c) The following example shows how to determine NMHCE emissions based on ethanol (C_2H_5OH), methanol (CH_3OH), acetaldehyde (C_2H_4O), and formaldehyde (CH_2O) as C_1-equivalent molar concentrations:

$x_{THC[THC\text{-}FID]cor}$ = 145.6 μmol/mol

x_{CH4} = 18.9 μmol/mol

x_{C2H5OH} = 100.8 μmol/mol

x_{CH3OH} = 1.1 μmol/mol

x_{C2H4O} = 19.1 μmol/mol

x_{CH2O} = 1.3 μmol/mol

$RF_{CH4[THC\text{-}FID]}$ = 1.07

$RF_{C2H5OH[THC\text{-}FID]}$ = 0.76

$RF_{CH3OH[THC\text{-}FID]}$ = 0.74

$RF_{H2H4O[THC\text{-}FID]}$ = 0.50

$RF_{CH2O[THC\text{-}FID]}$ = 0.0

$$x_{NMHCE} = x_{THC[THC\text{-}FID]cor} - (x_{C2H5OH} \cdot RF_{C2H5OH[THC\text{-}FID]} + x_{CH3OH} \cdot RF_{CH3OH[THC\text{-}FID]} + x_{C2H4O} \cdot RF_{C2H4O[THC\text{-}FID]} + x_{CH2O} \cdot RF_{CH2O[THC\text{-}FID]}) + x_{C2H5OH} + x_{CH3OH} + x_{C2H4O} + x_{CH2O} - (RF_{CH4[THC\text{-}FID]} \cdot x_{CH4})$$

$$x_{NMHCE} = 145.6 - (100.8 \cdot 0.76 + 1.1 \cdot 0.74 + 19.1 \cdot 0.50 + 1.3 \cdot 0) + 100.8 + 1.1 + 19.1 + 1.3 - (1.07 \cdot 18.9)$$

x_{NMHCE} = 160.71 μmol/mol

§ 1065.667 Dilution air background emission correction.

(a) To determine the mass of background emissions to subtract from a diluted exhaust sample, first determine the total flow of dilution air, n_{dil}, over the test interval. This may be a measured quantity or a calculated quantity. Multiply the total flow of dilution air by the mean mole fraction (i.e., concentration) of a background emission. This may be a time-weighted mean or a flow-weighted mean (e.g., a proportionally sampled background). Finally, multiply by the molar mass, M, of the associated gaseous emission constituent. The product of n_{dil} and the mean molar concentration of a background emission and its molar mass, M, is the total background emission mass, m. In the case of PM, where the mean PM concentration is already in units of mass per mole of sample, $\overline{M}_{PM}$, multiply it by the total amount of dilution air flow, and the result is the total background mass of PM, m_{PM}. Subtract total background mass from total mass to correct for background emissions.

(b) You may determine the total flow of dilution air by a direct flow measurement.

(c) You may determine the total flow of dilution air by subtracting the calculated raw exhaust molar flow as described in § 1065.655(f) from the measured dilute exhaust flow. This may be

done by totaling continuous calculations or by using batch results.
(d) You may determine the total flow of dilution air from the measured dilute exhaust flow and a chemical balance of the fuel, intake air, and dilute exhaust as described in § 1065.655. For this option, the molar flow of dilution air is calculated by multiplying the dilute exhaust flow by the mole fraction of dilution gas to dilute exhaust, $x_{dil/exh}$, from the dilute chemical balance. This may be done by totaling continuous calculations or by using batch results. For example, to use batch results, the total flow of dilution air is calculated by multiplying the total flow of diluted exhaust, n_{dexh}, by the flow-weighted mean mole fraction of dilution air in diluted exhaust, $\overline{x}_{dil/exh}$. Calculate $\overline{x}_{dil/exh}$ using flow-weighted mean concentrations of emissions in the chemical balance, as described in § 1065.655. The chemical balance in § 1065.655 assumes that your engine operates stoichiometrically, even if it is a lean-burn engine, such as a compression-ignition engine. Note that for lean-burn engines this assumption could result in an error in emission calculations. This error could occur because the chemical balance in § 1065.655 treats excess air passing through a lean-burn engine as if it was dilution air. If an emission concentration expected at the standard is about 100 times its dilution air background concentration, this error is negligible. However, if an emission concentration expected at the standard is similar to its background concentration, this error could be significant. If this error might affect your ability to show that your engines comply with applicable standards, we recommend that you either determine the total flow of dilution air using one of the more accurate methods in paragraph (b) or (c) of this section, or remove background emissions from dilution air by HEPA filtration, chemical adsorption, or catalytic scrubbing. You might also consider using a partial-flow dilution technique such as a bag mini-diluter, which uses purified air as the dilution air.
(e) The following is an example of using the flow-weighted mean fraction of dilution air in diluted exhaust, $\overline{x}_{dil/exh}$, and the total mass of background emissions calculated using the total flow of diluted exhaust, n_{dexh}, as described in § 1065.650(c):

$$m_{bkgnd} = \overline{x}_{dil/exh} \cdot m_{bkgnddexh}$$

Eq. 1065.667-1

$$m_{bkgnddexh} = M \cdot \overline{x}_{bkgnd} \cdot n_{dexh}$$

Eq. 1065.667-2

Example:
$M_{NOx} = 46.0055$ g/mol
$\overline{x}_{bkgnd} = 0.05$ µmol/mol $= 0.05 \cdot 10^{-6}$ mol/mol
$n_{dexh} = 23280.5$ mol
$\overline{x}_{dil/exh} = 0.843$ mol/mol

$$m_{bkgndNOxdexh} = 46.0055 \cdot 0.05 \cdot 10^{-6} \cdot 23280.5$$

$m_{bkgndNOxdexh} = 0.0536$ g
$m_{bkgndNOx} = 0.843 \cdot 0.0536$
$m_{bkgndNOx} = 0.0452$ g
(f) The following is an example of using the fraction of dilution air in diluted exhaust, $x_{dil/exh}$, and the mass rate of background emissions calculated using the flow rate of diluted exhaust, $\dot{n}_{dexh}$, as described in § 1065.650(c) :

$\dot{m}_{bkgnd} = x_{dil/exh} \cdot \dot{m}_{bkgnddexh}$

Eq. 1065.667-3

$\dot{m}_{bkgnddexh} = M \cdot x_{bkgnd} \cdot \dot{n}_{dexh}$

Eq. 1065.667-4

Example:

$M_{NOx} = 46.0055$ g/mol

$x_{bkgnd} = 0.05$ µmol/mol $= 0.05 \cdot 10^{-6}$ mol/mol

$\dot{n}_{dexh} = 23280.5$ mol/s

$x_{dil/exh} = 0.843$ mol/mol

$\dot{m}_{bkgndNOxdexh} = 46.0055 \cdot 0.05 \cdot 10^{-6} \cdot 23280.5$

$\dot{m}_{bkgndNOxdexh} = 0.0536$ g/hr

$\dot{m}_{bkgndNOx} = 0.843 \cdot 0.0536$

$\dot{m}_{bkgndNOx} = 0.0452$ g/hr

§ 1065.670 NO_x intake-air humidity and temperature corrections.

See the standard-setting part to determine if you may correct NO_x emissions for the effects of intake-air humidity or temperature. Use the NO_x intake-air humidity and temperature corrections specified in the standard-setting part instead of the NO_x intake-air humidity correction specified in this part 1065. If the standard-setting part does not prohibit correcting NO_x emissions for intake-air humidity according to this part 1065, correct NO_x concentrations for intake-air humidity as described in this section. See § 1065.650(c)(1) for the proper sequence for applying the NO_x intake-air humidity and temperature corrections. You may use a time-weighted mean combustion air humidity to calculate this correction if your combustion air humidity remains within a tolerance of ±0.0025 mol/mol of the mean value over the test interval. For intake-air humidity correction, use one of the following approaches:

(a) For compression-ignition engines, correct for intake-air humidity using the following equation:

$x_{NOxcor} = x_{NOxuncor} \cdot (9.953 \cdot x_{H2O} + 0.832)$

Eq. 1065.670-1

Example:

$x_{NOxuncor} = 700.5$ µmol/mol

$x_{H2O} = 0.022$ mol/mol

$x_{NOxcor} = 700.5 \cdot (9.953 \cdot 0.022 + 0.832)$

$x_{NOxcor} = 736.2$ µmol/mol

(b) For spark-ignition engines, correct for intake-air humidity using the following equation:

$x_{NOxcor} = x_{NOxuncor} \cdot (18.840 \cdot x_{H2O} + 0.68094)$

Eq. 1065.670-2

Example:

$x_{NOxuncor} = 154.7$ µmol/mol

$x_{H2O} = 0.022$ mol/mol

$x_{NOxcor} = 154.7 \cdot (18.840 \cdot 0.022 + 0.68094)$

$x_{NOxcor} = 169.5$ µmol/mol

(c) Develop your own correction, based on good engineering judgment.

§ 1065.672 Drift correction.

(a) Scope and frequency. Perform the calculations in this section to determine if gas analyzer drift invalidates the results of a test interval. If drift does not invalidate the results of a test interval, correct that test interval's gas analyzer responses for drift according to this section. Use the drift-corrected gas analyzer responses in all subsequent emission calculations. Note that the acceptable threshold for gas analyzer drift over a test interval is specified in § 1065.550 for both laboratory testing and field testing.

(b) Correction principles. The calculations in this section utilize a gas analyzer's responses to reference zero and span concentrations of analytical gases, as determined sometime before and after a test interval. The calculations correct the gas analyzer's responses that were recorded during a test interval. The correction is based on an analyzer's mean responses to reference zero and span gases, and it is based on the reference concentrations of the zero and span gases themselves. Validate and correct for drift as follows:

(c) Drift validation. After applying all the other corrections–except drift correction–to all the gas analyzer signals, calculate brake-specific emissions according to § 1065.650. Then correct all gas analyzer signals for drift according to this section. Recalculate brake-specific emissions using all of the drift-corrected gas analyzer signals. Validate and report the brake-specific emission results before and after drift correction according to § 1065.550.

(d) Drift correction. Correct all gas analyzer signals as follows:

(1) Correct each recorded concentration, x_i, for continuous sampling or for batch sampling, $\overline{x}$.

(2) Correct for drift using the following equation:

$$x_{\text{idriftcorrected}} = x_{\text{refzero}} + \left(x_{\text{refspan}} - x_{\text{refzero}}\right) \cdot \frac{2x_{\text{i}} - \left(x_{\text{prezero}} + x_{\text{postzero}}\right)}{\left(x_{\text{prespan}} + x_{\text{postspan}}\right) - \left(x_{\text{prezero}} + x_{\text{postzero}}\right)}$$

Eq. 1065.672-1

Where:

$x_{\text{idriftcorrected}}$ = concentration corrected for drift.

x_{refzero} = reference concentration of the zero gas, which is usually zero unless known to be otherwise.

x_{refspan} = reference concentration of the span gas.

x_{prespan} = pre-test interval gas analyzer response to the span gas concentration.

x_{postspan} = post-test interval gas analyzer response to the span gas concentration.

x_{i} or $\overline{x}$ = concentration recorded during test, before drift correction.

x_{prezero} = pre-test interval gas analyzer response to the zero gas concentration.

x_{postzero} = post-test interval gas analyzer response to the zero gas concentration.

Example:

x_{refzero} = 0 μmol/mol

x_{refspan} = 1800.0 μmol/mol

x_{prespan} = 1800.5 μmol/mol

x_{postspan} = 1695.8 μmol/mol

x_{i} or $\overline{x}$ = 435.5 μmol/mol

x_{prezero} = 0.6 μmol/mol

$x_{postzero} = -5.2$ μmol/mol

$$x_{idriftcorrected} = 0 + (1800.0 - 0) \cdot \frac{2 \cdot 435.5 - (0.6 + (-5.2))}{(1800.5 + 1695.8) - (0.6 + (-5.2))}$$

$x_{idriftcorrected} = 450.2$ μmol/mol

(3) For any pre-test interval concentrations, use concentrations determined most recently before the test interval. For some test intervals, the most recent pre-zero or pre-span might have occurred before one or more previous test intervals.

(4) For any post-test interval concentrations, use concentrations determined most recently after the test interval. For some test intervals, the most recent post-zero or post-span might have occurred after one or more subsequent test intervals.

(5) If you do not record any pre-test interval analyzer response to the span gas concentration, $x_{prespan}$, set $x_{prespan}$ equal to the reference concentration of the span gas: $x_{prespan} = x_{refspan}$.

(6) If you do not record any pre-test interval analyzer response to the zero gas concentration, $x_{prezero}$, set $x_{prezero}$ equal to the reference concentration of the zero gas: $x_{prezero} = x_{refzero}$.

(7) Usually the reference concentration of the zero gas, $x_{refzero}$, is zero: $x_{refzero} = 0$ μmol/mol. However, in some cases you might know that $x_{refzero}$ has a non-zero concentration. For example, if you zero a CO_2 analyzer using ambient air, you may use the default ambient air concentration of CO_2, which is 375 μmol/mol. In this case, $x_{refzero} = 375$ μmol/mol. Note that when you zero an analyzer using a non-zero $x_{refzero}$, you must set the analyzer to output the actual $x_{refzero}$ concentration. For example, if $x_{refzero} = 375$ μmol/mol, set the analyzer to output a value of 375 μmol/mol when the zero gas is flowing to the analyzer.

§ 1065.675 CLD quench verification calculations.

Perform CLD quench-check calculations as follows:

(a) Perform a CLD analyzer quench verification test as described in § 1065.370.

(b) Estimate the maximum expected mole fraction of water during emission testing, x_{H2Oexp}. Make this estimate where the humidified NO span gas was introduced in § 1065.370(e)(6). When estimating the maximum expected mole fraction of water, consider the maximum expected water content in combustion air, fuel combustion products, and dilution air (if applicable). If you introduced the humidified NO span gas into the sample system upstream of a sample dryer during the verification test, you need not estimate the maximum expected mole fraction of water and you must set x_{H2Oexp} equal to $x_{H2Omeas}$.

(c) Estimate the maximum expected CO_2 concentration during emission testing, x_{CO2exp}. Make this estimate at the sample system location where the blended NO and CO_2 span gases are introduced according to § 1065.370(d)(10). When estimating the maximum expected CO_2 concentration, consider the maximum expected CO_2 content in fuel combustion products and dilution air.

(d) Calculate quench as follows:

$$quench = \left(\left(\frac{\frac{x_{NOwet}}{1 - x_{H2Omeas}}}{x_{NOdry}} - 1 \right) \cdot \frac{x_{H2Oexp}}{x_{H2Omeas}} + \left(\frac{x_{NOmeas}}{x_{NOact}} - 1 \right) \cdot \frac{x_{CO2exp}}{x_{CO2act}} \right) \cdot 100\ \%$$

Eq. 1065.675-1

Where:
quench = amount of CLD quench.
x_{NOdry} = concentration of NO upstream of a bubbler, according to § 1065.370(e)(4).
x_{NOwet} = measured concentration of NO downstream of a bubbler, according to § 1065.370(e)(9).
x_{H2Oexp} = maximum expected mole fraction of water during emission testing, according to paragraph (b) of this section.
$x_{H2Omeas}$ = measured mole fraction of water during the quench verification, according to § 1065.370(e)(7).
x_{NOmeas} = measured concentration of NO when NO span gas is blended with CO_2 span gas, according to § 1065.370(d)(10).
x_{NOact} = actual concentration of NO when NO span gas is blended with CO_2 span gas, according to § 1065.370(d)(11) and calculated according to Equation 1065.675-2.
x_{CO2exp} = maximum expected concentration of CO_2 during emission testing, according to paragraph (c) of this section.
x_{CO2act} = actual concentration of CO_2 when NO span gas is blended with CO_2 span gas, according to § 1065.370(d)(9).

$$x_{NOact} = \left(1 - \frac{x_{CO2act}}{x_{CO2span}}\right) \cdot x_{NOspan}$$

Eq. 1065.675-2

Where:
x_{NOspan} = the NO span gas concentration input to the gas divider, according to § 1065.370(d)(5).
$x_{CO2span}$ = the CO_2 span gas concentration input to the gas divider, according to § 1065.370(d)(4).

Example:
x_{NOdry} = 1800.0 μmol/mol
x_{NOwet} = 1739.6 μmol/mol
x_{H2Oexp} = 0.030 mol/mol
$x_{H2Omeas}$ = 0.030 mol/mol
x_{NOmeas} = 1515.2 μmol/mol
x_{NOspan} = 3001.6 μmol/mol
x_{CO2exp} = 3.2 %
$x_{CO2span}$ = 6.1 %
x_{CO2act} = 2.98 %

$$x_{NOact} = \left(1 - \frac{2.98}{6.1}\right) \cdot 3001.6 = 1535.24459 \text{ μmol/mol}$$

$$quench = \left(\left(\frac{\frac{1739.6}{1-0.030}}{1800.0} - 1\right) \cdot \frac{0.030}{0.030} + \left(\frac{1515.2}{1535.24459} - 1\right) \cdot \frac{3.2}{2.98}\right) \cdot 100\ \%$$

$$quench = (-0.0036655 - 0.014020171) \cdot 100\ \% = -1.7685671\ \%$$

§1065.680 Adjusting emission levels to account for infrequently regenerating aftertreatment devices.

This section describes how to calculate and apply emission adjustment factors for engines using aftertreatment technology with infrequent regeneration events that may occur during testing.

These adjustment factors are typically calculated based on measurements conducted for the purposes of engine certification, and then used to adjust the results of testing related to demonstrating compliance with emission standards. For this section, "regeneration" means an intended event during which emission levels change while the system restores aftertreatment performance. For example, exhaust gas temperatures may increase temporarily to remove sulfur from adsorbers or to oxidize accumulated particulate matter in a trap. Also, "infrequent" refers to regeneration events that are expected to occur on average less than once over a transient or ramped-modal duty cycle, or on average less than once per mode in a discrete-mode test.

(a) Applying adjustment factors. Apply adjustment factors based on whether there is active regeneration during the test segment. The test segment may be a test interval or a full duty cycle, as described in paragraph (b) of this section. For engines subject to standards over more than one duty cycle, you must develop adjustment factors under this section for each separate duty cycle. You must be able to identify active regeneration in a way that is readily apparent during all testing.

(1) If active regeneration does not occur during a test segment, apply an upward adjustment factor, *UAF*, that will be added to the measured emission rate for that test segment. Use the following equation to calculate *UAF*:

$$UAF_{[cycle]} = EF_{A[cycle]} - EF_{L[cycle]}$$

Eq. 1065.680-1

Where:

$EF_{A[cycle]}$ = the average emission factor over the test segment as determined in paragraph (a)(4) of this section.

$EF_{L[cycle]}$ = measured emissions over a complete test segment in which active regeneration does not occur.

Example:

EF_{ARMC} = 0.15 g/kW·hr

EF_{LRMC} = 0.11 g/kW·hr

UAF_{RMC} = 0.15 − 0.11 = 0.04 g/kW·hr

(2) If active regeneration occurs or starts to occur during a test segment, apply a downward adjustment factor, *DAF*, that will be subtracted from the measured emission rate for that test segment. Use the following equation to calculate *DAF*:

$$DAF_{[cycle]} = EF_{H[cycle]} - EF_{A[cycle]}$$

Eq. 1065.680-2

Where:

$EF_{H[cycle]}$ = measured emissions over the test segment from a complete regeneration event, or the average emission rate over multiple complete test segments with regeneration if the complete regeneration event lasts longer than one test segment.

Example:

EF_{ARMC} = 0.15 g/kW·hr

EF_{HRMC} = 0.50 g/kW·hr

DAF_{RMC} = 0.50 − 0.15 = 0.35 g/kW·hr

(3) Note that emissions for a given pollutant may be lower during regeneration, in which case EF_L would be greater than EF_H, and both *UAF* and *DAF* would be negative.

(4) Calculate the average emission factor, EF_A, as follows:

$$EF_{A[cycle]} = F_{[cycle]} \cdot EF_{H[cycle]} + (1.00 - F_{[cycle]}) \cdot EF_{L[cycle]}$$

Eq. 1065.680-3

Where:

$F_{[cycle]}$ = the frequency of the regeneration event during normal in-use operation, expressed in terms of the fraction of equivalent test segments during which active regeneration occurs, as described in paragraph (a)(5) of this section.

Example:

$F_{RMC} = 0.10$

$EF_{ARMC} = 0.10 \cdot 0.50 + (1.00 - 0.10) \cdot 0.11 = 0.15$ g/kW·hr

(5) The frequency of regeneration, F, generally characterizes how often a regeneration event occurs within a series of test segments. Determine F using the following equation, subject to the provisions of paragraph (a)(6) of this section:

$$F_{[cycle]} = \frac{i_{r[cycle]}}{i_{f[cycle]} + i_{r[cycle]}}$$

Eq. 1065.680-4

Where:

$i_{r[cycle]}$ = the number of successive test segments required to complete an active regeneration, rounded up to the next whole number.

$i_{f[cycle]}$ = the number of test segments from the end of one complete regeneration event to the start of the next active regeneration, without rounding.

Example:

$i_{rRMC} = 2$

$i_{fRMC} = 17.86$

$$F_{RMC} = \frac{2}{17.86 + 2} = 0.10$$

(6) Use good engineering judgment to determine i_r and i_f, as follows:

(i) Consider an example for an engine that is designed to regenerate its PM filter 500 minutes after the end of the last regeneration event, with the regeneration event lasting 30 minutes. If the RMC takes 28 minutes, $i_{rRMC} = 2$ (30÷28=1.07, which rounds up to 2), and $i_{fRMC} = 500 \div 28 = 17.86$.

(ii) For engines subject to standards over multiple duty cycles, such as for transient and steady-state testing, apply this same calculation to determine a value of F for each duty cycle.

(ii) For engines that are not programmed to regenerate at a specific time, perform testing with repeat duty cycles to establish the duration of a regeneration event and the time between regeneration events for each duty cycle and perform the calculation illustrated in paragraph (a)(6)(i) of this section.

(b) Develop adjustment factors for different types of testing as follows:

(1) Discrete-mode testing. Develop separate adjustment factors for each test mode (test interval) of a discrete-mode test. When measuring EF_H, if a regeneration event has started but is not complete when you reach the end of the sampling time for a test interval, extend the sampling period for that test interval until the regeneration event is complete.

(2) Ramped-modal and transient testing. Develop a separate set of adjustment factors for an entire ramped-modal cycle or transient duty cycle. For engines subject to cold-start testing requirements, see the standard-setting part to determine how to incorporate cold-start into this analysis. When measuring EF_H, if a regeneration event has started but is not complete when you reach the end of the duty-cycle, start the next repeat test as soon as possible, allowing for the time needed to complete emission measurement and installation of new filters for PM measurement; in that case EF_H is the average emission level for the test segments that included regeneration.
(c) If an engine has multiple regeneration strategies, determine and apply adjustment factors under this section separately for each type of regeneration.

§ 1065.690 Buoyancy correction for PM sample media.
(a) General. Correct PM sample media for their buoyancy in air if you weigh them on a balance. The buoyancy correction depends on the sample media density, the density of air, and the density of the calibration weight used to calibrate the balance. The buoyancy correction does not account for the buoyancy of the PM itself, because the mass of PM typically accounts for only (0.01 to 0.10) % of the total weight. A correction to this small fraction of mass would be at the most 0.010 %.
(b) PM sample media density. Different PM sample media have different densities. Use the known density of your sample media, or use one of the densities for some common sampling media, as follows:
(1) For PTFE-coated borosilicate glass, use a sample media density of 2300 kg/m^3.
(2) For PTFE membrane (film) media with an integral support ring of polymethylpentene that accounts for 95 % of the media mass, use a sample media density of 920 kg/m^3.
(3) For PTFE membrane (film) media with an integral support ring of PTFE, use a sample media density of 2144 kg/m^3.
(c) Air density. Because a PM balance environment must be tightly controlled to an ambient temperature of (22 ±1) °C and humidity has an insignificant effect on buoyancy correction, air density is primarily a function of atmospheric pressure. Therefore you may use nominal constant values for temperature and humidity in the buoyancy correction equation in Eq. 1065.690-2.
(d) Calibration weight density. Use the stated density of the material of your metal calibration weight. The example calculation in this section uses a density of 8000 kg/m^3, but you should know the density of your weight from the calibration weight supplier or the balance manufacturer if it is an internal weight.
(e) Correction calculation. Correct the PM sample media for buoyancy using the following equations:

$$m_{cor} = m_{uncor} \cdot \left(\frac{1 - \frac{\rho_{air}}{\rho_{weight}}}{1 - \frac{\rho_{air}}{\rho_{media}}} \right)$$

Eq. 1065.690-1

Where:
m_{cor} = PM mass corrected for buoyancy.
m_{uncor} = PM mass uncorrected for buoyancy.
ρ_{air} = density of air in balance environment.

ρ_{weight} = density of calibration weight used to span balance.
ρ_{media} = density of PM sample media, such as a filter.

$$\rho_{air} = \frac{p_{abs} \cdot M_{mix}}{R \cdot T_{amb}}$$

Eq. 1065.690-2

Where:
p_{abs} = absolute pressure in balance environment.
M_{mix} = molar mass of air in balance environment.
R = molar gas constant.
T_{amb} = absolute ambient temperature of balance environment.

Example:
p_{abs} = 99.980 kPa
$T_{sat} = T_{dew}$ = 9.5 °C
Using Eq. 1065.645-1,
p_{H2O} = 1.1866 kPa
Using Eq. 1065.645-3,
x_{H2O} = 0.011868 mol/mol
Using Eq. 1065.640-9,
M_{mix} = 28.83563 g/mol
R = 8.314472 J/(mol·K)
T_{amb} = 20 °C

$$\rho_{air} = \frac{99.980 \cdot 28.83563}{8.314472 \cdot 293.15}$$

ρ_{air} = 1.18282 kg/m^3
m_{uncorr} = 100.0000 mg
ρ_{weight} = 8000 kg/m^3
ρ_{media} = 920 kg/m^3

$$m_{cor} = 100.0000 \cdot \left(\frac{1 - \frac{1.18282}{8000}}{1 - \frac{1.18282}{920}} \right)$$

m_{cor} = 100.1139 mg

§ 1065.695 Data requirements.
(a) To determine the information we require from engine tests, refer to the standard-setting part and request from your Designated Compliance Officer the format used to apply for certification or demonstrate compliance. We may require different information for different purposes, such as for certification applications, approval requests for alternate procedures, selective enforcement audits, laboratory audits, production-line test reports, and field-test reports.
(b) See the standard-setting part and § 1065.25 regarding recordkeeping.
(c) We may ask you the following about your testing, and we may ask you for other information as allowed under the Act:
(1) What approved alternate procedures did you use? For example:
(i) Partial-flow dilution for proportional PM.

(ii) CARB test procedures.
(iii) ISO test procedures.
(2) What laboratory equipment did you use? For example, the make, model, and description of the following:
(i) Engine dynamometer and operator demand.
(ii) Probes, dilution, transfer lines, and sample preconditioning components.
(iii) Batch storage media (such as the bag material or PM filter material).
(3) What measurement instruments did you use? For example, the make, model, and description of the following:
(i) Speed and torque instruments.
(ii) Flow meters.
(iii) Gas analyzers.
(iv) PM balance.
(4) When did you conduct calibrations and performance checks and what were the results? For example, the dates and results of the following:
(i) Linearity verification.
(ii) Interference checks.
(iii) Response checks.
(iv) Leak checks.
(v) Flow meter checks.
(5) What engine did you test? For example, the following:
(i) Manufacturer.
(ii) Family name on engine label.
(iii) Model.
(iv) Model year.
(v) Identification number.
(6) How did you prepare and configure your engine for testing? Consider the following examples:
(i) Dates, hours, duty cycle and fuel used for service accumulation.
(ii) Dates and description of scheduled and unscheduled maintenance.
(iii) Allowable pressure range of intake restriction.
(iv) Allowable pressure range of exhaust restriction.
(v) Charge air cooler volume.
(vi) Charge air cooler outlet temperature, specified engine conditions and location of temperature measurement.
(vii) Fuel temperature and location of measurement.
(viii) Any aftertreatment system configuration and description.
(ix) Any crankcase ventilation configuration and description (e.g., open, closed, PCV, crankcase scavenged).
(x) Number and type of preconditioning cycles.
(7) How did you test your engine? For example:
(i) Constant speed or variable speed.
(ii) Mapping procedure (step or sweep).
(iii) Continuous or batch sampling for each emission.
(iv) Raw or dilute sampling; any dilution-air background sampling.
(v) Duty cycle and test intervals.

(vi) Cold-start, hot-start, warmed-up running.
(vii) Absolute pressure, temperature, and dewpoint of intake and dilution air.
(viii) Simulated engine loads, curb idle transmission torque value.
(ix) Warm-idle speed value.
(x) Simulated vehicle signals applied during testing.
(xi) Bypassed governor controls during testing.
(xii) Date, time, and location of test (e.g., dynamometer laboratory identification).
(xiii) Cooling medium for engine and charge air.
(xiv) Operating temperatures of coolant, head, and block.
(xv) Natural or forced cool-down and cool-down time.
(xvi) Canister loading.
(8) How did you validate your testing? For example, results from the following:
(i) Duty cycle regression statistics for each test interval.
(ii) Proportional sampling.
(iii) Drift.
(iv) Reference PM sample media in PM-stabilization environment.
(9) How did you calculate results? For example, results from the following:
(i) Drift correction.
(ii) Noise correction.
(iii) "Dry-to-wet" correction.
(iv) NMHC, CH_4, and contamination correction.
(v) NO_x humidity correction.
(vi) Brake-specific emission formulation—total mass divided by total work, mass rate divided by power, or ratio of mass to work.
(vii) Rounding emission results.
(10) What were the results of your testing? For example:
(i) Maximum mapped power and speed at maximum power.
(ii) Maximum mapped torque and speed at maximum torque.
(iii) For constant-speed engines: no-load governed speed.
(iv) For constant-speed engines: test torque.
(v) For variable-speed engines: maximum test speed.
(vi) Speed versus torque map.
(vii) Speed versus power map.
(viii) Brake-specific emissions over the duty cycle and each test interval.
(ix) Brake-specific fuel consumption.
(11) What fuel did you use? For example:
(i) Fuel that met specifications of subpart H of this part.
(ii) Alternate fuel.
(iii) Oxygenated fuel.
(12) How did you field test your engine? For example:
(i) Data from paragraphs (c)(1), (3), (4), (5), and (9) of this section.
(ii) Probes, dilution, transfer lines, and sample preconditioning components.
(iii) Batch storage media (such as the bag material or PM filter material).
(iv) Continuous or batch sampling for each emission.
(v) Raw or dilute sampling; any dilution air background sampling.
(vi) Cold-start, hot-start, warmed-up running.

(vii) Intake and dilution air absolute pressure, temperature, dewpoint.
(viii) Curb idle transmission torque value.
(ix) Warm idle speed value, any enhanced idle speed value.
(x) Date, time, and location of test (e.g., identify the testing laboratory).
(xi) Proportional sampling validation.
(xii) Drift validation.
(xiii) Operating temperatures of coolant, head, and block.
(xiv) Vehicle make, model, model year, identification number.

Subpart H—ENGINE FLUIDS, TEST FUELS, ANALYTICAL GASES AND OTHER CALIBRATION STANDARDS

§ 1065.701 General requirements for test fuels.

(a) General. For all emission measurements, use test fuels that meet the specifications in this subpart, unless the standard-setting part directs otherwise. Section 1065.10(c)(1) does not apply with respect to test fuels. Note that the standard-setting parts generally require that you design your emission controls to function properly when using commercially available fuels, even if they differ from the test fuel. Where we specify multiple grades of a certain fuel type (such as diesel fuel with different sulfur concentrations), see the standard-setting part to determine which grade to use.

(b) Fuels meeting alternate specifications. We may allow you to use a different test fuel (such as California Phase 2 gasoline) if it does not affect your ability to show that your engines would comply with all applicable emission standards using the fuel specified in this subpart.

(c) Fuels not specified in this subpart. If you produce engines that run on a type of fuel (or mixture of fuels) that we do not specify in this subpart, you must get our written approval to establish the appropriate test fuel. See the standard-setting part for provisions related to fuels and fuel mixtures not specified in this subpart.

(1) For engines designed to operate on a single fuel, we will generally allow you to use the fuel if you show us all the following things are true:

(i) Show that your engines will use only the designated fuel in service.

(ii) Show that this type of fuel is commercially available.

(iii) Show that operating the engines on the fuel we specify would be inappropriate, as in the following examples:

(A) The engine will not run on the specified fuel.

(B) The engine or emission controls will not be durable or work properly when operating with the specified fuel.

(C) The measured emission results would otherwise be substantially unrepresentative of in-use emissions.

(2) For engines that are designed to operate on different fuel types, the provisions of paragraphs (c)(1)(ii) and (iii) of this section apply with respect to each fuel type.

(3) For engines that are designed to operate on different fuel types as well as continuous mixtures of those fuels, we may require you to test with either the worst-case fuel mixture or the most representative fuel mixture, unless the standard-setting part specifies otherwise.

(d) Fuel specifications. Specifications in this section apply as follows:

(1) Measure and calculate values as described in the appropriate reference procedure. Record and report final values expressed to at least the same number of decimal places as the applicable limit value. The right-most digit for each limit value is significant unless specified otherwise. For example, for a specified distillation temperature of 60 °C, determine the test fuel's value to at least the nearest whole number.

(2) The fuel parameters specified in this subpart depend on measurement procedures that are incorporated by reference. For any of these procedures, you may instead rely upon the procedures identified in 40 CFR part 80 for measuring the same parameter. For example, we may identify different reference procedures for measuring gasoline parameters in 40 CFR 80.46.

(e) Two-stroke fuel/oil mixing. For two-stroke engines, use a fuel/oil mixture meeting the manufacturer's specifications.

(f) Service accumulation and field testing fuels. If we do not specify a service-accumulation or field-testing fuel in the standard-setting part, use an appropriate commercially available fuel such as those meeting minimum specifications from the following table:

TABLE 1 OF § 1065.701–EXAMPLES OF SERVICE-ACCUMULATION AND FIELD-TESTING FUELS

Fuel category	Subcategory	Reference procedure[1]
Diesel	Light distillate and light blends with residual	ASTM D975
	Middle distillate	ASTM D6985
	Biodiesel (B100)	ASTM D6751
Intermediate and residual fuel	All	See § 1065.705
Gasoline	Automotive gasoline	ASTM D4814
	Automotive gasoline with ethanol concentration up to 10 volume %.	ASTM D4814
Alcohol	Ethanol (E51-83)	ASTM D5798
	Methanol (M70-M85)	ASTM D5797
Aviation fuel	Aviation gasoline	ASTM D910
	Gas turbine	ASTM D1655
	Jet B wide cut	ASTM D6615
Gas turbine fuel	General	ASTM D2880

[1]ASTM specifications are incorporated by reference in § 1065.1010.

§ 1065.703 Distillate diesel fuel.

(a) Distillate diesel fuels for testing must be clean and bright, with pour and cloud points adequate for proper engine operation.

(b) There are three grades of #2 diesel fuel specified for use as a test fuel. See the standard-setting part to determine which grade to use. If the standard-setting part does not specify which grade to use, use good engineering judgment to select the grade that represents the fuel on which the engines will operate in use. The three grades are specified in Table 1 of this section.

(c) You may use the following nonmetallic additives with distillate diesel fuels:

(1) Cetane improver.

(2) Metal deactivator.

(3) Antioxidant, dehazer.

(4) Rust inhibitor.

(5) Pour depressant.

(6) Dye.

(7) Dispersant.

(8) Biocide.

TABLE 1 OF § 1065.703–TEST FUEL SPECIFICATIONS FOR DISTILLATE DIESEL FUEL

Property	Unit	Ultra Low Sulfur	Low Sulfur	High Sulfur	Reference Procedure[1]
Cetane Number	—	40 - 50	40 - 50	40 - 50	ASTM D613
Distillation range: Initial boiling point 10 pct. point 50 pct. point 90 pct. point Endpoint	°C	 171 - 204 204 - 238 243 - 282 293 - 332 321 - 366	 171 - 204 204 - 238 243 - 282 293 - 332 321 - 366	 171 - 204 204 - 238 243 - 282 293 - 332 321 - 366	ASTM D86
Gravity	°API	32 - 37	32 - 37	32 - 37	ASTM D4052
Total sulfur, ultra low sulfur	mg/kg	7 – 15			See 40 CFR 80.580
Total sulfur, low and high sulfur	mg/kg		300 - 500	800 - 2500	ASTM D2622or alternates as allowed under 40 CFR 80.580
Aromatics, min. (Remainder shall be paraffins, naphthenes, and olefins)	g/kg	100	100	100	ASTM D5186
Flashpoint, min.	°C	54	54	54	ASTM D93
Kinematic Viscosity	cSt	2.0 - 3.2	2.0 - 3.2	2.0 - 3.2	ASTM D445

[1]ASTM procedures are incorporated by reference in § 1065.1010. See § 1065.701(d) for other allowed procedures.

§ 1065.705 Residual and intermediate residual fuel.

This section describes the specifications for fuels meeting the definition of residual fuel in 40 CFR 80.2, including fuels marketed as intermediate fuel. Residual fuels for service accumulation and any testing must meet the following specifications:

(a) The fuel must be a commercially available fuel that is representative of the fuel that will be used by the engine in actual use.

(b) The fuel must be free of used lubricating oil. Demonstrate this by showing that the fuel meets at least one of the following specifications.

(1) Zinc is at or below 15 mg per kg of fuel based on the procedures specified in IP470, IP501, or ISO 8217 (incorporated by reference in § 1065.1010).

(2) Phosphorus is at or below 15 mg per kg of fuel based on the procedures specified in IP500, IP501, or ISO 8217 (incorporated by reference in § 1065.1010).

(3) Calcium is at or below 30 mg per kg of fuel based on the procedures specified in IP470, IP501, or ISO 8217 (incorporated by reference in § 1065.1010).

(c) The fuel must meet the specifications for one of the categories in the following table:

TABLE 1 OF § 1065.705–SERVICE ACCUMULATION AND TEST FUEL SPECIFICATIONS FOR RESIDUAL FUEL

Property	Unit	Category ISO-F-										Reference Procedure [1]
		RMA 30	RMB 30	RMD 80	RME 180	RMF 180	RMG 380	RMH 380	RMK 380	RMH 700	RMK 700	
Density at 15 °C, max.	kg/m^3	960.0	975.0	980.0	991.0		991.0		1010.0	991.0	1010.0	ISO 3675 or ISO 12185 (see also ISO 8217)
Kinematic viscosity at 50 °C, max.	cSt	30.0		80.0	180.0		380.0		700.0			ISO 3104
Flash point, min.	°C	60		60	60		60		60			ISO 2719 (see also ISO 8217)
Pour point (upper) Winter quality, max. Summer quality, max.	°C	 0 6	 24 24	 30 30	 30 30		 30 30		 30 30			ISO 3016
Carbon residue, max.	(kg/kg) %	10		14	15	20	18	22	22			ISO 10370
Ash, max.	(kg/kg) %	0.10		0.10	0.10	0.15	0.15		0.15			ISO 6245
Water, max.	(m^3/m^3) %	0.5		0.5	0.5		0.5		0.5			ISO 3733
Sulfur, max.	(kg/kg) %	3.50		4.00	4.50		4.50		4.50			ISO 8754 or ISO 14596 (see also ISO 8217)
Vanadium, max.	mg/kg	150		350	200	500	300	600	600			ISO 14597 or IP 501 or IP 470 (see also ISO 8217)
Total sediment potential, max.	(kg/kg) %	0.10		0.10	0.10		0.10		0.10			ISO 10307-2 (see also ISO 8217)
Aluminium plus silicon, max.	mg/kg	80		80	80		80		80			ISO 10478 or IP 501 or IP 470 (see also ISO 8217:2012)

[1] ISO procedures are incorporated by reference in § 1065.1010. See § 1065.701(d) for other allowed procedures.

§ 1065.710 Gasoline.

(a) This section specifies test fuel properties for gasoline with ethanol (low-level blend only) and for gasoline without ethanol. Note that the "fuel type" for the fuels specified in paragraphs (b) and (c) of this section is considered to be gasoline. In contrast, fuels with higher ethanol concentrations, such as fuel containing 82 percent ethanol, are considered to be ethanol fuels rather than gasoline. We specify some test fuel parameters that apply uniquely for low-temperature testing and for testing at altitudes above 1,219 m. For all other testing, use the test fuel parameters specified for general testing. Unless the standard-setting part specifies otherwise, use the fuel specified in paragraph (c) of this section for general testing.

(b) The following specifications apply for a blended gasoline test fuel that has nominally 10 % ethanol (commonly called E10 test fuel):

(1) Prepare the blended test fuel from typical refinery gasoline blending components. You may not use pure compounds, except as follows:

(i) You may use neat ethanol as a blendstock.

(ii) You may adjust the test fuel's vapor pressure by adding butane.

(iii) You may adjust the test fuel's benzene content by adding benzene.

(iv) You may adjust the test fuel's sulfur content by adding sulfur compounds that are representative of those found with in-use fuels.

(2) Table 1 of this section identifies limit values consistent with the units in the reference procedure for each fuel property. These values are generally specified in international units. Values presented in parentheses are for information only. Table 1 follows:

TABLE 1 OF § 1065.710–TEST FUEL SPECIFICATIONS FOR A LOW-LEVEL ETHANOL-GASOLINE BLEND

Property	Unit	SPECIFICATION			Reference Procedure[1]
		General Testing	Low-Temperature Testing	High Altitude Testing	
Antiknock Index (R+M)/2	-	87.0 - 88.4[2]		87.0 Minimum	ASTM D2699 and D2700
Sensitivity (R-M)	-	7.5 Minimum			ASTM D2699 and D2700
Dry Vapor Pressure Equivalent (*DVPE*)[3,4]	kPa (psi)	60.0-63.4 (8.7-9.2)	77.2-81.4 (11.2-11.8)	52.4-55.2 (7.6-8.0)	ASTM D5191
Distillation[4] 10% evaporated	°C (°F)	49-60 (120-140)	43-54 (110-130)	49-60 (120-140)	ASTM D86
50% evaporated	°C (°F)	88-99 (190-210)			
90% evaporated	°C (°F)	157-168 (315-335)			
Evaporated final boiling point	°C (°F)	193-216 (380-420)			
Residue	milliliter	2.0 Maximum			
Total Aromatic Hydrocarbons	volume %	21.0-25.0			ASTM D5769
C6 Aromatics (benzene)	volume %	0.5-0.7			
C7 Aromatics (toluene)	volume %	5.2-6.4			
C8 Aromatics	volume %	5.2-6.4			
C9 Aromatics	volume %	5.2-6.4			
C10+ Aromatics	volume %	4.4-5.6			
Olefins[5]	mass %	4.0-10.0			ASTM D6550
Ethanol blended	volume %	9.6-10.0			See paragraph (b)(3) of this section.
Ethanol confirmatory[6]	volume %	9.4-10.2			ASTM D4815 or D5599
Total Content of Oxygenates Other than Ethanol[6]	volume %	0.1 Maximum			ASTM D4815 or D5599
Sulfur	mg/kg	8.0-11.0			ASTM D2622, D5453 or D7039
Lead	g/liter	0.0026 Maximum			ASTM D3237
Phosphorus	g/liter	0.0013 Maximum			ASTM D3231
Copper Corrosion	-	No. 1 Maximum			ASTM D130
Solvent-Washed Gum Content	mg/100 milliliter	3.0 Maximum			ASTM D381
Oxidation Stability	minute	1000 Minimum			ASTM D525

[1]ASTM procedures are incorporated by reference in § 1065.1010. See § 1065.701(d) for other allowed procedures.
[2]Octane specifications apply only for testing related to exhaust emissions. For engines or vehicles that require the use of premium fuel, as described in paragraph (d) of this section, the adjusted specification for antiknock index is a minimum value of 91.0; no maximum value applies. All other specifications apply for this high-octane fuel.
[3]Calculate dry vapor pressure equivalent, *DVPE*, based on the measured total vapor pressure, p_T, using the following equation: $DVPE$ (kPa) = $0.956 \cdot p_T - 2.39$ or $DVPE$ (psi) = $0.956 \cdot p_T - 0.347$. *DVPE* is intended to be equivalent to Reid Vapor Pressure using a different test method.
[4]Parenthetical values are shown for informational purposes only.
[5]The reference procedure prescribes measurement of olefin concentration in mass %. Multiply this result by 0.857 and round to the first decimal place to determine the olefin concentration in volume %.
[6]ASTM D5599 prescribes concentration measurements for ethanol and other oxygenates in mass %. Convert results to volume % as specified in Section 14.3 of ASTM D4815.

(3) The ethanol-blended specification in Table 1 of this section is based on the volume % ethanol content of the fuel as determined during blending by the fuel supplier and as stated by the supplier at the time of fuel delivery. Use good engineering judgment to determine the volume % of ethanol based on the volume of each blendstock. We recommend using a flow-based or gravimetric procedure that has an accuracy and repeatability of ± 0.1 %.

(c) The specifications of this paragraph (c) apply for testing with neat gasoline. This is sometimes called indolene or E0 test fuel. Gasoline for testing must have octane values that represent commercially available fuels for the appropriate application. Test fuel specifications apply as follows:

TABLE 2 OF § 1065.710–TEST FUEL SPECIFICATIONS FOR NEAT (E0) GASOLINE

Property	Unit	SPECIFICATION		Reference Procedure[1]
		General Testing	Low-Temperature Testing	
Distillation Range: Evaporated initial boiling point 10% evaporated 50% evaporated 90% evaporated Evaporated final boiling point	°C	 24 - 35[2] 49 - 57 93 - 110 149 - 163 Maximum, 213	 24 - 36 37 - 48 82 - 101 158 - 174 Maximum, 212	ASTM D86
Hydrocarbon composition: Olefins Aromatics Saturates	volume %	 Maximum, 10 Maximum, 35 Remainder	 Maximum, 17.5 Maximum, 30.4 Remainder	ASTM D1319
Lead	g/liter	Maximum, 0.013	Maximum, 0.013	ASTM D3237
Phosphorous	g/liter	Maximum, 0.0013	Maximum, 0.005	ASTM D3231
Total sulfur	mg/kg	Maximum, 80	Maximum, 80	ASTM D2622
Dry vapor pressure equivalent[3]	kPa	60.0 - 63.4[2,4]	77.2 - 81.4	ASTM D5191

[1]ASTM procedures are incorporated by reference in § 1065.1010. See § 1065.701(d) for other allowed procedures.

[2]For testing at altitudes above 1219 m, the specified initial boiling point range is (23.9 to 40.6) °C and the specified volatility range is (52.0 to 55.2) kPa.

[3]Calculate dry vapor pressure equivalent, *DVPE*, based on the measured total vapor pressure, p_T, in kPa using the following equation: $DVPE$ (kPa) = $0.956 \cdot p_T - 2.39$ or $DVPE$ (psi) = $0.956 \cdot p_T - 0.347$. *DVPE* is intended to be equivalent to Reid Vapor Pressure using a different test method.

[4]For testing unrelated to evaporative emissions, the specified range is (55.2 to 63.4) kPa.

(d) Use the high-octane gasoline specified in paragraph (b) of this section only for engines or vehicles for which the manufacturer conditions the warranty on the use of premium gasoline.

§ 1065.715 Natural gas.

(a) Except as specified in paragraph (b) of this section, natural gas for testing must meet the specifications in the following table:

TABLE 1 OF § 1065.715–TEST FUEL SPECIFICATIONS FOR NATURAL GAS

Property	Value[1]
Methane, CH_4	Minimum, 0.87 mol/mol
Ethane, C_2H_6	Maximum, 0.055 mol/mol
Propane, C_3H_8	Maximum, 0.012 mol/mol
Butane, C_4H_{10}	Maximum, 0.0035 mol/mol
Pentane, C_5H_{12}	Maximum, 0.0013 mol/mol
C_6 and higher	Maximum, 0.001 mol/mol
Oxygen	Maximum, 0.001 mol/mol
Inert gases (sum of CO_2 and N_2)	Maximum, 0.051 mol/mol

[1] Demonstrate compliance with fuel specifications based on the reference procedures in ASTM D1945 (incorporated by reference in § 1065.1010), or on other measurement procedures using good engineering judgment. See § 1065.701(d) for other allowed procedures.

(b) In certain cases you may use test fuel not meeting the specifications in paragraph (a) of this section, as follows:
(1) You may use fuel that your in-use engines normally use, such as pipeline natural gas.
(2) You may use fuel meeting alternate specifications if the standard-setting part allows it.
(3) You may ask for approval to use fuel that does not meet the specifications in paragraph (a) of this section, but only if using the fuel would not adversely affect your ability to demonstrate compliance with the applicable standards.
(c) When we conduct testing using natural gas, we will use fuel that meets the specifications in paragraph (a) of this section.
(d) At ambient conditions, natural gas must have a distinctive odor detectable down to a concentration in air not more than one-fifth the lower flammable limit.

§ 1065.720 Liquefied petroleum gas.
(a) Except as specified in paragraph (b) of this section, liquefied petroleum gas for testing must meet the specifications in the following table:

TABLE 1 OF § 1065.720–TEST FUEL SPECIFICATIONS FOR LIQUEFIED PETROLEUM GAS

Property	Value	Reference Procedure[1]
Propane, C_3H_8	Minimum, 0.85 m^3/m^3	ASTM D2163
Vapor pressure at 38 °C	Maximum, 1400 kPa	ASTM D1267or D2598[2]
Volatility residue (evaporated temperature, 35 °C)	Maximum, -38 °C	ASTM D1837
Butanes	Maximum, 0.05 m^3/m^3	ASTM D2163
Butenes	Maximum, 0.02 m^3/m^3	ASTM D2163
Pentenes and heavier	Maximum, 0.005 m^3/m^3	ASTM D2163
Propene	Maximum, 0.1 m^3/m^3	ASTM D2163
Residual matter (residue on evaporation of 100 ml oil stain observation)	Maximum, 0.05 ml pass[3]	ASTM D2158
Corrosion, copper strip	Maximum, No. 1	ASTM D1838
Sulfur	Maximum, 80 mg/kg	ASTM D2784
Moisture content	pass	ASTM D2713

[1]ASTM procedures are incorporated by reference in § 1065.1010. See § 1065.701(d) for other allowed procedures.
[2]If these two test methods yield different results, use the results from ASTM D1267.
[3]The test fuel must not yield a persistent oil ring when you add 0.3 ml of solvent residue mixture to a filter paper in 0.1 ml increments and examine it in daylight after two minutes.

(b) In certain cases you may use test fuel not meeting the specifications in paragraph (a) of this section, as follows:
(1) You may use fuel that your in-use engines normally use, such as commercial-quality liquefied petroleum gas.

(2) You may use fuel meeting alternate specifications if the standard-setting part allows it.
(3) You may ask for approval to use fuel that does not meet the specifications in paragraph (a) of this section, but only if using the fuel would not adversely affect your ability to demonstrate compliance with the applicable standards.
(c) When we conduct testing using liquefied petroleum gas, we will use fuel that meets the specifications in paragraph (a) of this section.
(d) At ambient conditions, liquefied petroleum gas must have a distinctive odor detectable down to a concentration in air not more than one-fifth the lower flammable limit.

§ 1065.725 High-level ethanol-gasoline blends.
For testing vehicles capable of operating on a high-level ethanol-gasoline blend, create a test fuel as follows:
(a) Add ethanol to an E10 fuel meeting the specifications described in § 1065.710 until the ethanol content of the blended fuel is between 80 and 83 volume %.
(b) You may alternatively add ethanol to a gasoline base fuel with no ethanol if you can demonstrate that such a base fuel blended with the proper amount of ethanol would meet all the specifications for E10 test fuel described in § 1065.710, other than the ethanol content.
(c) The ethanol used for blending must be either denatured ethanol meeting the specifications in 40 CFR 80.1610, or fuel-grade ethanol with no denaturant. Account for the volume of any denaturant when calculating volumetric percentages.
(d) The blended test fuel must have a dry vapor pressure equivalent between 41.5 and 45.1 kPa (6.0 and 6.5 psi) when measured using the procedure specified in § 1065.710. You may add commercial grade butane as needed to meet this specification.

§ 1065.740 Lubricants.
(a) Use commercially available lubricating oil that represents the oil that will be used in your engine in use.
(b) You may use lubrication additives, up to the levels that the additive manufacturer recommends.

§ 1065.745 Coolants.
(a) You may use commercially available antifreeze mixtures or other coolants that will be used in your engine in use.
(b) For laboratory testing of liquid-cooled engines, you may use water with or without rust inhibitors.
(c) For coolants allowed in paragraphs (a) and (b) of this section, you may use rust inhibitors and additives required for lubricity, up to the levels that the additive manufacturer recommends.

§ 1065.750 Analytical gases.
Analytical gases must meet the accuracy and purity specifications of this section, unless you can show that other specifications would not affect your ability to show that you comply with all applicable emission standards.
(a) Subparts C, D, F, and J of this part refer to the following gas specifications:
(1) Use purified gases to zero measurement instruments and to blend with calibration gases. Use gases with contamination no higher than the highest of the following values in the gas cylinder or at the outlet of a zero-gas generator:

(i) 2 % contamination, measured relative to the flow-weighted mean concentration expected at the standard. For example, if you would expect a flow-weighted CO concentration of 100.0 μmol/mol, then you would be allowed to use a zero gas with CO contamination less than or equal to 2.000 μmol/mol.
(ii) Contamination as specified in the following table:

TABLE 1 OF § 1065.750–GENERAL SPECIFICATIONS FOR PURIFIED GASES[1]

Constituent	Purified Air	Purified N_2
THC (C_1-equivalent)	≤ 0.05 μmol/mol	≤ 0.05 μmol/mol
CO	≤ 1 μmol/mol	≤ 1 μmol/mol
CO_2	≤ 10 μmol/mol	≤ 10 μmol/mol
O_2	0.205 to 0.215 mol/mol	≤ 2 μmol/mol
NO_x	≤ 0.02 μmol/mol	≤ 0.02 μmol/mol
N_2O[2]	≤ 0.02 μmol/mol	≤ 0.02 μmol/mol

[1]We do not require these levels of purity to be NIST-traceable.
[2]The N_2O limit applies only if the standard-setting part requires you to report N_2O or certify to an N_2O standard.

(2) Use the following gases with a FID analyzer:
(i) FID fuel. Use FID fuel with a stated H_2 concentration of (0.39 to 0.41) mol/mol, balance He or N_2, and a stated total hydrocarbon concentration of 0.05 μmol/mol or less. For GC-FIDs that measure methane (CH_4) using a FID fuel that is balance N_2, perform the CH_4 measurement as described in SAE J1151 (incorporated by reference in § 1065.1010).
(ii) FID burner air. Use FID burner air that meets the specifications of purified air in paragraph (a)(1) of this section. For field testing, you may use ambient air.
(iii) FID zero gas. Zero flame-ionization detectors with purified gas that meets the specifications in paragraph (a)(1) of this section, except that the purified gas O_2 concentration may be any value. Note that FID zero balance gases may be any combination of purified air and purified nitrogen. We recommend FID analyzer zero gases that contain approximately the expected flow-weighted mean concentration of O_2 in the exhaust sample during testing.
(iv) FID propane span gas. Span and calibrate THC FID with span concentrations of propane, C_3H_8. Calibrate on a carbon number basis of one (C_1). For example, if you use a C_3H_8 span gas of concentration 200 μmol/mol, span a FID to respond with a value of 600 μmol/mol. Note that FID span balance gases may be any combination of purified air and purified nitrogen. We recommend FID analyzer span gases that contain approximately the flow-weighted mean concentration of O_2 expected during testing. If the expected O_2 concentration in the exhaust sample is zero, we recommend using a balance gas of purified nitrogen.
(v) FID CH_4 span gas. If you always span and calibrate a CH_4 FID with a nonmethane cutter, then span and calibrate the FID with span concentrations of CH_4. Calibrate on a carbon number basis of one (C_1). For example, if you use a CH_4 span gas of concentration 200 μmol/mol, span a FID to respond with a value of 200 μmol/mol. Note that FID span balance gases may be any combination of purified air and purified nitrogen. We recommend FID analyzer span gases that contain approximately the expected flow-weighted mean concentration of O_2 in the exhaust sample during testing. If the expected O_2 concentration in the exhaust sample is zero, we recommend using a balance gas of purified nitrogen.

(3) Use the following gas mixtures, with gases traceable within ±1 % of the NIST-accepted value or other gas standards we approve:
(i) CH_4, balance purified air and/or N_2 (as applicable).
(ii) C_2H_6, balance purified air and/or N_2 (as applicable).
(iii) C_3H_8, balance purified air and/or N_2 (as applicable).
(iv) CO, balance purified N_2.
(v) CO_2, balance purified N_2.
(vi) NO, balance purified N_2.
(vii)) NO_2, balance purified air.
(viii) O_2, balance purified N_2.
(ix) C_3H_8, CO, CO_2, NO, balance purified N_2.
(x) C_3H_8, CH_4, CO, CO_2, NO, balance purified N_2.
(xi) N_2O, balance purified air and/or N_2 (as applicable).
(4) You may use gases for species other than those listed in paragraph (a)(3) of this section (such as methanol in air, which you may use to determine response factors), as long as they are traceable to within ±3 % of the NIST-accepted value or other similar standards we approve, and meet the stability requirements of paragraph (b) of this section.
(5) You may generate your own calibration gases using a precision blending device, such as a gas divider, to dilute gases with purified N_2 or purified air. If your gas divider meets the specifications in § 1065.248, and the gases being blended meet the requirements of paragraphs (a)(1) and (3) of this section, the resulting blends are considered to meet the requirements of this paragraph (a).
(b) Record the concentration of any calibration gas standard and its expiration date specified by the gas supplier.
(1) Do not use any calibration gas standard after its expiration date, except as allowed by paragraph (b)(2) of this section.
(2) Calibration gases may be relabeled and used after their expiration date as follows:
(i) Alcohol/carbonyl calibration gases used to determine response factors according to subpart I of this part may be relabeled as specified in subpart I of this part.
(ii) Other gases may be relabeled and used after the expiration date only if we approve it in advance.
(c) Transfer gases from their source to analyzers using components that are dedicated to controlling and transferring only those gases. For example, do not use a regulator, valve, or transfer line for zero gas if those components were previously used to transfer a different gas mixture. We recommend that you label regulators, valves, and transfer lines to prevent contamination. Note that even small traces of a gas mixture in the dead volume of a regulator, valve, or transfer line can diffuse upstream into a high-pressure volume of gas, which would contaminate the entire high-pressure gas source, such as a compressed-gas cylinder.
(d) To maintain stability and purity of gas standards, use good engineering judgment and follow the gas standard supplier's recommendations for storing and handling zero, span, and calibration gases. For example, it may be necessary to store bottles of condensable gases in a heated environment.

§ 1065.790 Mass standards.
(a) PM balance calibration weights. Use PM balance calibration weights that are certified as NIST-traceable within 0.1 % uncertainty. Calibration weights may be certified by any

calibration lab that maintains NIST-traceability. Make sure your highest calibration weight has no greater than ten times the mass of an unused PM-sample medium.

(b) Dynamometer calibration weights. [Reserved]

Subpart I—TESTING WITH OXYGENATED FUELS

§ 1065.801 Applicability.

(a) This subpart applies for testing with oxygenated fuels. Unless the standard-setting part specifies otherwise, the requirements of this subpart do not apply for fuels that contain less than 25 % oxygenated compounds by volume. For example, you generally do not need to follow the requirements of this subpart for tests performed using a fuel containing 10 % ethanol and 90 % gasoline, but you must follow these requirements for tests performed using a fuel containing 85 % ethanol and 15 % gasoline.
(b) Section 1065.805 applies for all other testing that requires measurement of any alcohols or carbonyls.
(c) This subpart specifies sampling procedures and calculations that are different than those used for non-oxygenated fuels. All other test procedures of this part 1065 apply for testing with oxygenated fuels.

§ 1065.805 Sampling system.

(a) Dilute engine exhaust, and use batch sampling to collect proportional flow-weighted dilute samples of the applicable alcohols and carbonyls. You may not use raw sampling for alcohols and carbonyls.
(b) You may collect background samples for correcting dilution air for background concentrations of alcohols and carbonyls.
(c) Maintain sample temperatures within the dilution tunnel, probes, and sample lines high enough to prevent aqueous condensation up to the point where a sample is collected to prevent loss of the alcohols and carbonyls by dissolution in condensed water. Use good engineering judgment to ensure that surface reactions of alcohols and carbonyls do not occur, as surface decomposition of methanol has been shown to occur at temperatures greater than 120 °C in exhaust from methanol-fueled engines.
(d) You may bubble a sample of the exhaust through water to collect alcohols for later analysis. You may also use a photoacoustic analyzer to quantify ethanol and methanol in an exhaust sample as described in § 1065.269.
(e) Sample the exhaust through cartridges impregnated with 2,4-dinitrophenylhydrazine to collect carbonyls for later analysis. If the standard-setting part specifies a duty cycle that has multiple test intervals (such as multiple engine starts or an engine-off soak phase), you may proportionally collect a single carbonyl sample for the entire duty cycle. For example, if the standard-setting part specifies a six-to-one weighting of hot-start to cold-start emissions, you may collect a single carbonyl sample for the entire duty cycle by using a hot-start sample flow rate that is six times the cold-start sample flow rate.
(f) You may sample alcohols or carbonyls using "California Non-Methane Organic Gas Test Procedures" (incorporated by reference in § 1065.1010). If you use this method, follow its calculations to determine the mass of the alcohol/carbonyl in the exhaust sample, but follow subpart G of this part for all other calculations (40 CFR part 1066, subpart G, for vehicle testing).
(g) Use good engineering judgment to sample other oxygenated hydrocarbon compounds in the exhaust.

§ 1065.845 Response factor determination.

Since FID analyzers generally have an incomplete response to alcohols and carbonyls, determine each FID analyzer's alcohol/carbonyl response factor ($RF_{OHCi[THC\text{-}FID]}$) after FID optimization to subtract those responses from the FID reading. Use the most recently determined alcohol/carbonyl response factors to compensate for alcohol/carbonyl response. You are not required to determine the response factor for a compound unless you will subtract its response to compensate for a response.

(a) You may generate response factors as described in paragraph (b) of this section, or you may use the following default response factors, consistent with good engineering judgment:

TABLE 1 OF § 1065.845–DEFAULT VALUES FOR THC FID RESPONSE FACTOR RELATIVE TO PROPANE ON A C_1-EQUIVALENT BASIS

Compound	Response factor (*RF*)
acetaldehyde	0.50
ethanol	0.75
formaldehyde	0.00
methanol	0.63
propanol	0.85

(b) Determine the alcohol/carbonyl response factors as follows:

(1) Select a C_3H_8 span gas that meets the specifications of § 1065.750. Note that FID zero and span balance gases may be any combination of purified air or purified nitrogen that meets the specifications of § 1065.750. We recommend FID analyzer zero and span gases that contain approximately the flow-weighted mean concentration of O_2 expected during testing. Record the C_3H_8 concentration of the gas.

(2) Select or prepare an alcohol/carbonyl calibration gas that meets the specifications of § 1065.750 and has a concentration typical of the peak concentration expected at the hydrocarbon standard. Record the calibration concentration of the gas.

(3) Start and operate the FID analyzer according to the manufacturer's instructions.

(4) Confirm that the FID analyzer has been calibrated using C_3H_8. Calibrate on a carbon number basis of one (C_1). For example, if you use a C_3H_8 span gas of concentration 200 μmol/mol, span the FID to respond with a value of 600 μmol/mol.

(5) Zero the FID. Note that FID zero and span balance gases may be any combination of purified air or purified nitrogen that meets the specifications of § 1065.750. We recommend FID analyzer zero and span gases that contain approximately the flow-weighted mean concentration of O_2 expected during testing.

(6) Span the FID with the C_3H_8 span gas that you selected under paragraph (a)(1) of this section.

(7) Introduce at the inlet of the FID analyzer the alcohol/carbonyl calibration gas that you selected under paragraph (a)(2) of this section.

(8) Allow time for the analyzer response to stabilize. Stabilization time may include time to purge the analyzer and to account for its response.

(9) While the analyzer measures the alcohol/carbonyl concentration, record 30 seconds of sampled data. Calculate the arithmetic mean of these values.

(10) Divide the mean measured concentration by the recorded span concentration of the alcohol/carbonyl calibration gas on a C_1-equivalent basis. The result is the FID analyzer's response factor for alcohol/carbonyl, $RF_{OHCi[THC\text{-}FID]}$ on a C_1-equivalent basis.

(c) Alcohol/carbonyl calibration gases must remain within ±2 % of the labeled concentration. You must demonstrate the stability based on a quarterly measurement procedure with a precision of ±2 % percent or another method that we approve. Your measurement procedure may incorporate multiple measurements. If the true concentration of the gas changes deviates by more than ±2 %, but less than ±10 %, the gas may be relabeled with the new concentration.

§ 1065.850 Calculations.
Use the calculations specified in § 1065.665 to determine THCE or NMHCE and the calculations specified in 40 CFR 1066.635 to determine NMOG.

Subpart J—FIELD TESTING AND PORTABLE EMISSION MEASUREMENT SYSTEMS

§ 1065.901 Applicability.

(a) Field testing. This subpart specifies procedures for field-testing engines to determine brake-specific emissions using portable emission measurement systems (PEMS). These procedures are designed primarily for in-field measurements of engines that remain installed in vehicles or equipment the field. Field-test procedures apply to your engines only as specified in the standard-setting part.

(b) Laboratory testing. You may use PEMS for any testing in a laboratory or similar environment without restriction or prior approval if the PEMS meets all applicable specifications for laboratory testing. You may also use PEMS for any testing in a laboratory or similar environment if we approve it in advance, subject to the following provisions:

(1) Follow the laboratory test procedures specified in this part 1065, according to § 1065.905(e).

(2) Do not apply any PEMS-related field-testing adjustments or measurement allowances to laboratory emission results or standards.

(3) Do not use PEMS for laboratory measurements if it prevents you from demonstrating compliance with the applicable standards. Some of the PEMS requirements in this part 1065 are less stringent than the corresponding laboratory requirements. Depending on actual PEMS performance, you might therefore need to account for some additional measurement uncertainty when using PEMS for laboratory testing. If we ask, you must show us by engineering analysis that any additional measurement uncertainty due to your use of PEMS for laboratory testing is offset by the extent to which your engine's emissions are below the applicable standards. For example, you might show that PEMS versus laboratory uncertainty represents 5 % of the standard, but your engine's deteriorated emissions are at least 20 % below the standard for each pollutant.

§ 1065.905 General provisions.

(a) General. Unless the standard-setting part specifies deviations from the provisions of this subpart, field testing and laboratory testing with PEMS must conform to the provisions of this subpart. Use good engineering judgment when testing with PEMS to ensure proper function of the instruments under test conditions. For example, this may require additional maintenance or calibration for field testing or may require verification after moving the PEMS unit.

(b) Field-testing scope. Field testing conducted under this subpart may include any normal in-use operation of an engine.

(c) Field testing and the standard-setting part. This subpart J specifies procedures for field-testing various categories of engines. See the standard-setting part for specific provisions for a particular type of engine. Before using this subpart's procedures for field testing, read the standard-setting part to answer at least the following questions:

(1) How many engines must I test in the field?

(2) How many times must I repeat a field test on an individual engine?

(3) How do I select vehicles for field testing?

(4) What maintenance steps may I take before or between tests?

(5) What data are needed for a single field test on an individual engine?

(6) What are the limits on ambient conditions for field testing? Note that the ambient condition limits in § 1065.520 do not apply for field testing. Field testing may occur at any ambient temperature, pressure, and humidity unless otherwise specified in the standard-setting part.
(7) Which exhaust constituents do I need to measure?
(8) How do I account for crankcase emissions?
(9) Which engine and ambient parameters do I need to measure?
(10) How do I process the data recorded during field testing to determine if my engine meets field-testing standards? How do I determine individual test intervals? Note that "test interval" is defined in subpart K of this part 1065.
(11) Should I warm up the test engine before measuring emissions, or do I need to measure cold-start emissions during a warm-up segment of in-use operation?
(12) Do any unique specifications apply for test fuels?
(13) Do any special conditions invalidate parts of a field test or all of a field test?
(14) Does any special measurement allowance apply to field-test emission results or standards, based on using PEMS for field-testing versus using laboratory equipment and instruments for laboratory testing?
(15) Do results of initial field testing trigger any requirement for additional field testing or laboratory testing?
(16) How do I report field-testing results?
(d) Field testing and this part 1065. Use the following specifications for field testing:
(1) Use the applicability and general provisions of subpart A of this part.
(2) Use equipment specifications in § 1065.101 and in the sections from § 1065.140 to the end of subpart B of this part, with the exception of § 1065.140(e)(1) and (4), § 1065.170(c)(1)(vi), and § 1065.195(c). Section 1065.910 identifies additional equipment that is specific to field testing.
(i) For PM samples, configure dilution systems as follows:
(A) Use good engineering judgment to control dilution air temperature. If you choose to directly and actively control dilution air temperature, set the temperature to 25 °C.
(B) Control sample temperature to a (32 to 62) °C tolerance, as measured anywhere within 20 cm upstream or downstream of the PM storage media (such as a filter or oscillating crystal), where the tolerance applies only during sampling.
(C) Maintain filter face velocity to a (5 to 100) cm/s tolerance for flow-through media. Compliance with this provision can be verified by engineering analysis. This provision does not apply for non-flow-through media.
(ii) For inertial PM balances, there is no requirement to control the stabilization environment temperature or dewpoint.
(3) Use measurement instruments in subpart C of this part, except as specified in § 1065.915.
(4) Use calibrations and verifications in subpart D of this part, except as specified in § 1065.920. Section 1065.920 also specifies additional calibrations and verifications for field testing.
(5) Use the provisions of the standard-setting part for selecting and maintaining engines in the field instead of the specifications in subpart E of this part.
(6) Use the procedures in § § 1065.930 and 1065.935 to start and run a field test. If you use a gravimetric balance for PM, weigh PM samples according to § § 1065.590 and 1065.595.
(7) Use the calculations in subpart G of this part to calculate emissions over each test interval. Note that "test interval" is defined in subpart K of this part 1065, and that the standard setting part indicates how to determine test intervals for your engine. Section 1065.940 specifies additional calculations for field testing. Use any calculations specified in the standard-setting

part to determine if your engines meet the field-testing standards. The standard-setting part may also contain additional calculations that determine when further field testing is required.
(8) Use a typical in-use fuel meeting the specifications of § 1065.701(d).
(9) Use the lubricant and coolant specifications in § 1065.740 and § 1065.745.
(10) Use the analytical gases and other calibration standards in § 1065.750 and § 1065.790.
(11) If you are testing with oxygenated fuels, use the procedures specified for testing with oxygenated fuels in subpart I of this part.
(12) Apply the definitions and reference materials in subpart K of this part.
(e) Laboratory testing using PEMS. You may use PEMS for testing in a laboratory as described in § 1065.901(b). Use the following procedures and specifications when using PEMS for laboratory testing:
(1) Use the applicability and general provisions of subpart A of this part.
(2) Use equipment specifications in subpart B of this part. Section 1065.910 specifies additional equipment specific to testing with PEMS.
(3) Use measurement instruments in subpart C of this part, except as specified in § 1065.915.
(4) Use calibrations and verifications in subpart D of this part, except as specified in § 1065.920. Section 1065.920 also specifies additional calibration and verifications for PEMS.
(5) Use the provisions of § 1065.401 for selecting engines for testing. Use the provisions of subpart E of this part for maintaining engines, except as specified in the standard-setting part.
(6) Use the procedures in subpart F of this part and in the standard-setting part to start and run a laboratory test.
(7) Use the calculations in subpart G of this part to calculate emissions over the applicable duty cycle. Section 1065.940 specifies additional calculations for testing with PEMS.
(8) Use a fuel meeting the specifications of subpart H of this part, as specified in the standard-setting part.
(9) Use the lubricant and coolant specifications in § 1065.740 and § 1065.745.
(10) Use the analytical gases and other calibration standards in § 1065.750 and § 1065.790.
(11) If you are testing with oxygenated fuels, use the procedures specified for testing with oxygenated fuels in subpart I of this part.
(12) Apply the definitions and reference materials in subpart K of this part.
(f) Summary. The following table summarizes the requirements of paragraphs (d) and (e) of this section:

TABLE 1 OF § 1065.905–SUMMARY OF TESTING REQUIREMENTS SPECIFIED OUTSIDE OF THIS SUBPART J

Subpart	Applicability for field testing[1]	Applicability for laboratory or similar testing with PEMS without restriction[1]	Applicability for laboratory or similar testing with PEMS with restrictions[1]
A: Applicability and general provisions	Use all.	Use all.	Use all.
B: Equipment for testing	Use § 1065.101 and § 1065.140 through the end of subpart B, except § 1065.140(e)(1) and (4), § 1065.170(c)(1)(vi), and § 1065.195(c). § 1065.910 specifies equipment specific to field testing.	Use all.	Use all. § 1065.910 specifies equipment specific to laboratory testing with PEMS.
C: Measurement instruments	Use all. § 1065.915 allows deviations.	Use all except § 1065.295(c).	Use all except § 1065.295(c). § 1065.915 allows deviations.
D: Calibrations and verifications	Use all except § 1065.308 and § 1065.309. § 1065.920 allows deviations, but also has additional specifications.	Use all.	Use all. § 1065.920 allows deviations, but also has additional specifications.
E: Test engine selection, maintenance, and durability	Do not use. Use standard-setting part.	Use all.	Use all.
F: Running an emission test in the laboratory	Use § § 1065.590 and 1065.595 for PM § 1065.930 and § 1065.935 to start and run a field test.	Use all.	Use all.
G: Calculations and data requirements	Use all. § 1065.940 has additional calculation instructions	Use all.	Use all. § 1065.940 has additional calculation instructions
H: Fuels, engine fluids, analytical gases, and other calibration materials	Use all.	Use all.	Use all.
I: Testing with oxygenated fuels	Use all.	Use all.	Use all.
K: Definitions and reference materials	Use all.	Use all.	Use all.

[1]Refer to paragraphs (d) and (e) of this section for complete specifications.

§ 1065.910 PEMS auxiliary equipment for field testing.
For field testing you may use various types of auxiliary equipment to attach PEMS to a vehicle or engine and to power PEMS.
(a) When you use PEMS, you may route engine intake air or exhaust through a flow meter. Route the engine intake air or exhaust as follows:
(1) Flexible connections. Use short flexible connectors where necessary.
(i) You may use flexible connectors to enlarge or reduce the pipe diameters to match that of your test equipment.
(ii) We recommend that you use flexible connectors that do not exceed a length of three times their largest inside diameter.
(iii) We recommend that you use four-ply silicone-fiberglass fabric with a temperature rating of at least 315 °C for flexible connectors. You may use connectors with a spring-steel wire helix for support and you may use Nomex™ coverings or linings for durability. You may also use any other nonreactive material with equivalent permeation-resistance and durability, as long as it seals tightly.
(iv) Use stainless-steel hose clamps to seal flexible connectors, or use clamps that seal equivalently.
(v) You may use additional flexible connectors to connect to flow meters.
(2) Tubing. Use rigid 300 series stainless steel tubing to connect between flexible connectors. Tubing may be straight or bent to accommodate vehicle geometry. You may use "T" or "Y" fittings made of 300 series stainless steel tubing to join multiple connections, or you may cap or plug redundant flow paths if the engine manufacturer recommends it.
(3) Flow restriction. Use flow meters, connectors, and tubing that do not increase flow restriction so much that it exceeds the manufacturer's maximum specified value. You may verify this at the maximum exhaust flow rate by measuring pressure at the manufacturer-specified location with your system connected. You may also perform an engineering analysis to verify an acceptable configuration, taking into account the maximum exhaust flow rate expected, the field test system's flexible connectors, and the tubing's characteristics for pressure drops versus flow.
(b) For vehicles or other motive equipment, we recommend installing PEMS in the same location where a passenger might sit. Follow PEMS manufacturer instructions for installing PEMS in cargo spaces, engine spaces, or externally such that PEMS is directly exposed to the outside environment. We recommend locating PEMS where it will be subject to minimal sources of the following parameters:
(1) Ambient temperature changes.
(2) Ambient pressure changes.
(3) Electromagnetic radiation.
(4) Mechanical shock and vibration.
(5) Ambient hydrocarbons–if using a FID analyzer that uses ambient air as FID burner air.
(c) Use mounting hardware as required for securing flexible connectors, ambient sensors, and other equipment. Use structurally sound mounting points such as vehicle frames, trailer hitch receivers, walk spaces, and payload tie-down fittings. We recommend mounting hardware such as clamps, suction cups, and magnets that are specifically designed for your application. We also recommend considering mounting hardware such as commercially available bicycle racks, trailer hitches, and luggage racks where applicable.

(d) Field testing may require portable electrical power to run your test equipment. Power your equipment, as follows:
(1) You may use electrical power from the vehicle, equipment, or vessel, up to the highest power level, such that all the following are true:
(i) The power system is capable of safely supplying power, such that the power demand for testing does not overload the power system.
(ii) The engine emissions do not change significantly as a result the power demand for testing.
(iii) The power demand for testing does not increase output from the engine by more than 1 % of its maximum power.
(2) You may install your own portable power supply. For example, you may use batteries, fuel cells, a portable generator, or any other power supply to supplement or replace your use of vehicle power. You may connect an external power source directly to the vehicle's, vessel's, or equipment's power system; however, during a test interval (such as an NTE event) you must not supply power to the vehicle's power system in excess of 1 % of the engine's maximum power.

§ 1065.915 PEMS instruments.
(a) Instrument specifications. We recommend that you use PEMS that meet the specifications of subpart C of this part. For unrestricted use of PEMS in a laboratory or similar environment, use a PEMS that meets the same specifications as each lab instrument it replaces. For field testing or for testing with PEMS in a laboratory or similar environment, under the provisions of § 1065.905(b), the specifications in the following table apply instead of the specifications in Table 1 of § 1065.205.

TABLE 1 OF § 1065.915–RECOMMENDED MINIMUM PEMS MEASUREMENT INSTRUMENT PERFORMANCE

Measurement	Measured quantity symbol	Rise time, $t_{10\text{-}90}$, and Fall time, $t_{90\text{-}10}$	Recording update frequency	Accuracy[1]	Repeatability[1]	Noise[1]
Engine speed transducer	f_n	1 s	1 Hz means	5 % of pt. or 1 % of max.	2 % of pt. or 1 % of max.	0.5 % of max
Engine torque estimator, BSFC (This is a signal from an engine's ECM)	T or BSFC	1 s	1 Hz means	8 % of pt. or 5 % of max.	2 % of pt. or 1 % of max.	1 % of max.
General pressure transducer (not a part of another instrument)	p	5 s	1 Hz	5 % of pt. or 5 % of max.	2 % of pt. or 0.5 % of max.	1 % of max
Atmospheric pressure meter	p_{atmos}	50 s	0.1 Hz	250 Pa	200 Pa	100 Pa
General temperature sensor (not a part of another instrument)	T	5 s	1 Hz	1 % of pt. K or 5 K	0.5 % of pt. K or 2 K	0.5 % of max 0.5 K
General dewpoint sensor	T_{dew}	50 s	0.1 Hz	3 K	1 K	1 K
Exhaust flow meter	$\dot{n}$	1 s	1 Hz means	5 % of pt. or 3 % of max.	2 % of pt.	2 % of max.
Dilution air, inlet air, exhaust, and sample flow meters	$\dot{n}$	1 s	1 Hz means	2.5 % of pt. or 1.5 % of max.	1.25 % of pt. or 0.75 % of max.	1 % of max.
Continuous gas analyzer	x	5 s	1 Hz	4 % of pt. or 4 % of meas.	2 % of pt. or 2 % of meas.	1 % of max.
Gravimetric PM balance	m_{PM}	—	—	See § 1065.790	0.5 µg	—
Inertial PM balance	m_{PM}	—	—	4 % of pt. or 4 % of meas.	2 % of pt. or 2 % of meas.	1 % of max

[1]Accuracy, repeatability, and noise are all determined with the same collected data, as described in § 1065.305, and based on absolute values. "pt." refers to the overall flow-weighted mean value expected at the standard; "max." refers to the peak value expected at the standard over any test interval, not the maximum of the instrument's range; "meas" refers to the actual flow-weighted mean measured over any test interval.

(b) Redundant measurements. For all PEMS described in this subpart, you may use data from multiple instruments to calculate test results for a single test. If you use redundant systems, use good engineering judgment to use multiple measured values in calculations or to disregard individual measurements. Note that you must keep your results from all measurements, as described in § 1065.25. This requirement applies whether or not you actually use the measurements in your calculations.
(c) Field-testing ambient effects on PEMS. We recommend that you use PEMS that are only minimally affected by ambient conditions such as temperature, pressure, humidity, physical orientation, mechanical shock and vibration, electromagnetic radiation, and ambient hydrocarbons. Follow the PEMS manufacturer's instructions for proper installation to isolate PEMS from ambient conditions that affect their performance. If a PEMS is inherently affected by ambient conditions that you cannot control, you may monitor those conditions and adjust the PEMS signals to compensate for the ambient effect. The standard-setting part may also specify the use of one or more field-testing adjustments or measurement allowances that you apply to results or standards to account for ambient effects on PEMS.
(d) ECM signals. You may use signals from the engine's electronic control module (ECM) in place of values measured by individual instruments within a PEMS, subject to the following provisions:
(1) Recording ECM signals. If your ECM updates a broadcast signal more or less frequently than 1 Hz, process data as follows:
(i) If your ECM updates a broadcast signal more frequently than 1 Hz, use PEMS to sample and record the signal's value more frequently. Calculate and record the 1 Hz mean of the more frequently updated data.
(ii) If your ECM updates a broadcast signal less frequently than 1 Hz, use PEMS to sample and record the signal's value at the most frequent rate. Linearly interpolate between recorded values and record the interpolated values at 1 Hz.
(iii) Optionally, you may use PEMS to electronically filter the ECM signals to meet the rise time and fall time specifications in Table 1 of this section. Record the filtered signal at 1 Hz.
(2) Omitting ECM signals. Replace any discontinuous or irrational ECM data with linearly interpolated values from adjacent data.
(3) Aligning ECM signals with other data. You must perform time-alignment and dispersion of ECM signals, according to PEMS manufacturer instructions and using good engineering judgment.
(4) ECM signals for determining test intervals. You may use any combination of ECM signals, with or without other measurements, to determine the start-time and end-time of a test interval.
(5) ECM signals for determining brake-specific emissions. You may use any combination of ECM signals, with or without other measurements, to estimate engine speed, torque, brake-specific fuel consumption (BSFC, in units of mass of fuel per kW-hr), and fuel rate for use in brake-specific emission calculations. We recommend that the overall performance of any speed, torque, or BSFC estimator should meet the performance specifications in Table 1 of this section. We recommend using one of the following methods:
(i) Speed. Use the engine speed signal directly from the ECM. This signal is generally accurate and precise. You may develop your own speed algorithm based on other ECM signals.
(ii) Torque. Use one of the following:

(A) ECM torque. Use the engine-torque signal directly from the ECM, if broadcast. Determine if this signal is proportional to indicated torque or brake torque. If it is proportional to indicated torque, subtract friction torque from indicated torque and record the result as brake torque. Friction torque may be a separate signal broadcast from the ECM or you may have to determine it from laboratory data as a function of engine speed.
(B) ECM %-load. Use the %-load signal directly from the ECM, if broadcast. Determine if this signal is proportional to indicated torque or brake torque. If it is proportional to indicated torque, subtract the minimum %-load value from the %-load signal. Multiply this result by the maximum brake torque at the corresponding engine speed. Maximum brake torque versus speed information is commonly published by the engine manufacturer.
(C) Your algorithms. You may develop and use your own combination of ECM signals to determine torque.
(iii) BSFC. Use one of the following:
(A) Use ECM engine speed and ECM fuel flow signals to interpolate brake-specific fuel consumption data, which might be available from an engine laboratory as a function of ECM engine speed and ECM fuel signals.
(B) Use a single BSFC value that approximates the BSFC value over a test interval (as defined in subpart K of this part). This value may be a nominal BSFC value for all engine operation determined over one or more laboratory duty cycles, or it may be any other BSFC that you determine. If you use a nominal BSFC, we recommend that you select a value based on the BSFC measured over laboratory duty cycles that best represent the range of engine operation that defines a test interval for field-testing. You may use the methods of this paragraph (d)(5)(iii)(B) only if it does not adversely affect your ability to demonstrate compliance with applicable standards.
(C) You may develop and use your own combination of ECM signals to determine BSFC.
(iv) ECM fuel rate. Use the fuel rate signal directly from the ECM and chemical balance to determine the molar flow rate of exhaust. Use § 1065.655(d) to determine the carbon mass fraction of fuel. Note that if the fuel rate drops below 10 % of the manufacturer-declared maximum fuel rate, the ratio of the emission concentrations to fuel rate will be held constant at that value; this ratio will apply until the fuel rate increases above 10 % of the manufacturer-declared maximum fuel rate. You may alternatively develop and use your own combination of ECM signals to determine fuel mass flow rate.
(v) Other ECM signals. You may ask to use other ECM signals for determining brake-specific emissions, such as ECM air flow. We must approve the use of such signals in advance.
(6) Permissible deviations. ECM signals may deviate from the specifications of this part 1065, but the expected deviation must not prevent you from demonstrating that you meet the applicable standards. For example, your emission results may be sufficiently below an applicable standard, such that the deviation would not significantly change the result. As another example, a very low engine-coolant temperature may define a logical statement that determines when a test interval may start. In this case, even if the ECM's sensor for detecting coolant temperature was not very accurate or repeatable, its output would never deviate so far as to significantly affect when a test interval may start.
(e) Engine speed transducers. You may use an externally mounted engine speed transducer to measure engine speed. Select an engine speed transducer that generates a signal in linear proportion to engine speed. We recommend that you use an engine speed transducer that meets

the specifications in Table 1 of this section. Record engine speed transducer output according to this subpart J. Calibrate and verify engine transducer performance according to § 1065.920(c). You may use any type of engine speed transducer that meets the calibration and verification requirements in § 1065.920(c) , including the following specific types:
(1) A magnetic flux sensor speed transducer mounted on the housing of an engine-driven alternator.
(2) A ferromagnetic material sensor speed transducer (known as a "mag pickup") that detects when a ferromagnetic rotating engine part periodically comes close to the sensor.
(3) A ripple voltage sensor speed transducer connected across the positive and negative terminals of an engine's electrical system, where the electrical system is powered by an engine-driven alternator. In some cases this sensor may be simply plugged into an electric accessory receptacle such as for cigarette lighters.
(4) An optical sensor speed transducer that detects when a light-reflective rotating engine part periodically comes close to the sensor. Reflective tape or other reflective material may be added to the rotating engine part for clearer detection.

§ 1065.920 PEMS calibrations and verifications.
(a) Subsystem calibrations and verifications. Use all the applicable calibrations and verifications in subpart D of this part, including the linearity verifications in § 1065.307, to calibrate and verify PEMS. Note that a PEMS does not have to meet the system-response and updating-recording verifications of § 1065.308 and § 1065.309 if it meets the overall verification described in paragraph (b) of this section or if it measures PM using any method other than that described in § 1065.170(c)(1). This section does not apply to ECM signals. Note that because the regulations of this part require you to use good engineering judgment, it may be necessary to perform additional verifications and analysis. It may also be necessary to limit the range of conditions under which the PEMS can be used or to include specific additional maintenance to ensure that it functions properly under the test conditions. As provided in 40 CFR 1068.5, we will deem your system to not meet the requirements of this section if we determine that you did not use good engineering judgment to verify the measurement equipment. We may also deem your system to meet these requirements only under certain test conditions. If we ask for it, you must send us a summary of your verifications. We may also ask you to provide additional information or analysis to support your conclusions.
(b) Overall verification. This paragraph (b) specifies methods and criteria for verifying the overall performance of systems not fully compliant with requirements that apply for laboratory testing. Maintain records to show that the particular make, model, and configuration of your PEMS meets this verification. You may rely on data and other information from the PEMS manufacturer. However, we recommend that you generate your own records to show that your specific PEMS meets this verification. If you upgrade or change the configuration of your PEMS, your record must show that your new configuration meets this verification. The verification required by this section consists of operating an engine over a duty cycle in the laboratory and statistically comparing data generated and recorded by the PEMS with data simultaneously generated and recorded by laboratory equipment as follows:
(1) Mount an engine on a dynamometer for laboratory testing. Prepare the laboratory and PEMS for emission testing, as described in this part, to get simultaneous measurements. We

recommend selecting an engine with emission levels close to the applicable duty-cycle standards, if possible.
(2) Select or create a duty cycle that has all the following characteristics:
(i) Engine operation that represents normal in-use speeds, loads, and degree of transient activity. Consider using data from previous field tests to generate a cycle.
(ii) A duration of (20 to 40) min.
(iii) At least 50 % of engine operating time must include at least 10 valid test intervals for calculating emission levels for field testing. For example, for highway compression-ignition engines, select a duty cycle in which at least 50 % of the engine operating time can be used to calculate valid NTE events.
(3) Starting with a warmed-up engine, run a valid emission test with the duty cycle from paragraph (b)(2) of this section. The laboratory and PEMS must both meet applicable validation requirements, such as drift validation, hydrocarbon contamination validation, and proportional validation.
(4) Determine the brake-specific emissions for each test interval for both laboratory and the PEMS measurements, as follows:
(i) For both laboratory and PEMS measurements, use identical values to determine the beginning and end of each test interval.
(ii) For both laboratory and PEMS measurements, use identical values to determine total work over each test interval.
(iii) If the standard-setting part specifies the use of a measurement allowance for field testing, also apply the measurement allowance during calibration using good engineering judgment. If the measurement allowance is normally added to the standard, this means you must subtract the measurement allowance from the measured PEMS brake-specific emission result.
(iv) Round results to the same number of significant digits as the standard.
(5) Repeat the engine duty cycle and calculations until you have at least 100 valid test intervals.
(6) For each test interval and emission, subtract the lab result from the PEMS result.
(7) The PEMS passes the verification of this paragraph (b) if any one of the following are true for each constituent:
(i) 91 % or more of the differences are zero or greater than zero.
(ii) The entire set of test-interval results passes the 95 % confidence alternate-procedure statistics for field testing (t-test and F-test) specified in § 1065.12.
(c) Calibration and verification of engine speed transducers. Calibrate and verify the performance of externally mounted engine speed transducers in-situ as follows:
(1) Scope and frequency. Calibrate and verify the transducer after you have mounted it to the equipment and connected it to the PEMS. Calibrate and verify the transducer using a reference tachometer.
(2) Measurement principles. The transducer must be calibrated in-situ because its output signal (voltage, current, or frequency) may depend on an input signal from a component whose rotational speed differs from the engine's rotational speed.
(3) System requirements. Calibrate the speed transducer and verify the calculated conversion to engine speeds before starting each field test. The PEMS meets verification requirements if it records engine speed to within ±2.5 % of the appropriate reference speed at idle speed, at a midpoint engine speed, and at high engine speed.
(4) Speed transducer calibration procedure. Calibrate the speed transducer as follows:

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Comment [CAL9]: This begs the question – if the part rotates 1:1 with engine rpm, why is ex-situ not ok?

(i) Select a reference tachometer that is NIST-traceable within ±0.1 % uncertainty over the engine's speed range. Pair the reference tachometer with an engine component that has the same rotational speed as the crankshaft. You may accomplish this either by mechanically coupling the reference tachometer to the engine component or by using an optical reference tachometer that measures light reflected from the engine component. We recommend you use a reference tachometer that records average engine speed over at least a 30 second interval.
(ii) Set up the reference tachometer according to the tachometer manufacturer's instructions. Mount and connect the engine speed transducer and the PEMS as they will be installed during the field test according to transducer and PEMS manufacturers' instructions.
(iii) Start the engine and operate it at idle speed. Allow time for the engine speed to stabilize. This may include time for the engine to reach a stable operating temperature.
(iv) While the PEMS receives the engine speed transducer signal and the reference tachometer measures engine speed, record at least 30 seconds of this speed data with both the PEMS and the reference tachometer. Calculate the arithmetic means for the PEMS and the reference tachometer data.
(v) Increase operator demand with no engine loading to achieve an engine speed at the highest speed expected during testing. Allow time for the engine speed to stabilize. This may include time for the engine to reach a stable operating temperature at the higher speed. Repeat the measurement and calculation described in paragraph (c)(4)(iv) of this section.
(vi) Calculate the slope, a_{1y}, and intercept, a_{0y}, of the arithmetic means, using the reference tachometer's means as the y_i and the PEMS's means as y_{refi}. See § 1065.602(h) and (i). Use these slope and intercept values to convert the engine speed transducer signals to engine speed. Do this by multiplying each value from the engine speed transducer by a_{1y} and then adding a_{0y}. We recommend programming this conversion into the PEMS such that it converts the speed transducer data directly to engine speed; you may instead do this conversion with a separate post-processor.
(5) Speed conversion verification procedure. Verify the conversion of engine speed transducer data to engine speed as follows:
(i) Start and operate it at idle speed. Allow time for the engine speed to stabilize. This may include time for the engine to reach a stable operating temperature. Perform the measurement and calculation described in paragraph (c)(4)(iv) of this section.
(ii) Increase operator demand with no engine loading to achieve an engine speed near the midpoint between idle speed and the high engine speed used for calibration. Allow time for the engine speed to stabilize. This may include time for the engine to reach a stable operating temperature at the higher speed. Repeat the measurement and calculation described in paragraph (c)(4)(iv) of this section.
(iii) Increase operator demand with no engine loading to achieve an engine speed at the highest speed expected during testing. Allow time for the engine speed to stabilize. This may include time for the engine to reach a stable operating temperature at the higher speed. Repeat the measurement and calculation described in paragraph (c)(4)(iv) of this section.
(iv) Convert all engine speed transducer signals to engine speed as described in paragraph (c)(4)(vi) of this section.
(v) Verify that all the converted engine speed values for all three engine speeds are within the performance specification in paragraph (c)(3) of this section.

Comment [CAL10]: The engine is already stabilized at idle, so this sentence is only meaningful if we say that they need to re-stabilize for high speed, or? On the other hand, if the engine runs on a thermostat, I'm not sure that this applies. Same applies for (c)(5).

Comment [CAL11]: (vi) Establishes that the measured speeds belong to the PEMS (based on speed transducer inputs). I might rather describe these as "speed transducer measurements", but if we go with these as PEMS measurements, let's use that consistently.

(6) Remedial action. If any speed point falls outside the performance specification in paragraph (c)(3) of this section, we recommend taking the following remedial action and then repeating the calibration and verification procedure:
(i) Verify that the speed transducer is mounted securely and that the reference tachometer is functioning properly.
(ii) Verify that the rotating engine component sensed by the transducer is not subject to problems such as a slipping belt that might prevent the component from rotating at the same speed as the engine's crankshaft.
(iii) Verify the linearity of the speed transducer in a laboratory as described in § 1065.307.
(7) Exception. You may perform an emission test after failing to meet the performance specification in paragraph (c)(3) of this section if you show that such a failure does not adversely affect your ability to demonstrate compliance with applicable emission standards.

§ 1065.925 PEMS preparation for field testing.
Take the following steps to prepare PEMS for field testing:
(a) Verify that ambient conditions at the start of the test are within the limits specified in the standard-setting part. Continue to monitor these values to determine if ambient conditions exceed the limits during the test.
(b) Install a PEMS and any accessories needed to conduct a field test.
(c) Power the PEMS and allow pressures, temperatures, and flows to stabilize to their operating set points.
(d) Bypass or purge any gaseous sampling PEMS instruments with ambient air until sampling begins to prevent system contamination from excessive cold-start emissions.
(e) Conduct calibrations and verifications.
(f) Operate any PEMS dilution systems at their expected flow rates using a bypass.
(g) If you use a gravimetric balance to determine whether an engine meets an applicable PM standard, follow the procedures for PM sample preconditioning and tare weighing as described in § 1065.590. Operate the PM-sampling system at its expected flow rates using a bypass.
(h) Verify the amount of contamination in the PEMS HC sampling system before the start of the field test as follows:
(1) Select the HC analyzer range for measuring the maximum concentration expected at the HC standard.
(2) Zero the HC analyzer using a zero gas or ambient air introduced at the analyzer port. When zeroing a FID, use the FID's burner air that would be used for in-use measurements (generally either ambient air or a portable source of burner air).
(3) Span the HC analyzer using span gas introduced at the analyzer port.
(4) Overflow zero or ambient air at the HC probe inlet or into a tee near the probe outlet.
(5) Measure the HC concentration in the sampling system:
(i) For continuous sampling, record the mean HC concentration as overflow zero air flows.
(ii) For batch sampling, fill the sample medium and record its mean concentration.
(6) Record this value as the initial HC concentration, $x_{THCinit}$, and use it to correct measured values as described in § 1065.660.
(7) If the initial HC concentration exceeds the greater of the following values, determine the source of the contamination and take corrective action, such as purging the system or replacing contaminated portions:

(i) 2 % of the flow-weighted mean concentration expected at the standard or measured during testing.
(ii) 2 μmol/mol.
(8) If corrective action does not resolve the deficiency, you may use a contaminated HC system if it does not prevent you from demonstrating compliance with the applicable emission standards.

§ 1065.930 Engine starting, restarting, and shutdown.
Unless the standard-setting part specifies otherwise, start, restart, and shut down the test engine for field testing as follows:
(a) Start or restart the engine as described in the owners manual.
(b) If the engine does not start after 15 seconds of cranking, stop cranking and determine the reason it failed to start. However, you may crank the engine longer than 15 seconds, as long as the owners manual or the service-repair manual describes the longer cranking time as normal.
(c) Respond to engine stalling with the following steps:
(1) If the engine stalls during a required warm-up before emission sampling begins, restart the engine and continue warm-up.
(2) If the engine stalls at any other time after emission sampling begins, restart the engine and continue testing.
(d) Shut down and restart the engine according to the manufacturer's specifications, as needed during normal operation in-use, but continue emission sampling until the field test is complete.

§ 1065.935 Emission test sequence for field testing.
(a) Time the start of field testing as follows:
(1) If the standard-setting part requires only hot-stabilized emission measurements, operate the engine in-use until the engine coolant, block, or head absolute temperature is within ±10 % of its mean value for the previous 2 min or until an engine thermostat controls engine temperature with coolant or air flow.
(2) If the standard-setting part requires hot-start emission measurements, shut down the engine after at least 2 min at the temperature tolerance specified in paragraph (a)(1) of this section. Start the field test within 20 min of engine shutdown.
(3) If the standard-setting part requires cold-start emission measurements, proceed to the steps specified in paragraph (b) of this section.
(b) Take the following steps before emission sampling begins:
(1) For batch sampling, connect clean storage media, such as evacuated bags or tare-weighed PM sample media.
(2) Operate the PEMS according to the instrument manufacturer's instructions and using good engineering judgment.
(3) Operate PEMS heaters, dilution systems, sample pumps, cooling fans, and the data-collection system.
(4) Pre-heat or pre-cool PEMS heat exchangers in the sampling system to within their tolerances for operating temperatures.
(5) Allow all other PEMS components such as sample lines, filters, and pumps to stabilize at operating temperature.
(6) Verify that no significant vacuum-side leak exists in the PEMS, as described in § 1065.345.
(7) Adjust PEMS flow rates to desired levels, using bypass flow if applicable.

(8) Zero and span all PEMS gas analyzers using NIST-traceable gases that meet the specifications of § 1065.750.
(c) Start testing as follows:
(1) Before the start of the first test interval, zero or re-zero any PEMS electronic integrating devices, as needed.
(2) If the engine is already running and warmed up and starting is not part of field testing, start the field test by simultaneously starting to sample exhaust, record engine and ambient data, and integrate measured values using a PEMS.
(3) If engine starting is part of field testing, start field testing by simultaneously starting to sample from the exhaust system, record engine and ambient data, and integrate measured values using a PEMS. Then start the engine.
(d) Continue the test as follows:
(1) Continue to sample exhaust, record data and integrate measured values throughout normal in-use operation of the engine.
(2) Between each test interval, zero or re-zero any electronic integrating devices, and reset batch storage media, as needed.
(3) The engine may be stopped and started, but continue to sample emissions throughout the entire field test.
(4) Conduct periodic verifications such as zero and span verifications on PEMS gas analyzers, as recommended by the PEMS manufacturer or as indicated by good engineering judgment. Results from these verifications will be used to calculate and correct for drift according to paragraph (g) of this section. Do not include data recorded during verifications in emission calculations.
(5) You may periodically condition and analyze batch samples in-situ, including PM samples; for example you may condition an inertial PM balance substrate if you use an inertial balance to measure PM.
(6) You may have personnel monitoring and adjusting the PEMS during a test, or you may operate the PEMS unattended.
(e) Stop testing as follows:
(1) Continue sampling as needed to get an appropriate amount of emission measurement, according to the standard setting part. If the standard-setting part does not describe when to stop sampling, develop a written protocol before you start testing to establish how you will stop sampling. You may not determine when to stop testing based on emission results.
(2) At the end of the field test, allow the sampling systems' response times to elapse and then stop sampling. Stop any integrators and indicate the end of the test cycle on the data-collection medium.
(3) You may shut down the engine before or after you stop sampling.
(f) For any proportional batch sample, such as a bag sample or PM sample, verify for each test interval whether or not proportional sampling was maintained according to § 1065.545. Void the sample for any test interval that did not maintain proportional sampling according to § 1065.545.
(g) Take the following steps after emission sampling is complete:
(1) As soon as practical after the emission sampling, analyze any gaseous batch samples.
(2) If you used dilution air, either analyze background samples or assume that background emissions were zero. Refer to § 1065.140 for dilution-air specifications.

(3) After quantifying all exhaust gases, record mean analyzer values after stabilizing a zero gas to each analyzer, then record mean analyzer values after stabilizing the span gas to the analyzer. Stabilization may include time to purge an analyzer of any sample gas, plus any additional time to account for analyzer response. Use these recorded values to correct for drift as described in § 1065.550.
(4) Invalidate any test intervals that do not meet the range criteria in § 1065.550. Note that it is acceptable that analyzers exceed 100 % of their ranges when measuring emissions between test intervals, but not during test intervals. You do not have to retest an engine in the field if the range criteria are not met.
(5) Invalidate any test intervals that do not meet the drift criterion in § 1065.550. For NMHC, invalidate any test intervals if the difference between the uncorrected and the corrected brake-specific NMHC emission values are within ±10 % of the uncorrected results or the applicable standard, whichever is greater. For test intervals that do meet the drift criterion, correct those test intervals for drift according to § 1065.672 and use the drift corrected results in emissions calculations.
(6) Unless you weighed PM in-situ, such as by using an inertial PM balance, place any used PM samples into covered or sealed containers and return them to the PM-stabilization environment and weigh them as described in § 1065.595.

§ 1065.940 Emission calculations.
(a) Perform emission calculations as described in § 1065.650 to calculate brake-specific emissions for each test interval using any applicable information and instructions in the standard-setting part. You must report emission results using the same calculation method (§ 1065.650(b)(1), § 1065.650(b)(3), or § 1065.915(d)(5)(iv)) for all regulated pollutants for a given shift-day.
(b) You may use a fixed molar mass for the diluted exhaust mixture for field testing. Determine this fixed value by engineering analysis.

Subpart K—DEFINITIONS AND OTHER REFERENCE INFORMATION

§ 1065.1001 Definitions.

The definitions in this section apply to this part. The definitions apply to all subparts unless we note otherwise. All undefined terms have the meaning the Act gives them. The definitions follow:

300 series stainless steel means any stainless steel alloy with a Unified Numbering System for Metals and Alloys number designated from S30100 to S39000. For all instances in this part where we specify 300 series stainless steel, such parts must also have a smooth inner-wall construction. We recommend an average roughness, R_a, no greater than 4 μm.

Accuracy means the absolute difference between a reference quantity and the arithmetic mean of ten mean measurements of that quantity. Determine instrument accuracy, repeatability, and noise from the same data set. We specify a procedure for determining accuracy in § 1065.305.

Act means the Clean Air Act, as amended, 42 U.S.C. 7401 - 7671q.

Adjustable parameter means any device, system, or element of design that someone can adjust (including those which are difficult to access) and that, if adjusted, may affect emissions or engine performance during emission testing or normal in-use operation. This includes, but is not limited to, parameters related to injection timing and fueling rate. In some cases, this may exclude a parameter that is difficult to access if it cannot be adjusted to affect emissions without significantly degrading engine performance, or if it will not be adjusted in a way that affects emissions during in-use operation.

Aerodynamic diameter means the diameter of a spherical water droplet that settles at the same constant velocity as the particle being sampled.

Aftertreatment means relating to a catalytic converter, particulate filter, or any other system, component, or technology mounted downstream of the exhaust valve (or exhaust port) whose design function is to decrease emissions in the engine exhaust before it is exhausted to the environment. Exhaust-gas recirculation (EGR) and turbochargers are not aftertreatment.

Allowed procedures means procedures that we either specify in this part 1065 or in the standard-setting part or approve under § 1065.10.

Alternate procedures means procedures allowed under § 1065.10(c)(7).

Applicable standard means an emission standard to which an engine is subject; or a family emission limit to which an engine is certified under an emission credit program in the standard-setting part.

Aqueous condensation means the precipitation of water-containing constituents from a gas phase to a liquid phase. Aqueous condensation is a function of humidity, pressure, temperature, and concentrations of other constituents such as sulfuric acid. These parameters vary as a function of engine intake-air humidity, dilution-air humidity, engine air-to-fuel ratio, and fuel composition—including the amount of hydrogen and sulfur in the fuel.

Atmospheric pressure means the wet, absolute, atmospheric static pressure. Note that if you measure atmospheric pressure in a duct, you must ensure that there are negligible pressure losses between the atmosphere and your measurement location, and you must account for changes in the duct's static pressure resulting from the flow.

Auto-ranging means a gas analyzer function that automatically changes the analyzer digital resolution to a larger range of concentrations as the concentration approaches 100 % of

the analyzer's current range. Auto-ranging does not mean changing an analog amplifier gain within an analyzer.

Auxiliary emission-control device means any element of design that senses temperature, motive speed, engine RPM, transmission gear, or any other parameter for the purpose of activating, modulating, delaying, or deactivating the operation of any part of the emission-control system.

Brake power has the meaning given in the standard-setting part. If it is not defined in the standard-setting part, brake power means the usable power output of the engine, not including power required to fuel, lubricate, or heat the engine, circulate coolant to the engine, or to operate aftertreatment devices. If the engine does not power these accessories during a test, subtract the work required to perform these functions from the total work used in brake-specific emission calculations. Subtract engine fan work from total work only for air-cooled engines.

C_1 equivalent (or basis) means a convention of expressing HC concentrations based on the total number of carbon atoms present, such that the C_1 equivalent of a molar HC concentration equals the molar concentration multiplied by the mean number of carbon atoms in each HC molecule. For example, the C_1 equivalent of 10 μmol/mol of propane (C_3H_8) is 30 μmol/mol. C_1 equivalent molar values may be denoted as "ppmC" in the standard-setting part. Molar mass may also be expressed on a C_1 basis. Note that calculating HC masses from molar concentrations and molar masses is only valid where they are each expressed on the same carbon basis.

Calibration means the process of setting a measurement system's response so that its output agrees with a range of reference signals. Contrast with "verification".

Calibration gas means a purified gas mixture used to calibrate gas analyzers. Calibration gases must meet the specifications of § 1065.750. Note that calibration gases and span gases are qualitatively the same, but differ in terms of their primary function. Various performance verification checks for gas analyzers and sample handling components might refer to either calibration gases or span gases.

Certification means relating to the process of obtaining a certificate of conformity for an engine family that complies with the emission standards and requirements in the standard-setting part.

Compression-ignition means relating to a type of reciprocating, internal-combustion engine that is not a spark-ignition engine.

Confidence interval means the range associated with a probability that a quantity will be considered statistically equivalent to a reference quantity.

Constant-speed engine means an engine whose certification is limited to constant-speed operation. Engines whose constant-speed governor function is removed or disabled are no longer constant-speed engines.

Constant-speed operation means engine operation with a governor that automatically controls the operator demand to maintain engine speed, even under changing load. Governors do not always maintain speed exactly constant. Typically speed can decrease (0.1 to 10) % below the speed at zero load, such that the minimum speed occurs near the engine's point of maximum power.

Coriolis meter means a flow-measurement instrument that determines the mass flow of a fluid by sensing the vibration and twist of specially designed flow tubes as the flow passes through them. The twisting characteristic is called the Coriolis effect. According to Newton's

Second Law of Motion, the amount of sensor tube twist is directly proportional to the mass flow rate of the fluid flowing through the tube. See § 1065.220.

Designated Compliance Officer means the Director, Compliance and Innovative Strategies Division (6405-J), U.S. Environmental Protection Agency, 1200 Pennsylvania Ave., NW., Washington, DC 20460.

Dewpoint means a measure of humidity stated as the equilibrium temperature at which water condenses under a given pressure from moist air with a given absolute humidity. Dewpoint is specified as a temperature in °C or K, and is valid only for the pressure at which it is measured. See § 1065.645 to determine water vapor mole fractions from dewpoints using the pressure at which the dewpoint is measured.

Discrete-mode means relating to a discrete-mode type of steady-state test, as described in the standard-setting part.

Dispersion means either:

(1) The broadening and lowering of a signal due to any fluid capacitance, fluid mixing, or electronic filtering in a sampling system. (Note: To adjust a signal so its dispersion matches that of another signal, you may adjust the system's fluid capacitance, fluid mixing, or electronic filtering.)

(2) The mixing of a fluid, especially as a result of fluid mechanical forces or chemical diffusion.

Dilution ratio (DR) means the amount of diluted exhaust per amount of undiluted exhaust.

Drift means the difference between a zero or calibration signal and the respective value reported by a measurement instrument immediately after it was used in an emission test, as long as you zeroed and spanned the instrument just before the test.

Duty cycle means one of the following:

(1) A series of speed and torque values (or power values) that an engine must follow during a laboratory test. Duty cycles are specified in the standard-setting part. A single duty cycle may consist of one or more test intervals. A series of speed and torque values meeting the definition of this paragraph (1) may also be considered a test cycle. For example, a duty cycle may be a ramped-modal cycle, which has one test interval; a cold-start plus hot-start transient cycle, which has two test intervals; or a discrete-mode cycle, which has one test interval for each mode.

(2) A set of weighting factors and the corresponding speed and torque values, where the weighting factors are used to combine the results of multiple test intervals into a composite result.

Electric power generation application means an application whose purpose is to generate a precise frequency of electricity, which is characterized by an engine that controls engine speed very precisely. This would generally not apply to welders or portable home generators.

Electronic control module means an engine's electronic device that uses data from engine sensors to control engine parameters.

Emission-control system means any device, system, or element of design that controls or reduces the emissions of regulated pollutants from an engine.

Emission-data engine means an engine that is tested for certification. This includes engines tested to establish deterioration factors.

Emission-related maintenance means maintenance that substantially affects emissions or is likely to substantially affect emission deterioration.

Engine family means a group of engines with similar emission characteristics throughout the useful life, as specified in the standard-setting part.

Engine governed speed means the engine operating speed when it is controlled by the installed governor.

Exhaust-gas recirculation means a technology that reduces emissions by routing exhaust gases that had been exhausted from the combustion chamber(s) back into the engine to be mixed with incoming air before or during combustion. The use of valve timing to increase the amount of residual exhaust gas in the combustion chamber(s) that is mixed with incoming air before or during combustion is not considered exhaust-gas recirculation for the purposes of this part.

Fall time, $t_{90\text{-}10}$, means the time interval of a measurement instrument's response after any step decrease to the input between the following points:

(1) The point at which the response has fallen 10% of the total amount it will fall in response to the step change.

(2) The point at which the response has fallen 90% of the total amount it will fall in response to the step change.

Flow-weighted mean means the mean of a quantity after it is weighted proportional to a corresponding flow rate. For example, if a gas concentration is measured continuously from the raw exhaust of an engine, its flow-weighted mean concentration is the sum of the products of each recorded concentration times its respective exhaust flow rate, divided by the sum of the recorded flow rates. As another example, the bag concentration from a CVS system is the same as the flow-weighted mean concentration, because the CVS system itself flow-weights the bag concentration.

Fuel type means a general category of fuels such as gasoline or LPG. There can be multiple grades within a single type of fuel, such as all-season and winter-grade gasoline.

Good engineering judgment means judgments made consistent with generally accepted scientific and engineering principles and all available relevant information. See 40 CFR 1068.5 for the administrative process we use to evaluate good engineering judgment.

HEPA filter means high-efficiency particulate air filters that are rated to achieve a minimum initial particle-removal efficiency of 99.97 % using ASTM F1471 (incorporated by reference in § 1065.1010).

High-idle speed means the engine speed at which an engine governor function controls engine speed with operator demand at maximum and with zero load applied. "Warm high-idle speed" is the high-idle speed of a warmed-up engine.

High-speed governor means any device, system, or element of design that modulates the engine output torque for the purpose of limiting the maximum engine speed.

Hydraulic diameter means the diameter of a circle whose area is equal to the area of a noncircular cross section of tubing, including its wall thickness. The wall thickness is included only for the purpose of facilitating a simplified and nonintrusive measurement.

Hydrocarbon (HC) means THC, THCE, NMHC, NMOG, or NMHCE, as applicable. Hydrocarbon generally means the hydrocarbon group on which the emission standards are based for each type of fuel and engine.

Identification number means a unique specification (for example, a model number/serial number combination) that allows someone to distinguish a particular engine from other similar engines.

Idle speed means the engine speed at which an engine governor function controls engine speed with operator demand at minimum and with minimum load applied (greater than or equal to zero). For engines without a governor function that controls idle speed, idle speed means the manufacturer-declared value for lowest engine speed possible with minimum load. This definition does not apply for operation designated as "high-idle speed." "Warm idle speed" is the idle speed of a warmed-up engine.

Intermediate test speed has the meaning given in § 1065.610.

Linearity means the degree to which measured values agree with respective reference values. Linearity is quantified using a linear regression of pairs of measured values and reference values over a range of values expected or observed during testing. Perfect linearity would result in an intercept, a_0, equal to zero, a slope, a_1, of one, a coefficient of determination, r^2, of one, and a standard error of the estimate, *SEE*, of zero. The term "linearity" is not used in this part to refer to the shape of a measurement instrument's unprocessed response curve, such as a curve relating emission concentration to voltage output. A properly performing instrument with a nonlinear response curve will meet linearity specifications.

Manufacturer has the meaning given in section 216(1) of the Act. In general, this term includes any person who manufactures an engine or vehicle for sale in the United States or otherwise introduces a new nonroad engine into commerce in the United States. This includes importers who import engines or vehicles for resale.

Maximum test speed has the meaning given in § 1065.610.

Maximum test torque has the meaning given in § 1065.610.

Measurement allowance means a specified adjustment in the applicable emission standard or a measured emission value to reflect the relative quality of the measurement. See the standard-setting part to determine whether any measurement allowances apply for your testing. Measurement allowances generally apply only for field testing and are intended to account for reduced accuracy or precision that result from using field-grade measurement systems.

Mode means one of the following:

(1) A distinct combination of engine speed and load for steady-state testing.

(2) A continuous combination of speeds and loads specifying a transition during a ramped-modal test.

(3) A distinct operator demand setting, such as would occur when testing locomotives or constant-speed engines.

NIST-accepted means relating to a value that has been assigned or named by NIST.

NIST-traceable means relating to a standard value that can be related to NIST-stated references through an unbroken chain of comparisons, all having stated uncertainties, as specified in NIST Technical Note 1297 (incorporated by reference in § 1065.1010). Allowable uncertainty limits specified for NIST-traceability refer to the propagated uncertainty specified by NIST. You may ask to use other internationally recognized standards that are equivalent to NIST standards.

Noise means the precision of 30 seconds of updated recorded values from a measurement instrument as it quantifies a zero or reference value. Determine instrument noise, repeatability, and accuracy from the same data set. We specify a procedure for determining noise in § 1065.305.

Nonmethane hydrocarbons (NMHC) means the sum of all hydrocarbon species except methane. Refer to § 1065.660 for NMHC determination.

Nonmethane hydrocarbon equivalent (NMHCE) means the sum of the carbon mass contributions of non-oxygenated nonmethane hydrocarbons, alcohols and aldehydes, or other organic compounds that are measured separately as contained in a gas sample, expressed as exhaust nonmethane hydrocarbon from petroleum-fueled engines. The hydrogen-to-carbon ratio of the equivalent hydrocarbon is 1.85:1.

Nonroad means relating to nonroad engines.

Nonroad engine has the meaning we give in 40 CFR 1068.30. In general this means all internal-combustion engines except motor vehicle engines, stationary engines, engines used solely for competition, or engines used in aircraft.

Open crankcase emissions means any flow from an engine's crankcase that is emitted directly into the environment. Crankcase emissions are not "open crankcase emissions" if the engine is designed to always route all crankcase emissions back into the engine (for example, through the intake system or an aftertreatment system) such that all the crankcase emissions, or their products, are emitted into the environment only through the engine exhaust system.

Operator demand means an engine operator's input to control engine output. The "operator" may be a person (i.e., manual), or a governor (i.e., automatic) that mechanically or electronically signals an input that demands engine output. Input may be from an accelerator pedal or signal, a throttle-control lever or signal, a fuel lever or signal, a speed lever or signal, or a governor setpoint or signal. Output means engine power, P, which is the product of engine speed, f_n, and engine torque, T.

Oxides of nitrogen means NO and NO_2 as measured by the procedures specified in § 1065.270. Oxides of nitrogen are expressed quantitatively as if the NO is in the form of NO_2, such that you use an effective molar mass for all oxides of nitrogen equivalent to that of NO_2.

Oxygenated fuels means fuels composed of at least 25 % oxygen-containing compounds, such as ethanol or methanol. Testing engines that use oxygenated fuels generally requires the use of the sampling methods in subpart I of this part. However, you should read the standard-setting part and subpart I of this part to determine appropriate sampling methods.

Partial pressure means the pressure, p, attributable to a single gas in a gas mixture. For an ideal gas, the partial pressure divided by the total pressure is equal to the constituent's molar concentration, x.

Percent (%) means a representation of exactly 0.01. Numbers expressed as percentages in this part (such as a tolerance of ±2 %) have infinite precision, so 2 % and 2.000000000 % have the same meaning. This means that where we specify some percentage of a total value, the calculated value has the same number of significant digits as the total value. For example, 2 % of a span value where the span value is 101.3302 is 2.026604.

Portable emission measurement system (PEMS) means a measurement system consisting of portable equipment that can be used to generate brake-specific emission measurements during field testing or laboratory testing.

Precision means two times the standard deviation of a set of measured values of a single zero or reference quantity. See also the related definitions of noise and repeatability in this section.

Procedures means all aspects of engine testing, including the equipment specifications, calibrations, calculations and other protocols and specifications needed to measure emissions, unless we specify otherwise.

Proving ring is a device used to measure static force based on the linear relationship between stress and strain in an elastic material. It is typically a steel alloy ring, and you measure the deflection (strain) of its diameter when a static force (stress) is applied across its diameter.

PTFE means polytetrafluoroethylene, commonly known as Teflon™.

Purified air means air meeting the specifications for purified air in § 1065.750. Purified air may be produced by purifying ambient air. The purification may occur at the test site or at another location (such as at a gas supplier's facility). Alternatively, purified air may be synthetically generated, using good engineering judgment, from purified oxygen and nitrogen. The addition of other elements normally present in purified ambient air (such as Ar) is not required.

Ramped-modal means relating to a ramped-modal type of steady-state test, as described in the standard-setting part.

Recommend has the meaning given in § 1065.201.

Regression statistics means any of the regression statistics specified in § 1065.602.

Regulated pollutant means an exhaust constituent for which an emission standard or a reporting requirement applies.

Repeatability means the precision of ten mean measurements of a reference quantity. Determine instrument repeatability, accuracy, and noise from the same data set. We specify a procedure for determining repeatability in § 1065.305.

Revoke has the meaning given in 40 CFR 1068.30.

Rise time, $t_{10\text{-}90}$, means the time interval of a measurement instrument's response after any step increase to the input between the following points:

(1) The point at which the response has risen 10% of the total amount it will rise in response to the step change.

(2) The point at which the response has risen 90% of the total amount it will rise in response to the step change.

Roughness (or average roughness, R_a) means the size of finely distributed vertical surface deviations from a smooth surface, as determined when traversing a surface. It is an integral of the absolute value of the roughness profile measured over an evaluation length.

Round means to apply the rounding convention specified in § 1065.20(e), unless otherwise specified.

Scheduled maintenance means adjusting, repairing, removing, disassembling, cleaning, or replacing components or systems periodically to keep a part or system from failing, malfunctioning, or wearing prematurely. It also may mean actions you expect are necessary to correct an overt indication of failure or malfunction for which periodic maintenance is not appropriate.

Shared atmospheric pressure meter means an atmospheric pressure meter whose output is used as the atmospheric pressure for an entire test facility that has more than one dynamometer test cell.

Shared humidity measurement means a humidity measurement that is used as the humidity for an entire test facility that has more than one dynamometer test cell.

Span means to adjust an instrument so that it gives a proper response to a calibration standard that represents between 75 % and 100 % of the maximum value in the instrument range or expected range of use.

Span gas means a purified gas mixture used to span gas analyzers. Span gases must meet the specifications of § 1065.750. Note that calibration gases and span gases are qualitatively the same, but differ in terms of their primary function. Various performance verification checks for gas analyzers and sample handling components might refer to either calibration gases or span gases.

Spark-ignition means relating to a gasoline-fueled engine or any other type of engine with a spark plug (or other sparking device) and with operating characteristics significantly similar to the theoretical Otto combustion cycle. Spark-ignition engines usually use a throttle to regulate intake air flow to control power during normal operation.

Special procedures means procedures allowed under § 1065.10(c)(2).

Specified procedures means procedures we specify in this part 1065 or the standard-setting part. Other procedures allowed or required by § 1065.10(c) are not specified procedures.

Standard deviation has the meaning given in § 1065.602. Note this is the standard deviation for a non-biased sample.

Standard-setting part means the part in the Code of Federal Regulations that defines emission standards for a particular engine. See § 1065.1(a).

Steady-state means relating to emission tests in which engine speed and load are held at a finite set of nominally constant values. Steady-state tests are either discrete-mode tests or ramped-modal tests.

Stoichiometric means relating to the particular ratio of air and fuel such that if the fuel were fully oxidized, there would be no remaining fuel or oxygen. For example, stoichiometric combustion in a gasoline-fueled engine typically occurs at an air-to-fuel mass ratio of about 14.7:1.

Storage medium means a particulate filter, sample bag, or any other storage device used for batch sampling.

Test engine means an engine in a test sample.

Test interval means a duration of time over which you determine brake-specific emissions. For example, the standard-setting part may specify a complete laboratory duty cycle as a cold-start test interval, plus a hot-start test interval. As another example, a standard-setting part may specify a field-test interval, such as a "not-to-exceed" (NTE) event, as a duration of time over which an engine operates within a certain range of speed and torque. In cases where multiple test intervals occur over a duty cycle, the standard-setting part may specify additional calculations that weight and combine results to arrive at composite values for comparison against the applicable standards.

Test sample means the collection of engines selected from the population of an engine family for emission testing.

Tolerance means the interval in which at least 95 % of a set of recorded values of a certain quantity must lie. Use the specified recording frequencies and time intervals to determine if a quantity is within the applicable tolerance. The concept of tolerance is intended to address random variability. You may not take advantage of the tolerance specification to incorporate a bias into a measurement.

Total hydrocarbon (THC) means the combined mass of organic compounds measured by the specified procedure for measuring total hydrocarbon, expressed as a hydrocarbon with a hydrogen-to-carbon mass ratio of 1.85:1.

Total hydrocarbon equivalent (THCE) means the sum of the carbon mass contributions of non-oxygenated hydrocarbons, alcohols and aldehydes, or other organic compounds that are measured separately as contained in a gas sample, expressed as exhaust hydrocarbon from petroleum-fueled engines. The hydrogen-to-carbon ratio of the equivalent hydrocarbon is 1.85:1.

Transformation time, t_{50}, means the overall system response time to any step change in input, generally the average of the time to reach 50% response to a step increase, $t_{0\text{-}50}$, or to a step decrease, $t_{100\text{-}50}$.

$t_{0\text{-}50}$ means the time interval of a measurement system's response after any step increase to the input between the following points:

(1) The point at which the step change is initiated at the sample probe.

(2) The point at which the response has risen 50% of the total amount it will rise in response to the step change.

$t_{100\text{-}50}$ means the time interval of a measurement system's response after any step decrease to the input between the following points:

(1) The point at which the step change is initiated at the sample probe.

(2) The point at which the response has fallen 50% of the total amount it will fall in response to the step change.

Uncertainty means uncertainty with respect to NIST-traceability. See the definition of NIST-traceable in this section.

United States means the States, the District of Columbia, the Commonwealth of Puerto Rico, the Commonwealth of the Northern Mariana Islands, Guam, American Samoa, and the U.S. Virgin Islands.

Useful life means the period during which a new engine is required to comply with all applicable emission standards. The standard-setting part defines the specific useful-life periods for individual engines.

Variable-speed engine means an engine that is not a constant-speed engine.

Vehicle means any vehicle, vessel, or type of equipment using engines to which this part applies. For purposes of this part, the term "vehicle" may include nonmotive machines or equipment such as a pump or generator.

Verification means to evaluate whether or not a measurement system's outputs agree with a range of applied reference signals to within one or more predetermined thresholds for acceptance. Contrast with "calibration".

We (us, our) means the Administrator of the Environmental Protection Agency and any authorized representatives.

Work has the meaning given in § 1065.110.

Zero means to adjust an instrument so it gives a zero response to a zero calibration standard, such as purified nitrogen or purified air for measuring concentrations of emission constituents.

Zero gas means a gas that yields a zero response in an analyzer. This may either be purified nitrogen, purified air, a combination of purified air and purified nitrogen. For field testing, zero gas may include ambient air.

§ 1065.1005 Symbols, abbreviations, acronyms, and units of measure.

The procedures in this part generally follow the International System of Units (SI), as detailed in NIST Special Publication 811, which we incorporate by reference in § 1065.1010. See §

1065.20 for specific provisions related to these conventions. This section summarizes the way we use symbols, units of measure, and other abbreviations.

(a) Symbols for quantities. This part uses the following symbols and units of measure for various quantities:

Symbol	Quantity	Unit	Unit symbol	Units in terms of SI base units
α	atomic hydrogen-to-carbon ratio	mole per mole	mol/mol	1
A	area	square meter	m^2	m^2
a_0	intercept of least squares regression			
a_1	slope of least squares regression			
a_g	acceleration of Earth's gravity	meter per square second	m/s^2	m/s^2
β	ratio of diameters	meter per meter	m/m	1
β	atomic oxygen-to-carbon ratio	mole per mole	mol/mol	1
$C_\#$	number of carbon atoms in a molecule			
C_d	discharge coefficient			
C_f	flow coefficient			
δ	atomic nitrogen-to-carbon ratio	mole per mole	mol/mol	1
d	Diameter	meter	m	m
DR	dilution ratio	mole per mole	mol/mol	1
ε	error between a quantity and its reference			
e	brake-specific emission or fuel consumption	gram per kilowatt hour	g/(kW·hr)	$g \cdot 3.6^{-1} \cdot 10^6 \cdot m^{-2} \cdot kg \cdot s^2$
F	F-test statistic			
f	frequency	hertz	Hz	s^{-1}
f_n	angular speed (shaft)	revolutions per minute	r/min	$2 \cdot \pi \cdot 60^{-1} \cdot m \cdot m^{-1} \cdot s^{-1}$
γ	ratio of specific heats	(joule per kilogram kelvin) per (joule per kilogram kelvin)	(J/(kg·K))/(J/(kg·K))	1
γ	atomic sulfur-to-carbon ratio	mole per mole	mol/mol	1
K	correction factor			1
K_v	calibration coefficient		$m^4 \cdot s \cdot K^{0.5}/kg$	$m^4 \cdot s \cdot K^{0.5} \cdot kg^{-1}$
l	length	meter	m	m
μ	viscosity, dynamic	pascal second	Pa·s	$m^{-1} \cdot kg \cdot s^{-1}$
M	molar mass[1]	gram per mole	g/mol	$10^{-3} \cdot kg \cdot mol^{-1}$
m	mass	kilogram	kg	kg
$\dot{m}$	mass rate	kilogram per second	kg/s	$kg \cdot s^{-1}$
ν	viscosity, kinematic	meter squared per second	m^2/s	$m^2 \cdot s^{-1}$
N	total number in series			
n	amount of substance	mole	mol	mol
$\dot{n}$	amount of substance rate	mole per second	mol/s	$mol \cdot s^{-1}$
P	power	kilowatt	kW	$10^3 \cdot m^2 \cdot kg \cdot s^{-3}$
PF	penetration fraction			
p	pressure	pascal	Pa	$m^{-1} \cdot kg \cdot s^{-2}$
ρ	mass density	kilogram per cubic meter	kg/m^3	$kg \cdot m^{-3}$

Δp	differential static pressure	pascal	Pa	$m^{-1}\cdot kg\cdot s^{-2}$
r	ratio of pressures	pascal per pascal	Pa/Pa	1
r^2	coefficient of determination			
Ra	average surface roughness	micrometer	μm	10^{-6} m
$Re^{\#}$	Reynolds number			
RF	response factor			
RH	relative humidity			
σ	non-biased standard deviation			
S	Sutherland constant	kelvin	K	K
SEE	standard estimate of error			
T	absolute temperature	kelvin	K	K
T	Celsius temperature	degree Celsius	°C	K-273.15
T	torque (moment of force)	newton meter	N·m	$m^2\cdot kg\cdot s^{-2}$
θ	plane angle	degrees	°	rad
t	time	second	s	s
Δt	time interval, period, 1/frequency	second	s	s
V	volume	cubic meter	m^3	m^3
$\dot{V}$	volume rate	cubic meter per second	m^3/s	$m^3\cdot s^{-1}$
W	work	kilowatt hour	kW·hr	$3.6\cdot 10^{-6}\cdot m^2\cdot kg\cdot s^{-2}$
w_c	carbon mass fraction	gram per gram	g/g	1
x	amount of substance mole fraction[2]	mole per mole	mol/mol	1
$\overline{x}$	flow-weighted mean concentration	mole per mole	mol/mol	1
y	generic variable			
Z	compressibility factor			

[1] See paragraph (f)(2) of this section for the values to use for molar masses. Note that in the cases of NO_x and HC, the regulations specify effective molar masses based on assumed speciation rather than actual speciation.
[2] Note that mole fractions for THC, THCE, NMHC, NMHCE, and NOTHC are expressed on a C_1 equivalent basis.

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(b) Symbols for chemical species. This part uses the following symbols for chemical species and exhaust constituents:

Symbol	Species
Ar	argon
C	carbon
CH_2O	formaldehyde
CH_3OH	methanol
CH_4	methane
C_2H_4O	acetaldehyde
C_2H_5OH	ethanol
C_2H_6	ethane
C_3H_7OH	propanol
C_3H_8	propane
C_4H_{10}	butane
C_5H_{12}	pentane
CO	carbon monoxide
CO_2	carbon dioxide
H	atomic hydrogen

H_2	molecular hydrogen
H_2O	water
H_2SO_4	sulfuric acid
HC	hydrocarbon
He	helium
^{85}Kr	krypton 85
N_2	molecular nitrogen
NH_3	ammonia
NMHC	nonmethane hydrocarbon
NMHCE	nonmethane hydrocarbon equivalent
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
N_2O	nitrous oxide
NMOG	nonmethane organic gases
NONMHC	non-oxygenated nonmethane hydrocarbon
NOTHC	non-oxygenated total hydrocarbon
O_2	molecular oxygen
OHC	oxygenated hydrocarbon
^{210}Po	polonium 210
PM	particulate matter
S	sulfur
SVOC	semi-volatile organic compound
THC	total hydrocarbon
THCE	total hydrocarbon equivalent
ZrO_2	zirconium dioxide

(c) Prefixes. This part uses the following prefixes to define a quantity:

Symbol	Quantity	Value
μ	micro	10^{-6}
m	milli	10^{-3}
c	centi	10^{-2}
k	kilo	10^{3}
M	mega	10^{6}

(d) Superscripts. This part uses the following superscripts to define a quantity:

Superscript	Quantity
overbar (such as $\bar{y}$)	arithmetic mean
overdot (such as $\dot{y}$)	quantity per unit time

(e) Subscripts. This part uses the following subscripts to define a quantity:

Subscript	Quantity
abs	absolute quantity
act	actual condition
air	air, dry
amb	ambient

atmos	atmospheric
bkgnd	background
cal	calibration quantity
CFV	critical flow venturi
comb	combined
composite	composite value
cor	corrected quantity
dil	dilution air
dew	dewpoint
dexh	diluted exhaust
dry	dry condition
dutycycle	duty cycle
exh	raw exhaust
exp	expected quantity
fn	feedback speed
frict	friction
fuel	fuel consumption
hi,idle	condition at high-idle
i	an individual of a series
idle	condition at idle
in	quantity in
init	initial quantity, typically before an emission test
int	intake air
j	an individual of a series
mapped	conditions over which an engine can operate
max	the maximum (i.e., peak) value expected at the standard over a test interval; not the maximum of an instrument range
meas	measured quantity
media	PM sample media
mix	mixture of diluted exhaust and air
norm	normalized
out	quantity out
P	power
part	partial quantity
PDP	positive-displacement pump
post	after the test interval
pre	before the test interval
prod	stoichiometric product
record	record rate
ref	reference quantity
rev	revolution
sat	saturated condition
s	slip
span	span quantity
SSV	subsonic venturi
std	standard condition

stroke	engine strokes per power stroke
T	torque
test	test quantity
test,alt	alternate test quantity
uncor	uncorrected quantity
vac	vacuum side of the sampling system
weight	calibration weight
zero	zero quantity

(f) Constants. (1) This part uses the following constants for the composition of dry air:

Symbol	Quantity	mol/mol
x_{Arair}	amount of argon in dry air	0.00934
x_{CO2air}	amount of carbon dioxide in dry air	0.000375
x_{N2air}	amount of nitrogen in dry air	0.78084
x_{O2air}	amount of oxygen in dry air	0.209445

(2) This part uses the following molar masses or effective molar masses of chemical species:

Symbol	Quantity	g/mol (10^{-3}·kg·mol^{-1})
M_{air}	molar mass of dry air[1]	28.96559
M_{Ar}	molar mass of argon	39.948
M_{C}	molar mass of carbon	12.0107
M_{CH3OH}	molar mass of methanol	32.04186
M_{C2H5OH}	molar mass of ethanol	46.06844
M_{C2H4O}	molar mass of acetaldehyde	44.05256
$M_{C2H4N2O}$	molar mass of urea	44.05526
M_{C3H8}	molar mass of propane	44.09562
M_{C3H7OH}	molar mass of propanol	60.09502
M_{CO}	molar mass of carbon monoxide	28.0101
M_{CH4}	molar mass of methane	16.0425
M_{CO2}	molar mass of carbon dioxide	44.0095
M_{H}	molar mass of atomic hydrogen	1.00794
M_{H2}	molar mass of molecular hydrogen	2.01588
M_{H2O}	molar mass of water	18.01528
M_{CH2O}	molar mass of formaldehyde	30.02598
M_{He}	molar mass of helium	4.002602
M_{N}	molar mass of atomic nitrogen	14.0067
M_{N2}	molar mass of molecular nitrogen	28.0134
M_{NH3}	molar mass of ammonia	17.03052
M_{NMHC}	effective C_1 molar mass of nonmethane hydrocarbon[2]	13.875389
M_{NMHCE}	effective C_1 molar mass of nonmethane hydrocarbon equivalent[2]	13.875389
M_{NOx}	effective molar mass of oxides of nitrogen[3]	46.0055
M_{N2O}	molar mass of nitrous oxide	44.0128
M_{O}	molar mass of atomic oxygen	15.9994
M_{O2}	molar mass of molecular oxygen	31.9988
M_{S}	molar mass of sulfur	32.065

M_{THC}	effective C_1 molar mass of total hydrocarbon[2]	13.875389
M_{THCE}	effective C_1 molar mass of total hydrocarbon equivalent[2]	13.875389

[1]See paragraph (f)(1) of this section for the composition of dry air.
[2]The effective molar masses of THC, THCE, NMHC, and NMHCE are defined on a C_1 basis and are based on an atomic hydrogen-to-carbon ratio, α, of 1.85 (with β, γ, and δ equal to zero).
[3]The effective molar mass of NO_x is defined by the molar mass of nitrogen dioxide, NO_2.

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Comment [CAL13]: Italic.
Comment [CAL14]: Italic.
Comment [CAL15]: Italic.

(3) This part uses the following molar gas constant for ideal gases:

Symbol	Quantity	J/(mol·K) ($m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1} \cdot K^{-1}$)
R	molar gas constant	8.314472

(4) This part uses the following ratios of specific heats for dilution air and diluted exhaust:

Symbol	Quantity	[J/(kg·K)]/[J/(kg·K)]
γ_{air}	ratio of specific heats for intake air or dilution air	1.399
γ_{dil}	ratio of specific heats for diluted exhaust	1.399
γ_{exh}	ratio of specific heats for raw exhaust	1.385

(g) Other acronyms and abbreviations. This part uses the following additional abbreviations and acronyms:

ABS	acrylonitrile-butadiene-styrene
ASTM	American Society for Testing and Materials
BMD	bag mini-diluter
BSFC	brake-specific fuel consumption
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CFV	critical-flow venturi
CI	compression-ignition
CITT	Curb Idle Transmission Torque
CLD	chemiluminescent detector
CVS	constant-volume sampler
DF	deterioration factor
ECM	electronic control module
EFC	electronic flow control
e.g.	for example
EGR	exhaust gas recirculation
EPA	Environmental Protection Agency
FEL	Family Emission Limit
FID	flame-ionization detector
FTIR	Fourier transform infrared
GC	gas chromatograph
GC-ECD	gas chromatograph with an electron-capture detector
GC-FID	gas chromatograph with a flame ionization detector
HEPA	high-efficiency particulate air
IBP	initial boiling point

IBR	incorporated by reference
i.e.	in other words
ISO	International Organization for Standardization
LPG	liquefied petroleum gas
MPD	magnetopneumatic detection
NDIR	nondispersive infrared
NDUV	nondispersive ultraviolet
NIST	National Institute for Standards and Technology
NMC	nonmethane cutter
PDP	positive-displacement pump
PEMS	portable emission measurement system
PFD	partial-flow dilution
PLOT	porous layer open tubular
PMD	paramagnetic detection
PMP	Polymethylpentene
pt.	a single point at the mean value expected at the standard.
psi	pounds per square inch
PTFE	polytetrafluoroethylene (commonly known as Teflon™)
RE	rounding error
RESS	rechargeable energy storage system
RFPF	response factor penetration fraction
RMC	ramped-modal cycle
rms	root-mean square
RTD	resistive temperature detector
SAW	surface acoustic wave
SEE	standard estimate of error
SSV	subsonic venturi
SI	spark-ignition
THC-FID	total hydrocarbon flame ionization detector
TINV	inverse student *t*-test function in Microsoft Excel
UCL	upper confidence limit
UFM	ultrasonic flow meter
U.S.C.	United States Code

§ 1065.1010 Incorporation by reference.

(a) Certain material is incorporated by reference into this part with the approval of the Director of the Federal Register under 5 U.S.C. 552(a) and 1 CFR part 51. To enforce any edition other than that specified in this section, a document must be published in the **Federal Register** and the material must be available to the public. All approved materials are available for inspection at the Air and Radiation Docket and Information Center (Air Docket) in the EPA Docket Center (EPA/ DC) at Rm. 3334, EPA West Bldg., 1301 Constitution Ave. NW., Washington, DC. The EPA/DC Public Reading Room hours of operation are 8:30 a.m. to 4:30 p.m., Monday through Friday, excluding legal holidays. The telephone number of the EPA/DC Public Reading Room is (202) 566–1744, and the telephone number for the Air Docket is (202) 566–1742. These approved materials are also available for inspection at the National Archives and Records Administration (NARA). For information on the availability of this material at NARA, call

(202) 741–6030 or go to *http:// www.archives.gov/federal_register/ code_of_federal_regulations/ ibr_locations.html*. In addition, these materials are available from the sources listed below.

(b) *ASTM material*. The following standards are available from ASTM International, 100 Barr Harbor Dr., P.O. Box C700, West Conshohocken, PA 19428–2959, (877) 909–ASTM, or *http://www.astm.org*:

(1) ASTM D86-12, Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure, approved December 1, 2012, IBR approved for § § 1065.703(b) and 1065.710(b) and (c).

(2) ASTM D93-13, Standard Test Methods for Flash Point by Pensky- Martens Closed Cup Tester, approved July 15, 2013, IBR approved for § 1065.703(b).

(3) ASTM D130-12, Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test, approved November 1, 2012, IBR approved for § 1065.710(b).

(4) ASTM D381-12, Standard Test Method for Gum Content in Fuels by Jet Evaporation, approved April 15, 2012, IBR approved for § 1065.710(b).

(5) ASTM D445-12, Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), approved April 15, 2012, IBR approved for § 1065.703(b).

(6) ASTM D525-12a, Standard Test Method for Oxidation Stability of Gasoline (Induction Period Method), approved September 1, 2012, IBR approved for § 1065.710(b).

(7) ASTM D613-13, Standard Test Method for Cetane Number of Diesel Fuel Oil, approved December 1, 2013, IBR approved for § 1065.703(b).

(8) ASTM D910-13a, Standard Specification for Aviation Gasolines, approved December 1, 2013, IBR approved for § 1065.701(f).

(9) ASTM D975-13a, Standard Specification for Diesel Fuel Oils, approved December 1, 2013, IBR approved for § 1065.701(f).

(10) ASTM D1267-12, Standard Test Method for Gage Vapor Pressure of Liquefied Petroleum (LP) Gases (LP-Gas Method), approved November 1, 2012, IBR approved for § 1065.720(a).

(11) ASTM D1319-13, Standard Test Method for Hydrocarbon Types in Liquid Petroleum Products by Fluorescent Indicator Adsorption, approved May 1, 2013, IBR approved for § 1065.710(c).

(12) ASTM D1655-13a, Standard Specification for Aviation Turbine Fuels, approved December 1, 2013, IBR approved for § 1065.701(f).

(13) ASTM D1837-11, Standard Test Method for Volatility of Liquefied Petroleum (LP) Gases, approved October 1, 2011, IBR approved for § 1065.720(a).

(14) ASTM D1838-12a, Standard Test Method for Copper Strip Corrosion by Liquefied Petroleum (LP) Gases, approved December 1, 2012, IBR approved for § 1065.720(a).

(15) ASTM D1945-03 (Reapproved 2010), Standard Test Method for Analysis of Natural Gas by Gas Chromatography, approved January 1, 2010, IBR approved for § 1065.715(a).

(16) ASTM D2158-11, Standard Test Method for Residues in Liquefied Petroleum (LP) Gases, approved January 1, 2011, IBR approved for § 1065.720(a).

(17) ASTM D2163-07, Standard Test Method for Determination of Hydrocarbons in Liquefied Petroleum (LP) Gases and Propane/Propene Mixtures by Gas Chromatography, approved December 1, 2007, IBR approved for § 1065.720(a).

(18) ASTM D2598-12, Standard Practice for Calculation of Certain Physical Properties of Liquefied Petroleum (LP) Gases from Compositional Analysis, approved November 1, 2012, IBR approved for § 1065.720(a).
(19) ASTM D2622-10, Standard Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-ray Fluorescence Spectrometry, approved February 15, 2010, IBR approved for § § 1065.703(b) and 1065.710(b) and (c).
(20) ASTM D2699-13b, Standard Test Method for Research Octane Number of Spark-Ignition Engine Fuel, approved October 1, 2013, IBR approved for § 1065.710(b).
(21) ASTM D2700-13b, Standard Test Method for Motor Octane Number of Spark-Ignition Engine Fuel, approved October 1, 2013, IBR approved for § 1065.710(b).
(22) ASTM D2713-13, Standard Test Method for Dryness of Propane (Valve Freeze Method), approved October 1, 2013, IBR approved for § 1065.720(a).
(23) ASTM D2784-11, Standard Test Method for Sulfur in Liquefied Petroleum Gases (Oxy-Hydrogen Burner or Lamp), approved January 1, 2011, IBR approved for § 1065.720(a).
(24) ASTM D2880-13b, Standard Specification for Gas Turbine Fuel Oils, approved November 15, 2013, IBR approved for § 1065.701(f).
(25) ASTM D2986-95a, Standard Practice for Evaluation of Air Assay Media by the Monodisperse DOP (Dioctyl Phthalate) Smoke Test, approved September 10, 1995, IBR approved for § 1065.170(c). (Note: This standard was withdrawn by ASTM.)
(26) ASTM D3231-13, Standard Test Method for Phosphorus in Gasoline, approved June 15, 2013, IBR approved for § 1065.710(b) and (c).
(27) ASTM D3237-12, Standard Test Method for Lead in Gasoline By Atomic Absorption Spectroscopy, approved June 1, 2012, IBR approved for § 1065.710(b) and (c).
(28) ASTM D4052-11, Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter, approved October 15, 2011, IBR approved for § 1065.703(b).
(29) ASTM D4629-12, Standard Test Method for Trace Nitrogen in Liquid Petroleum Hydrocarbons by Syringe/Inlet Oxidative Combustion and Chemiluminescence Detection, approved April 15, 2012, IBR approved for § 1065.655(d).
(30) ASTM D4814-13b, Standard Specification for Automotive Spark-Ignition Engine Fuel, approved December 1, 2013, IBR approved for § 1065.701(f).
(31) ASTM D4815-13, Standard Test Method for Determination of MTBE, ETBE, TAME, DIPE, tertiary-Amyl Alcohol and C_1 to C_4 Alcohols in Gasoline by Gas Chromatography, approved October 1, 2013, IBR approved for § 1065.710(b).
(32) ASTM D5186-03 (Reapproved 2009), Standard Test Method for Determination of the Aromatic Content and Polynuclear Aromatic Content of Diesel Fuels and Aviation Turbine Fuels By Supercritical Fluid Chromatography, approved April 15, 2009, IBR approved for § 1065.703(b).
(33) ASTM D5191-13, Standard Test Method for Vapor Pressure of Petroleum Products (Mini Method), approved December 1, 2013, IBR approved for § 1065.710(b) and (c).
(34) ASTM D5291-10, Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants, approved May 1, 2010, IBR approved for § 1065.655(d).
(35) ASTM D5453-12, Standard Test Method for Determination of Total Sulfur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence, approved November 1, 2012, IBR approved for § 1065.710(b).

(36) ASTM D5599-00 (Reapproved 2010), Standard Test Method for Determination of Oxygenates in Gasoline by Gas Chromatography and Oxygen Selective Flame Ionization Detection, approved October 1, 2010, IBR approved for § § 1065.655(d) and 1065.710(b).
(37) ASTM D5762-12 Standard Test Method for Nitrogen in Petroleum and Petroleum Products by Boat-Inlet Chemiluminescence, approved April 15, 2012, IBR approved for § 1065.655(d).
(38) ASTM D5769-10, Standard Test Method for Determination of Benzene, Toluene, and Total Aromatics in Finished Gasolines by Gas Chromatography/Mass Spectrometry, approved May 1, 2010, IBR approved for § 1065.710(b).
(39) ASTM D5797-13, Standard Specification for Fuel Methanol (M70- M85) for Automotive Spark-Ignition Engines, approved June 15, 2013, IBR approved for § 1065.701(f).
(40) ASTM D5798-13a, Standard Specification for Ethanol Fuel Blends for Flexible Fuel Automotive Spark-Ignition Engines, approved June 15, 2013, IBR approved for § 1065.701(f).
(41) ASTM D6550-10, Standard Test Method for Determination of Olefin Content of Gasolines by Supercritical-Fluid Chromatography, approved October 1, 2010, IBR approved for § 1065.710(b).
(42) ASTM D6615-11a, Standard Specification for Jet B Wide-Cut Aviation Turbine Fuel, approved October 1, 2011, IBR approved for § 1065.701(f).
(43) ASTM D6751-12, Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels, approved August 1, 2012, IBR approved for § 1065.701(f).
(44) ASTM D6985-04a, Standard Specification for Middle Distillate Fuel Oil—Military Marine Applications, approved November 1, 2004, IBR approved for § 1065.701(f). (Note: This standard was withdrawn by ASTM.)
(45) ASTM D7039-13, Standard Test Method for Sulfur in Gasoline, Diesel Fuel, Jet Fuel, Kerosine, Biodiesel, Biodiesel Blends, and Gasoline-Ethanol Blends by Monochromatic Wavelength Dispersive X-ray Fluorescence Spectrometry, approved September 15, 2013, IBR approved for § 1065.710(b).
(46) ASTM F1471-09, Standard Test Method for Air Cleaning Performance of a High-Efficiency Particulate Air Filter System, approved March 1, 2009, IBR approved for § 1065.1001.
(c) *California Air Resources Board material.* The following documents are available from the California Air Resources Board, Haagen-Smit Laboratory, 9528 Telstar Ave., El Monte, CA 91731–2908, (800) 242–4450, or *http://www.arb.ca.gov*:
(1) California Non-Methane Organic Gas Test Procedures, Amended July 30, 2002, Mobile Source Division, California Air Resources Board, IBR approved for § 1065.805(f).
(2) [Reserved]
(d) *Institute of Petroleum material.* The following documents are available from the Energy Institute, 61 New Cavendish St., London, W1G 7AR, UK, or by calling +44–(0)20–7467–7100, or at *http://www.energyinst.org*:
(1) IP–470, 2005, Determination of aluminum, silicon, vanadium, nickel, iron, calcium, zinc, and sodium in residual fuels by atomic absorption spectrometry, IBR approved for § 1065.705(b).
(2) IP–500, 2003, Determination of the phosphorus content of residual fuels by ultra-violet spectrometry, IBR approved for § 1065.705(b).
(3) IP–501, 2005, Determination of aluminum, silicon, vanadium, nickel, iron, sodium, calcium, zinc and phosphorus in residual fuel oil by ashing, fusion and inductively coupled plasma emission spectrometry, IBR approved for § 1065.705(b).

(e) *ISO material.* The following standards are available from the International Organization for Standardization, 1, ch. de la Voie-Creuse, CP 56, CH–1211 Geneva 20, Switzerland, 41–22–749–01–11, or *http://www.iso.org*:
(1) ISO 2719:2002, Determination of flash point—Pensky-Martens closed cup method, IBR approved for § 1065.705(c).
(2) ISO 3016:1994, Petroleum products—Determination of pour point, IBR approved for § 1065.705(c).
(3) ISO 3104:1994/Cor 1:1997, Petroleum products—Transparent and opaque liquids—Determination of kinematic viscosity and calculation of dynamic viscosity, IBR approved for § 1065.705(c).
(4) ISO 3675:1998, Crude petroleum and liquid petroleum products— Laboratory determination of density— Hydrometer method, IBR approved for § 1065.705(c).
(5) ISO 3733:1999, Petroleum products and bituminous materials— Determination of water—Distillation method, IBR approved for § 1065.705(c).
(6) ISO 6245:2001, Petroleum products—Determination of ash, IBR approved for § 1065.705(c).
(7) ISO 8217:2012(E), Petroleum products—Fuels (class F)—Specifications of marine fuels, Fifth edition, August 15, 2012, IBR approved for § 1065.705(b) and (c).
(8) ISO 8754:2003, Petroleum products—Determination of sulfur content—Energy-dispersive X-ray Fluorescence spectrometry, IBR approved for § 1065.705(c).
(9) ISO 10307–2(E):2009, Petroleum products—Total sediment in residual fuel oils—Part 2: Determination using standard procedures for ageing, Second Ed., February 1, 2009, as modified by ISO 10307-2:2009/Cor.1:2010(E), Technical Corrigendum 1, published May 15, 2010, IBR approved for § 1065.705(c).
(10) ISO 10370:1993/Cor 1:1996, Petroleum products—Determination of carbon residue—Micro method, IBR approved for § 1065.705(c).
(11) ISO 10478:1994, Petroleum products—Determination of aluminium and silicon in fuel oils—Inductively coupled plasma emission and atomic absorption spectroscopy methods, IBR approved for § 1065.705(c).
(12) ISO 12185:1996/Cor 1:2001, Crude petroleum and petroleum products—Determination of density—Oscillating U-tube method, IBR approved for § 1065.705(c).
(13) ISO 14596:2007, Petroleum products—Determination of sulfur content—Wavelength-dispersive X-ray fluorescence spectrometry, IBR approved for § 1065.705(c).
(14) ISO 14597:1997, Petroleum products—Determination of vanadium and nickel content—Wavelength dispersive X-ray fluorescence spectrometry, IBR approved for § 1065.705(c).
(15) ISO 14644–1:1999, Cleanrooms and associated controlled environments, IBR approved for § 1065.190(b).
(f) *NIST material.* The following documents are available from National Institute of Standards and Technology, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, (301) 975-6478, or www.nist.gov:
(1) NIST Special Publication 811, 2008 Edition, Guide for the Use of the International System of Units (SI), March 2008, IBR approved for § § 1065.20(a) and 1065.1005.
(2) NIST Technical Note 1297, 1994 Edition, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, IBR approved for § 1065.1001.
(g) *SAE International material.* The following standards are available from SAE International, 400 Commonwealth Dr., Warrendale, PA 15096–0001, (724) 776–4841, or *http://www.sae.org*:

(1) SAE 770141, 1977, Optimization of Flame Ionization Detector for Determination of Hydrocarbon in Diluted Automotive Exhausts, Glenn D. Reschke, IBR approved for § 1065.360(c).
(2) SAE J1151, Methane Measurement Using Gas Chromatography, stabilized September 2011, IBR approved for § § 1065.267(b) and 1065.750(a).

Subpart L—METHODS FOR UNREGULATED AND SPECIAL POLLUTANTS

§ 1065.1101 Applicability.

This subpart specifies procedures that may be used to measure emission constituents that are not measured (or not separately measured) by the test procedures in the other subparts of this part. These procedures are included to facilitate consistent measurement of unregulated pollutants for purposes other than compliance with emission standards. Unless otherwise specified in the standard-setting part, use of these procedures is optional and does not replace any requirements in the rest of this part.

SEMI-VOLATILE ORGANIC COMPOUNDS

§ 1065.1103 General provisions for SVOC measurement.

The provisions of § § 1065.1103 through 1065.1111 specify procedures for measuring semi-volatile organic compounds (SVOC) along with PM. These sections specify how to collect a sample of the SVOCs during exhaust emission testing, as well as how to use wet chemistry techniques to extract SVOCs from the sample media for analysis. Note that the precise method you use will depend on the category of SVOCs being measured. For example, the method used to measure polynuclear aromatic hydrocarbons (PAHs) will differ slightly from the method used to measure dioxins. Follow standard analytic chemistry methods for any aspects of the analysis that are not specified.

(a) Laboratory cleanliness is especially important throughout SVOC testing. Thoroughly clean all sampling system components and glassware before testing to avoid sample contamination. For the purposes of this subpart, the sampling system is defined as sample pathway from the sample probe inlet to the downstream most point where the sample is captured (in this case the condensate trap).

(b) We recommend that media blanks be analyzed for each batch of sample media (sorbent, filters, etc.) prepared for testing. Blank sorbent modules (i.e., field blanks) should be stored in a sealed environment and should periodically accompany the test sampling system throughout the course of a test, including sampling system and sorbent module disassembly, sample packaging, and storage. Use good engineering judgment to determine the frequency with which you should generate field blanks. The field blank sample should be close to the sampler during testing.

(c) We recommend the use of isotope dilution techniques, including the use of isotopically labeled surrogate, internal, alternate, and injection standards.

(d) If your target analytes degrade when exposed to ultraviolet radiation, such as nitropolynuclear aromatic hydrocarbons (nPAHs), perform these procedures in the dark or with ultraviolet filters installed over the lights.

(e) The following definitions and abbreviations apply for SVOC measurements:

(1) Soxhlet extraction means the extraction method invented by Franz von Soxhlet, in which the sample is placed in a thimble and rinsed repeatedly with a recycle of the extraction solvent.

(2) XAD-2 means a hydrophobic crosslinked polystyrene copolymer resin adsorbent known commercially as Amberlite® XAD®-2, or an equivalent adsorbent like XAD-4.

(3) Semi-volatile organic compound (SVOC) means an organic compound that is sufficiently volatile to exist in vapor form in engine exhaust, but that readily condenses to liquid or solid form under atmospheric conditions. Most SVOCs have at least 14 carbon atoms per molecule or

they have a boiling point between (240 and 400) °C. SVOCs include dioxin, quinone, and nitro-PAH compounds. They may be a natural byproduct of combustion or they may be created post-combustion. Note that SVOCs may be included in measured values of hydrocarbons and/or PM using the procedures specified in this part.
(4) Kuderna-Danish concentrator means laboratory glassware known by this name that consists of an air-cooled condenser on top of an extraction bulb.
(5) Dean-Stark trap means laboratory glassware known by this name that uses a reflux condenser to collect water from samples extracted under reflux.
(6) PUF means polyurethane foam.
(7) Isotopically labeled means relating to a compound in which either all the hydrogen atoms are replaced with the atomic isotope hydrogen-2 (deuterium) or one of the carbon atoms at a defined position in the molecule is replaced with the atomic isotope carbon-13.

§ 1065.1105 Sampling system design.
(a) General. We recommend that you design your SVOC batch sampler to extract sample from undiluted emissions to maximize the sampled SVOC quantity. To the extent practical, adjust sampling times based on the emission rate of target analytes from the engine to obtain analyte concentrations above the detection limit. In some instances you may need to run repeat test cycles without replacing the sample media or disassembling the batch sampler.
(b) Sample probe, transfer lines, and sample media holder design and construction. The sampling system should consist of a sample probe, transfer line, PM filter holder, cooling coil, sorbent module, and condensate trap. Construct sample probes, transfer lines, and sample media holders that have inside surfaces of nickel, titanium or another nonreactive material capable of withstanding raw exhaust gas temperatures. Seal all joints in the hot zone of the system with gaskets made of nonreactive material similar to that of the sampling system components. You may use teflon gaskets in the cold zone. We recommend locating all components as close to probes as practical to shorten sampling system length and minimize the surface exposed to engine exhaust.
(c) Sample system configuration. This paragraph (c) specifies the components necessary to collect SVOC samples, along with our recommended design parameters. Where you do not follow our recommendations, use good engineering judgment to design your sampling system so it does not result in loss of SVOC during sampling. The sampling system should contain the following components in series in the order listed:
(1) Use a sample probe similar to the PM sample probe specified in subpart B of this part.
(2) Use a PM filter holder similar to the holder specified in subpart B of this part, although you will likely need to use a larger size to accommodate the high sample flow rates. We recommend using a 110 mm filter for testing spark ignition engines or engines that utilize exhaust aftertreatment for PM removal and a 293 mm filter for other engines. If you are not analyzing separately for SVOCs in gas and particle phases, you do not have to control the temperature of the filter holder. Note that this differs from normal PM sampling procedures, which maintain the filter at a much lower temperature to capture a significant fraction of exhaust SVOC on the filter. In this method, SVOCs that pass through the filter will be collected on the downstream sorbent module. If you are collecting SVOCs in gas and particle phases, control your filter face temperature according to § 1065.140(e)(4).

(3) Use good engineering judgment to design a cooling coil that will drop the sample temperature to approximately 5 °C. Note that downstream of the cooling coil, the sample will be a mixture of vapor phase hydrocarbons in CO_2, air, and a primarily aqueous liquid phase.
(4) Use a hydrophobic sorbent in a sealed sorbent module. Note that this sorbent module is intended to be the final stage for collecting the SVOC sample and should be sized accordingly. We recommend sizing the module to hold 40 g of XAD-2 along with PUF plugs at either end of the module, noting that you may vary the mass of XAD used for testing based on the anticipated SVOC emission rate.
(5) Include a condensate trap to separate the aqueous liquid phase from the gas stream. We recommend using a peristaltic pump to remove water from the condensate trap over the course of the test to prevent build-up of the condensate. Note that for some tests it may be appropriate to collect this water for analysis.
(d) Sampler flow control. For testing using the recommended filter and sorbent module sizes, we recommend targeting an average sample flow rate of 70 liters per minute to maximize SVOC collection. The sampler must be designed to maintain proportional sampling throughout the test. Verify proportional sampling after an emission test as described in § 1065.545.
(e) Water bath. Design the sample system with a water bath in which the cooling coil, sorbent module, and condensate trap will be submerged. Use a heat exchanger or ice to maintain the bath temperature at (3 to 7) °C.

§ 1065.1107 Sample media and sample system preparation; sample system assembly.
This section describes the appropriate types of sample media and the cleaning procedure required to prepare the media and wetted sample surfaces for sampling.
(a) Sample media. The sampling system uses two types of sample media in series: the first to simultaneously capture the PM and associated particle phase SVOCs, and a second to capture SVOCs that remain in the gas phase, as follows:
(1) For capturing PM, we recommend using pure quartz filters with no binder. Select the filter diameter to minimize filter change intervals, accounting for the expected PM emission rate, sample flow rate. Note that when repeating test cycles to increase sample mass, you may replace the filter without replacing the sorbent or otherwise disassembling the batch sampler. In those cases, include all filters in the extraction.
(2) For capturing gaseous SVOCs, utilize XAD-2 resin contained between two PUF plugs.
(b) Sample media and sampler preparation. Prepare pre-cleaned PM filters and pre-cleaned PUF plugs/XAD-2 as needed. Store sample media in containers protected from light and ambient air if you do not use them immediately after cleaning.
(1) Pre-clean the filters via Soxhlet extraction with methylene chloride for 24 hours and dry over dry nitrogen in a low-temperature vacuum oven.
(2) Pre-clean PUF and XAD-2 with a series of Soxhlet extractions: 8 hours with water, 22 hours with methanol, 22 hours with methylene chloride, and 22 hours with toluene, followed by drying with nitrogen.
(3) Clean sampler components, including the probe, filter holder, condenser, sorbent module, and condensate collection vessel by rinsing three times with methylene chloride and then three times with toluene. Prepare pre-cleaned aluminum foil for capping the probe inlet of the sampler after the sampling system has been assembled.

(c) Sorbent spiking. Use good engineering judgment to verify the extent to which your extraction methods recover SVOCs absorbed on the sample media. We recommend spiking the XAD-2 resin with a surrogate standard before testing with a carbon-13 or hydrogen-2 isotopically labeled standard for each of the class of analytes targeted for analysis. Perform this spiking as follows:
(1) Insert the lower PUF plug into the bottom of the sorbent module.
(2) Add half of one portion of XAD-2 resin to the module and spike the XAD-2 in the module with the standard.
(3) Wait 1 hour for the solvent from the standard(s) to evaporate, add the remaining 20 g of the XAD-2 resin to the module, and then insert a PUF plug in the top of the sorbent module.
(4) Cover the inlet and outlet of the sorbent module with pre-cleaned aluminum foil.
(d) Sampling system assembly. After preparing the sample media and the sampler, assemble the condensate trap, cooling coil, filter holder with filter, sample probe, and sorbent module, then lower the assembly into the reservoir. Cover the probe inlet with pre-cleaned aluminum foil.

§ 1065.1109 Post-test sampler disassembly and sample extraction.
This section describes the process for disassembling and rinsing the sampling system and extracting and cleaning up the sample.
(a) Sampling system disassembly. Disassemble the sampling system in a clean environment as follows after the test:
(1) Remove the PM filter, PUF plugs, and all the XAD-2 from the sampling system and place them into a Soxhlet extraction thimble. Store them at or below 37 °C until analysis.
(2) Rinse sampling system wetted surfaces upstream of the condensate trap with acetone followed by toluene (or a comparable solvent system), ensuring that all the solvent that remaining in liquid phase is collected (note that a fraction of the acetone and toluene will likely be lost to evaporation during mixing). Rinse with solvent volumes that are sufficient to cover all the surfaces exposed to the sample during testing. We recommend three fresh solvent rinses with acetone and two with toluene. We recommend rinse volumes of 60 ml per rinse for all sampling system components except the condenser coil, of which you should use 200 ml per rinse. Keep the acetone rinsate separate from the toluene rinsate to the extent practicable. Rinsate fractions should be stored separately in glass bottles that have been pre-rinsed with acetone, hexane, and toluene (or purchase pre-cleaned bottles).
(3) Use good engineering judgment to determine if you should analyze the aqueous condensate phase for SVOCs. If you determine that analysis is necessary, use toluene to perform a liquid-liquid extraction of the SVOCs from the collected aqueous condensate using a separatory funnel or an equivalent method. Add the toluene from this aqueous extraction to the toluene rinsate fraction described in paragraph (a)(2) of this section.
(4) Reduce rinsate solvent volumes as needed using a Kuderna-Danish concentrator or rotary evaporator and retain these rinse solvents for reuse during sample media extraction for the same test. Be careful to avoid loss of low molecular weight analytes when concentrating with rotary evaporation.
(b) Sample extraction. Extract the SVOCs from the sorbent using Soxhlet extraction as described in this paragraph (b). Two 16 hour extractions are necessary to accommodate the Soxhlet extractions of all SVOCs from a single sample. This reduces the possibility of losing low molecular weight SVOCs and promotes water removal. We recommend performing the first

extraction with acetone/hexane and the second using toluene (or an equivalent solvent system). You may alternatively use an equivalent method such as an automated solvent extractor.
(1) We recommend equipping the Soxhlet extractor with a Dean-Stark trap to facilitate removal of residual water from the sampling system rinse. The Soxhlet apparatus must be large enough to allow extraction of the PUF, XAD-2, and filter in a single batch. Include in the extractor setup a glass thimble with a coarse or extra coarse sintered glass bottom. Pre-clean the extractor using proper glass-cleaning procedures. We recommend that the Soxhlet apparatus be cleaned with a (4 to 8) hour Soxhlet extraction with methylene chloride at a cycling rate of three cycles per hour. Discard the solvent used for pre-cleaning (no analysis is necessary).
(2) Load the extractor thimble before placing it in the extractor by first rolling the PM filter around the inner circumference of the thimble, with the sampled side facing in. Push one PUF plug down into the bottom of the thimble, add approximately half of the XAD-2, and then spike the XAD-2 in the thimble with the isotopically labeled extraction standards of known mass. Target the center of the XAD-2 bed for delivering the extraction standard. We recommend using multiple isotopically labeled extraction standards that cover the range of target analytes. This generally means that you should use isotopically labeled standards at least for the lowest and highest molecular weight analytes for each category of compounds (such as PAHs and dioxins). These extraction standards monitor the efficiency of the extraction and are also used to determine analyte concentrations after analysis. Upon completion of spiking, add the remaining XAD-2 to the thimble, insert the remaining PUF plug, and place the thimble into the extractor. Note that if you are collecting and analyzing for SVOCs in gas and particle phases, perform separate extractions for the filter and XAD-2.
(3) For the initial extraction, combine the concentrated acetone rinses (from the sampling system in paragraph (a) of this section) with enough hexane to bring the solvent volume up to the target level of 700 ml. Assemble the extractor and turn on the heating controls and cooling water. Allow the sample to reflux for 16 hours with the rheostat adjusted to cycle the extraction at a rate of (3.0 ±0.5) cycles per hour. Drain the water from the Dean-Stark trap as it accumulates by opening the stopcock on the trap. Set aside the water for analysis or discard it. In most cases, any water present will be removed within approximately 2 hours after starting the extraction.
(4) After completing the initial extraction, remove the solvent and concentrate it to (4.0 ±0.5) ml using a Kuderna-Danish concentrator that includes a condenser such as a three-ball Snyder column with venting dimples and a graduated collection tube. Using this concentrator will minimize evaporative loss of analytes with lower molecular weight.
(i) Rinse the round bottom flask of the extractor with (60 to 100) ml of hexane and add the rinsate to this concentrated extract.
(ii) Concentrate the mixture to (4 ±0.5) ml using a Kuderna-Danish concentrator or similar apparatus.
(iii) Repeat the steps in paragraphs (b)(4)(i) and (ii) of this section three times, or as necessary to remove all the residual solvent from the round bottom flask of the extractor, concentrating the final rinsate to (4 ±0.5) ml.
(5) For the second extraction, combine the toluene rinses (from the sampling system in paragraph (a) of this section) with any additional toluene needed to bring the solvent volume up to the target level of 700 ml. As noted in paragraph (a) of this section, you may need to concentrate the rinsate before adding it to the extraction apparatus if the rinsate solvent volume is too large. Allow the sample to reflux for 16 hours with the rheostat adjusted to cycle the extraction at a rate

of (3.0 ±0.5) cycles per hour. Check the Dean-Stark trap for water during the first 2 hours of the extraction (though little or no water should be present during this stage).
(6) Upon completion of the second extraction, remove the solvent and concentrate it to (4 ±0.5) ml as described in paragraph (b)(4) of this section. Using hexane from paragraph (b)(4) of this section as the rinse solvent effectively performs a solvent exchange of toluene with hexane.
(7) Combine the concentrated extract from paragraph (b)(4) of this section with the concentrated extract from paragraph (b)(6) of this section. Divide the extract into a number of fractions based on the number of analyses you need to perform. Perform the separate sample clean-up described in paragraph (c) of this section as needed for each fraction.
(c) Sample clean-up. This paragraph (c) describes how to perform sample cleaning to remove from the sample extract any solids and any SVOCs that will not be analyzed. This process, known as "sample clean-up", reduces the potential for interference or co-elution of peaks during analytical analysis. Before performing the sample clean-up, spike the extract with an alternate standard that contains a known mass of isotopically labeled compounds that are identical to the target analytes (except for the labeling). The category of the target analyte compounds (such as PAHs or dioxin) will determine the number of compounds that make up the standard. For example, PAHs require the use of four compounds in the alternate standard to cover the four basic ring structures of PAHs (2-ring, 3-ring, 4-ring, and 5-ring structures). These alternate standards are used to monitor the efficiency of the clean-up procedure. Before sample clean-up, concentrate the fractionated sample to about 2 ml with a Kuderna-Danish concentrator or rotary evaporator, and then transfer the extract to an 8 ml test tube with hexane rinse. Concentrate it to a volume of about 1 ml using a Kuderna-Danish concentrator. Use good engineering judgment to select an appropriate column chromatographic clean-up option for your target analytes. Note that these clean-up techniques generally remove compounds based on their polarity. The following procedures are examples of clean-up techniques for PAHs and nPAHs.
(1) PAH clean-up. The following method is appropriate for clean-up of extracts intended for analysis of PAHs:
(i) Pack a glass gravity column (250 mm x 10 mm recommended) by inserting a clean glass wool plug into the bottom of the column and add 10 g of activated silica gel in methylene chloride. Tap the column to settle the silica gel and then add a 1 cm layer of anhydrous sodium sulfate. Verify the volume of solvent required to completely elute all the PAHs and adjust the weight of the silica gel accordingly to account for variations among batches of silica gel that may affect the elution volume of the various PAHs.
(ii) Elute the column with 40 ml of hexane. The rate for all elutions should be about 2 ml/min. You may increase the elution rate by using dry air or nitrogen to maintain the headspace slightly above atmospheric pressure. Discard the eluate just before exposing the sodium sulfate layer to the air or nitrogen and transfer the 1 ml sample extract onto the column using two additional 2 ml rinses of hexane. Just before exposing the sodium sulfate layer to the air or nitrogen, begin elution of the column with 25 ml of hexane followed by 25 ml of 40 volume % methylene chloride in hexane. Collect the entire eluate and concentrate it to about 5 ml using the Kuderna-Danish concentrator or a rotary evaporator. Make sure not to evaporate all the solvent from the extract during the concentration process. Transfer the eluate to a small sample vial using a hexane rinse and concentrate it to 100 µl using a stream of nitrogen without violently disturbing the solvent. Store the extracts in a refrigerator at or below 4 °C, and away from light.

(2) nPAH clean up. The following procedure, adapted from "Determination and Comparison of Nitrated-Polycyclic Aromatic Hydrocarbons Measured in Air and Diesel Particulate Reference Materials" (Bamford, H.A., *et al*, Chemosphere, Vol. 50, Issue 5, pages 575 – 587), is an appropriate method to clean up extracts intended for analysis of nPAHs:
(i) Condition an aminopropyl solid phase extraction (SPE) cartridge by eluting it with 20 ml of 20 volume % methylene chloride in hexane. Transfer the extract quantitatively to the SPE cartridge with at least two methylene chloride rinses. Elute the extract through the SPE cartridge by using 40 ml of 20 volume % methylene chloride in hexane to minimize potential interference of polar constituents, and then reduce the extract to 0.5 ml in hexane and subject it to normal-phase liquid chromatography using a pre-prepared 9.6 mm x 25 cm semi-preparative Chromegabond® amino/cyano column (5 μm particle size) to isolate the nPAH fraction. The mobile phase is 20 volume % methylene chloride in hexane at a constant flow rate of 5 ml per minute. Back-flash the column with 60 ml of methylene chloride and then condition it with 200 ml of 20 volume % methylene chloride in hexane before each injection. Collect the effluent and concentrate it to about 2 ml using the Kuderna-Danish concentrator or a rotary evaporator. Transfer it to a minivial using a hexane rinse and concentrate it to 100 μl using a gentle stream of nitrogen. Store the extracts at or below 4 °C, and away from light.
(ii) [Reserved]

§ 1065.1111 Sample analysis.
This subpart does not specify chromatographic or analytical methods to analyze extracts, because the appropriateness of such methods is highly dependent on the nature of the target analytes. However, we recommend that you spike the extract with an injection standard that contains a known mass of an isotopically labeled compound that is identical to one of the target analytes (except for labeling). This injection standard allows you to monitor the efficiency of the analytical process by verifying the volume of sample injected for analysis.

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/26/2015 2:23:01 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 2/19 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes, Mihai Dorobantu
- EPA – James Sanchez
- Navistar – David Gardner, Cortney Guzlas, Matt Hunkler
- PACCAR – Dan Kieffer, Erin Luke
- Allison – Mike Howenstein, Jeff Schultz

Discussion and follow-up items (with owner's name in **bold**):

- Analysis of engine cycles at ORNL, SwRI, Eaton for regression – James, Erik
    - Erik and James shared results of regression analysis on engine cycles at Eaton and ORNL, respectively.
    - Cycles were created at 1 Hz, and data was collected at 10 Hz at Eaton and 100 Hz at ORNL.
    - Some Eaton runs failed regression on torque on the ARB cycle, but time shifting and point deletion allowed in the CFR have not been applied yet. Continue processing the Eaton runs – **Erik**
    - ORNL runs passed regression. Need to check whether time shifting and point deletion were applied - **James**
    - Engine in GEM is responding faster than engine in test cell. Not clear yet if this is a big concern.
- Technical paper abstracts – Houshun, Jackie
    - Abstracts will be submitted to SAE on 2/20 (done).
    - Targeted COMVEC session is CV301 "Fuel Economy Improvement and CO2 Reduction – Joint Session with High Efficiency".
    - All companies will have an author listed on the industry paper abstract.
- Vehicle configs / engine max test speed data – Dan
    - Dan shared an updated summary of his vehicle analysis (emailed to the group separately) with Cummins engines included.
    - Vehicles with ISC, ISL, and ISL natural gas engines in particular had significant percentages where engine speed is above fntest (max test speed) at 65 mph.
    - Check on the following for the Cummins fntest data – **Jackie**
        - Plot ISL diesel and gas torque curves with fntest speed shown for both
        - What is ISC fntest speed (assumed the same as ISL in Dan's analysis)?
        - Were parent torque curves used to calculate fntest for all the families?
        - Was the "new" fntest calculation used?

Topics for future calls:

- (2/26) Regression analysis update – Erik, James (?)
- (2/26) Update on Cummins fntest data – Jackie
- (TBD) Data on pattern of map points – Matt H.
- (TBD) Engine cert ideas – Cummins
- (TBD) Update on powertrain family concept – Matt S.
- (TBD) Update on transient correction factor in primary approach – Matt S.

Regards,

Jackie Yeager
Global Energy Policy Director
Environmental Strategy and Compliance
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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/11/2015 4:22:55 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Gary C Salemme [gary.c.salemme@cummins.com]; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: 2/5 Phase 2 Collaboration Call Notes

Participants:

- Cummins – Jackie Yeager, Manik Narula
- Eaton – Erik Dykes
- EPA – Houshun Zhang, Matt Spears, James Sanchez
- Navistar – David Gardner, Cortney Guzlas
- PACCAR – Dan Kieffer, Erin Luke
- Allison – Mike Howenstein

Discussion and follow-up items (with owner's name in **bold**):

- Analysis of interpolation/extrapolation scheme – James
    - (Please check if I captured these notes correctly. I'm still a little fuzzy on the question/problem we're trying to answer. Is it: "How do we set the extrapolation limit described in #1 below?")
    - Two N/V bounds under consideration:
        1) threshold above which the vehicle is considered off-road and not regulated (extrapolation limit?)
        2) upper threshold for generic vehicle definition (previous strawman uses engine at max test speed at 65 mph)
    - Engine max test speed is defined in Part 1065.
    - An initial look by Dan showed a significant percentage of vehicles outside the 9 generic vehicle definitions, requiring extrapolation; re-check for vehicle configs where engine speed at 65 mph is above max test speed – **Dan**
    - Once the two N/V bounds have been defined, more analysis can be done to look at error of interpolation/extrapolation routines.
- Regression criteria for engine tests – James
    - Part 1065 has criteria for existing engine cycles, which are at 1 Hz.
    - Engine cycles generated from GEM have been 10 Hz.
    - Discussed looking at GEM cycles that have been run on engine to check how well it followed the cycle and would it pass the regression criteria as is. Focus on ARB transient cycle since it has the most shifting.
    - Look at ARB transient cycles run at ORNL, SwRI, and Eaton and report back on 2/19 call – **James, Erik**
- Technical paper abstracts – Houshun, Jackie
    - Draft abstracts for an EPA paper and an industry paper were circulated before the call.
    - Review abstracts and provide feedback on 2/12 call - **All**
- Other

- Reviewed latest NPRM timeline. Target an April 30 deadline for submitting any supporting information to the docket.

Topics for future calls:

- (2/12) Review technical paper abstracts – EPA, Cummins
- (2/12, 2/19?) Re-visit vehicle configs relative to generic vehicle definitions – Dan
- (2/19) Analysis of engine cycles at ORNL, SwRI, Eaton for regression – James, Erik
- (2/19) Feedback on modifying current regression criteria for engine tests – All
- (TBD) Engine cert ideas – Cummins
- (TBD) Update on powertrain family concept – Matt S.
- (TBD) Update on transient correction factor in primary approach – Matt S.

Regards,
Jackie Yeager
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Cummins Inc.

Encrypted message

From
jackie.m.yeager@cummins.com

To
charmley.william@epa.gov

To view the message on your computer...

Save and open the attachment (message.html), and then follow the instructions from there.

To view the message on an iPhone or iPad...

Open the message again, tap and hold the attachment, and select Open in OME Viewer.

If you don't have the OME Viewer app, download it now.

To view the message on an Android device...

Open the message again, tap the attachment, and select OME Viewer.

If you don't have the OME Viewer app, download it now.

Message encryption by Microsoft Office 365

Message

From: Gary C Salemme [gary.c.salemme@cummins.com]
Sent: 5/1/2015 2:13:58 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: New Copy of SAE Paper
Attachments: Engine and Powertrain Mapping SAE Paper Draft for Submission r2.pdf

All,

I made a mistake (it kills me to admit) that Erik caught and I had to change figures 15 and 16 to use the correct N/V powertrain N/V values. So I submitted this revision to SAE today.

Regards,

Gary

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2015-01-XXXX

An Engine and Powertrain Mapping Approach for Simulation of Vehicle CO_2 Emissions

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

Simulations used to estimate carbon dioxide (CO_2) emissions and fuel consumption of medium- and heavy-duty vehicles over prescribed drive cycles often employ engine fuel maps consisting of engine measurements at numerous steady-state operating conditions. However, simulating the engine in this way has limitations as engine controls become more complex, particularly when attempting to use steady-state measurements to represent transient operation. This paper explores an alternative approach to vehicle simulation that uses a "cycle average" engine map rather than a steady state engine fuel map. The map contains engine CO_2 values measured on an engine dynamometer on cycles derived from vehicle drive cycles for a range of generic vehicles. A similar cycle average mapping approach is developed for a powertrain (engine and transmission) in order to show the specific CO_2 improvements due to powertrain optimization that would not be recognized in other approaches. While a related paper [1] focuses primarily on simulation results, this paper summarizes the associated experimental results and development of the concept. Test results for an engine and a powertrain demonstrate the cycle average map is a smooth, continuous surface. The paper also compares accuracy of using the steady-state engine map versus the cycle average engine map. Considerations for using the cycle average map for vehicle simulation in the context of CO_2 regulations are also discussed with the conclusion that the cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation.

Introduction

An engine map is used to represent tested engine performance (fuel consumption, emissions, etc.) in a vehicle simulation in order to estimate drive cycle performance of the engine and vehicle [2, 3, 4]. The map is defined by triplets of engine speed, engine torque, and an engine performance parameter, for example brake specific fuel consumption. Figure 1 shows a schematic of the typical process to create such a map. An engine is run at steady speed and load conditions for some amount of time (usually minutes) for stabilization and data acquisition. After data collection at one point, the speed and load are ramped to another steady condition and the process repeated. The number of points varies depending on the intended use of the map, but can be over 100. Figure 2 shows an example map. Figure 3 shows how the map is used as part of a vehicle simulation, with each simulation time step using the map to predict instantaneous fuel consumption based on the current speed and load.

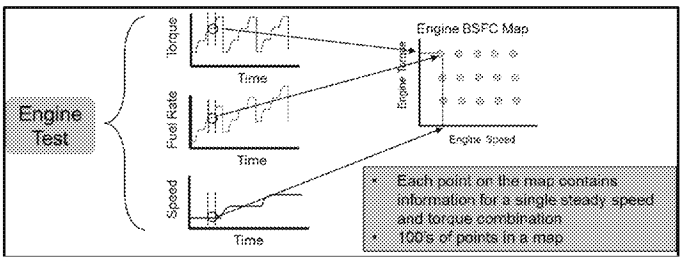

Figure 1. Typical steady state map generation process

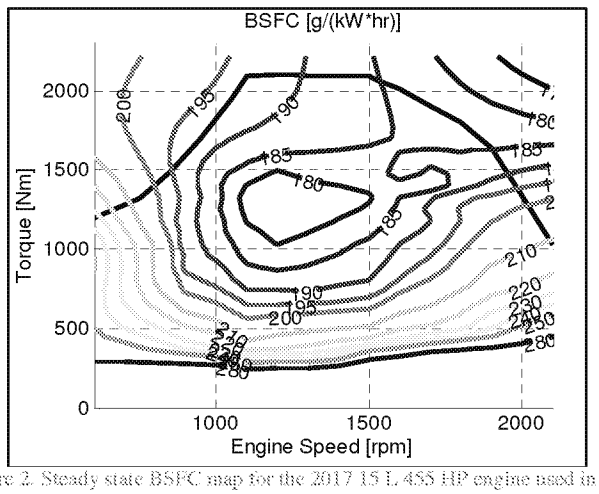

Figure 2. Steady state BSFC map for the 2017 15 L 455 HP engine used in GEM

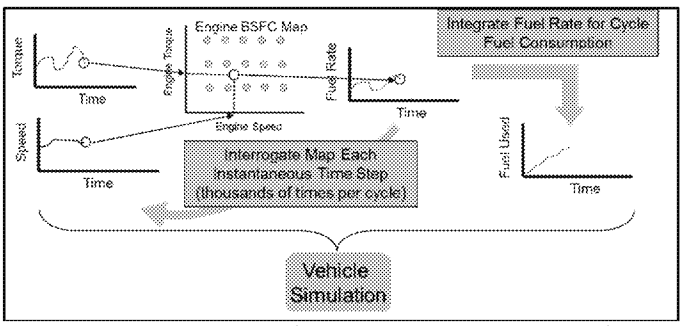

Figure 3. Process for using a steady state BSFC map in a vehicle simulation

This map can be used in a vehicle simulation for general vehicle performance understanding as well as powertrain matching of the engine, transmission, rear axle ratio, and tire size to the vehicle. Historically, the engine map approach has also been a reasonable method to predict vehicle drive cycle fuel consumption [2, 3].

However, there are some inherent assumptions in using an engine map in this manner:

- The test cell engine installation mimics the vehicle installation. This assumption includes considerations such as radiator performance, charge air cooler cooling performance as well as flow restriction, combustion air inlet restriction, exhaust system restriction, and ambient cooling of the engine.
- The engine performance is closely correlated to engine speed and engine torque. These parameters are the map axes for defining the engine performance.
- The engine performance at a speed and torque in transient operation is very close to the performance at a steady state operating point of the same speed and torque.
- The engine performance is "well behaved" in the speed and torque space so interpolation or surface fitting of the map can be used to represent non-tested operating points.

Traditionally, these assumptions have held well enough to use an engine map for relative comparisons of engine performance. However for modern diesel engines with aftertreatment and complex controls systems, the assumptions above are starting to be challenged. Engine performance is closely tied to aftertreatment performance, with closed loop feedback from the aftertreatment system to the engine. The aftertreatment performance is dependent on temperature, so ambient cooling differences between the test cell and the vehicle are becoming more important. Aftertreatment systems also have longer time responses than the base engine. It can take minutes for the aftertreatment to respond to engine changes [5]. So treating a speed and torque in a transient cycle the same as a steady state point becomes difficult and some model developers are looking for methods to correct the steady state map for transient behavior [6, 7].

In the past, heavy duty engines set controls references based on tables that had axes of engine speed and fueling (or torque), but modern engines have much more complex control algorithms that depend on ambient conditions, temperature of the aftertreatment, or storage state of the aftertreatment (ammonia or soot for example) [7]. These control systems do not necessarily repeat performance at the same engine speed and torque in two different drive cycles. With these changes in the engine system, steady state maps can be expected to have trouble predicting the fuel consumption of a vehicle drive cycle. So a new approach to model an engine in a vehicle simulation is needed.

Development of the Concept

Vehicle CO_2 Regulation Considerations

The EPA Greenhouse Gas (GHG) Regulations published in 2011 [8] ("Phase 1") use vehicle simulation to regulate CO_2 emissions from heavy duty vehicles [3]. This Greenhouse Gas Emissions Model simulation program (GEM) uses engine steady state maps to represent the engine performance in the vehicle. But note that the simulation is really just used to evaluate vehicle characteristics like aerodynamics, tire rolling resistance, and weight. There is a generic map and generic powertrain specification used for all vehicle technologies. This approach essentially builds the engine map into the standard and all vehicles in a class are evaluated on the same engine.

For the next round of GHG Regulations ("Phase 2"), there is a desire to use the specific engine performance along with the specific transmission, rear axle ratio, and tire size in the vehicle certification. In this way the vehicle will receive credit for an engine and powertrain specification performing better than the standard or take the penalty for an engine performing above the standard. This approach will require some method of representing the actual engine performance in GEM. Consequently, EPA has made significant improvements over Phase 1 GEM. The detailed improvements and features of this new GEM are described by Newman et al. [9] In this GEM, a steady state map representation of the engine is expected to be proposed. For a regulation there are some different considerations for the engine information used in a vehicle simulation than for a product development effort. A more complete discussion of regulatory considerations is provided by Zhang et al. [1] Some key considerations relevant to the discussion in this paper are:

- The engine information should be accurate, auditable, and relatively easy to collect. These requirements are not always consistent with each other, so trade-offs between them are likely to be needed.
- The engine should be evaluated in a manner consistent with how it will be used in the vehicle regulation.
- With future emphasis on recognizing the benefits of engine and transmission integration, some form of powertrain (engine and transmission) representation is desired for the vehicle regulation. A consistent approach for modeling the engine and powertrain for the vehicle regulation is desirable.

Options for Engine Model

With the above requirements in mind, it is useful to step back and consider what options exist to provide appropriate engine information to the vehicle regulatory program. Wurzenberger et al. [4] have taken a comprehensive look at engine modeling options, but for this work we want to look at some broad categories with respect to considerations for use in a regulation. The table in the Appendix compares some traditional options.

Each of the options in the table has some positive and negative attributes. A generic map puts no burden on the engine manufacturer but also gives no credit to the vehicle for a well performing engine. A single cycle value is simple, connected to the criteria emissions program, and auditable but depends on a single cycle operation matching the engine's operation in the vehicle. A steady state map doesn't capture engine transient behavior, but perhaps a new type of map can be used.

To consider such a map, it's worth noting that the cumulative vehicle CO_2 on any drive cycle can be considered in parts as shown in Figure 4. The engine CO_2 is just the cycle cumulative brake specific emissions of the engine that is typically measured and regulated. This value is a measure of the engine efficiency. The vehicle power demand is the cycle cumulative engine work normalized by the payload and distance travelled. Another way to consider this value is the average horsepower required to move a unit of payload at a given speed. It is a measure of the efficiency of the vehicle to move payload. Mathematically, these values can be calculated from any

drive cycle simulation and combined to provide the overall drive cycle vehicle CO_2 emissions.

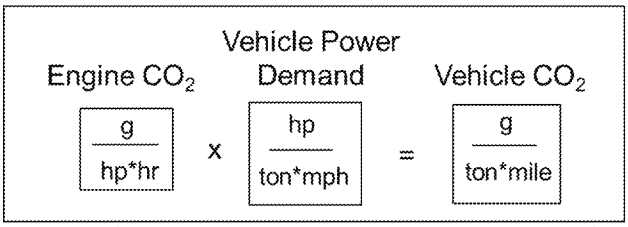

Figure 4. Relationship of engine brake specific CO_2, vehicle power demand, and vehicle emissions

The engine CO_2 part of Figure 4 can be represented by a cycle average BSFC map. The engine is tested on a cycle that matches vehicle operation well and the cycle cumulative fuel consumption is measured. The cycle can then be changed to represent slightly different vehicle operation for a new value of fuel consumption. In this way a set of cycles can be tested to "map" the engine's cumulative cycle fuel consumption response. A schematic of this approach is shown in Figure 5. An example cycle average map is shown in Figure 6. The process for using it in a vehicle simulation is shown in Figure 7. The entire cycle is simulated and then the cumulative cycle work, average engine speed, and average vehicle speed are used to interrogate the map for a cycle brake specific fuel consumption value. Then the relationship of Figure 4 is used to calculate the vehicle cycle fuel consumption or CO_2. Zhang et al. [1] describe this process as an alternative certification approach, which is supported by a large number of simulations and also the results of this paper.

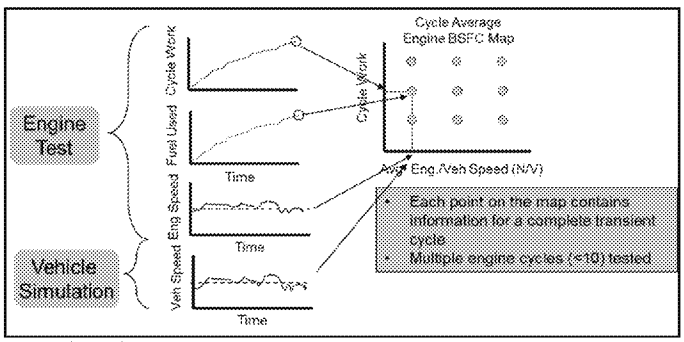

Figure 5. Cycle average map generation process

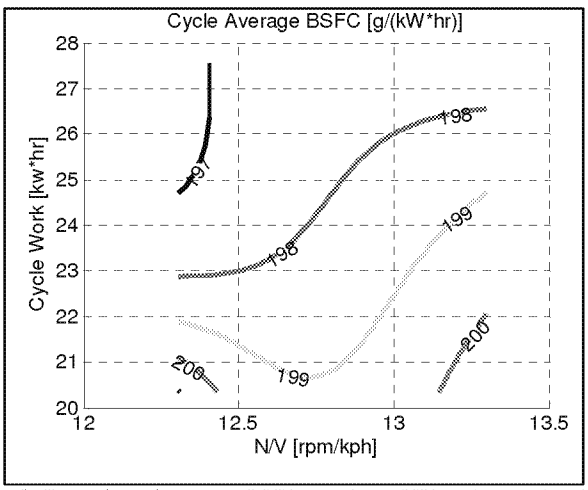

Figure 6. Example cycle average BSFC map for an ISX engine running the 55 MPH (88 KPH) GEM cycle

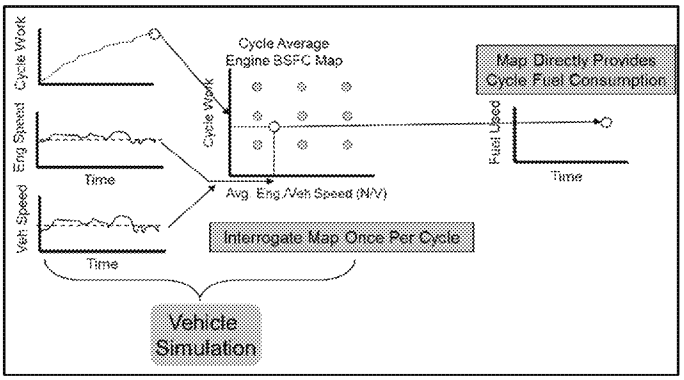

Figure 7. Process for using a cycle average BSFC map in a vehicle simulation

Average engine speed divided by average vehicle speed (denoted as N/V) has been used as a map axis to represent the nature of the engine speed operation on the cycle. Cycle work has been used as a second map axis to represent the engine loading on the cycle. These parameters are analogous to using engine speed and load as the axes for a steady state map. Other similarities between the steady state map and the cycle average map are:

- An engine test is completed with production controls in a 40 CFR Part 1065 capable test cell
- An extra test is required beyond what is used for the engine certification
- Points on the map can be audited
- Allows evaluation of the engine at speeds and loads that the engine sees in the vehicle

Based on the comparisons above, the cycle average map approach is a good alternative to investigate for modeling the engine performance in the vehicle CO_2 regulation protocol.

Validation of the Concept

Validation of the concept was first conducted through simulations using GEM [1]. In that study, a test matrix based on a Class 8 Kenworth T700 tractor with a Cummins ISX engine was carefully designed. It covered 32 vehicle configurations and three transmissions together with other relevant parameters, resulting in over one thousand simulations. In this paper, a hardware based approach with both engine and powertrain testing is used to further prove the concept. The combination of the two papers provides a complete picture of how this alternative certification concept has been developed and evaluated.

Similar to the study by Zhang et al. [1], some of the key questions to consider for the cycle average map are:

1. Is the map surface well behaved so that interpolation can represent points not tested?
2. How does the accuracy compare to a steady state map approach?
3. Is the test procedure robust and the results repeatable?

A first check of the surface shape was performed via simulation in GEM [1]. After reasonable results from a simulation study, two test programs were implemented to investigate the questions above. The first test program included only the engine and the second program included the powertrain (engine and transmission).

Engine Only Approach

Dykes and Dorobantu [10] describe the test setup in detail. The engine-only test cell as shown in Figure 8 was sized to accommodate a heavy-duty (HD) engine. A Cummins 15 liter ISX engine rated to 336kW (450 hp) with peak torque of 2375 Nm (1750 ft-lb) was used for the evaluation. A HD aftertreatment system was installed to meet the EPA and CARB emissions standards. The aftertreatment system utilized both a Diesel Particulate Filter (DPF) and a Selective Catalytic Reduction (SCR) system. To maintain a baseline condition for the DPF during testing, a DPF regeneration was forced prior to each set of tests to clean the DPF of stored particulates. The SCR system was operated during testing as would be witnessed in-vehicle operation to reduce NOx. The exhaust emissions were collected continuously using a Horiba Mexa7100D emission bench. The fuel was measured continuous during each test cycle using a ReSol RS438A-200 Fuel Flow Measurement System. The testing is completed using ultra low sulfur diesel fuel with a maximum sulfur concentration of 15 PPM. The engine intake air is temperature, humidity and pressure controlled to 25°C, 53% and 99kPa, respectively. All temperatures, pressures, fuel flow and emissions measurements were logged at a rate of 10 Hz.

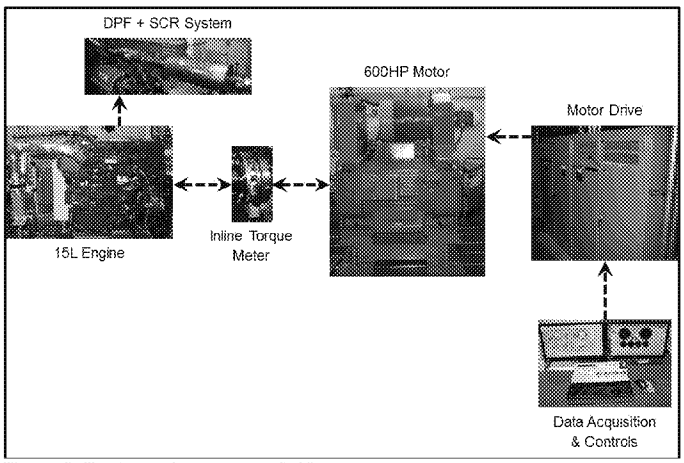

Figure 8. Engine only test setup [10]

The test cycles utilized for the engine only mapping approach were generated using GEM. Three separate vehicle configurations were input into the GEM model to generate speed and load points for each of the regulatory cycles (ARB, 65MPH, and 55 MPH). A total of nine traces were generated for each cycle. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle. A total of 27 engine tests were run (nine vehicle configurations x three test cycles). The vehicle configurations were chosen to provide a reasonably broad coverage of real-world specifications to give sufficient spread of the test points to allow an interpolation and extrapolation approach to be used for the even broader spectrum of customer vehicle specifications. The cycles run are shown in Figure 9. These are the GHG Phase 1 GEM cycles [3] with the change that the highway cycles have been modified to include grade profiles. The grade profiles were provided by the EPA [11].

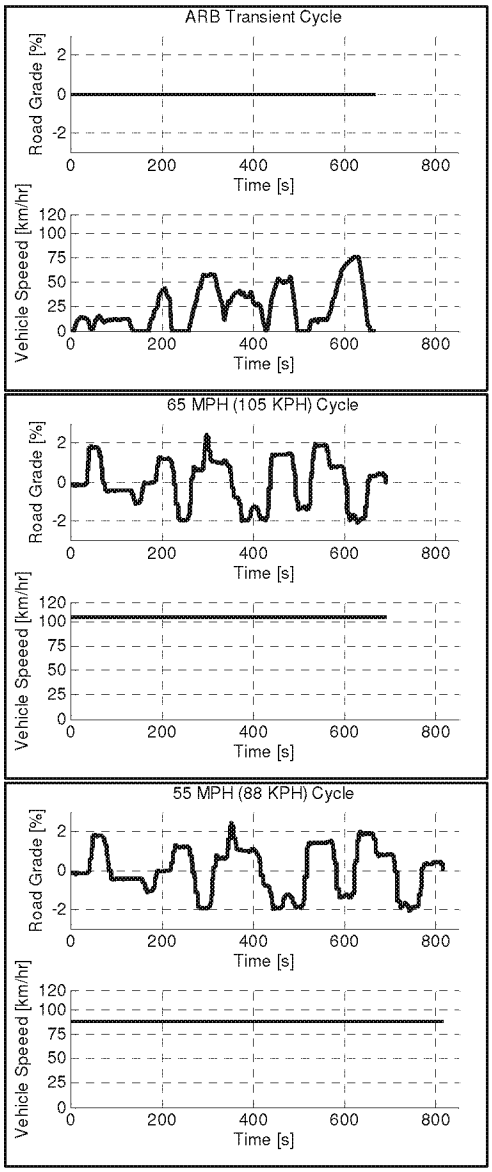

Figure 9. Vehicle cycles: a) Air Resources Board (ARB) transient cycle, b) 65 mph [105 kph] GEM cycle with road grade, c) 55 mph [88 kph] GEM cycle with road grade

Example engine map results are shown in Figure 10. These show a generally well behaved surface for either surface fitting or interpolation.

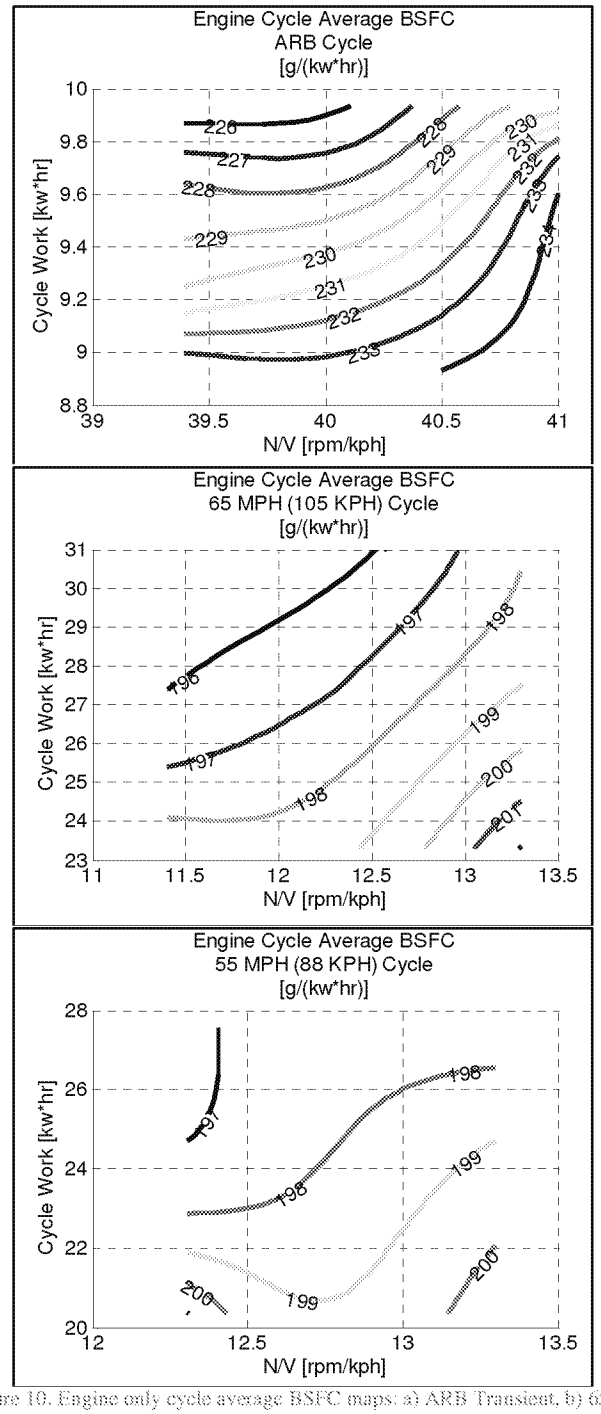

Figure 10. Engine only cycle average BSFC maps: a) ARB Transient, b) 65 mph, c) 55 mph

To check the predictive capability of the map, half the data set was used to fit BSFC to a linear model in N/V and cycle work. Testing this model on the other half of the data set shows the model performance as seen in Figure 11, indicating good behavior of the model to represent truck configurations different than those tested to create the map. Additionally, some extra truck configurations were tested at a later date as independent check points for the map. Those points are also shown in Figure 11, with similar good agreement between the model and test results. These findings are consistent with the observations obtained from the simulation study [1].

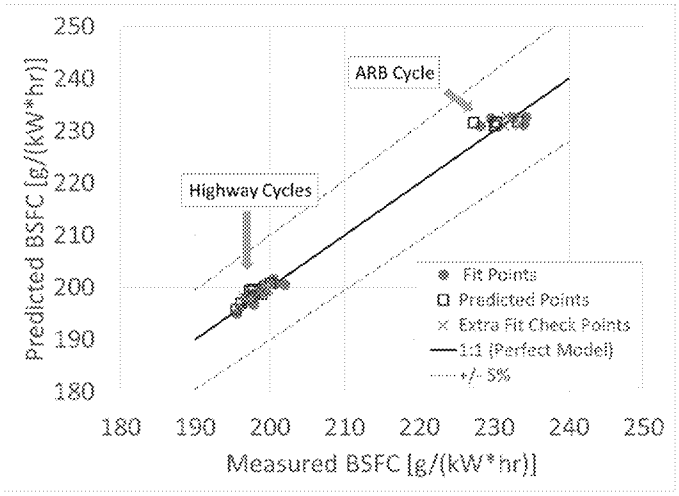

Figure 11. Engine cycle average map prediction capability with a linear fit in cycle work and N/V

A comparison of the cycle average map to the steady state map approach was completed and is shown in Figure 12. The steady state map results were taken directly from GEM [1] using a steady state map for the same engine model as tested for the cycle average map, but it was not the identical engine. So engine to engine and test cell to test cell variability need to be considered in comparing results. In the region of the 55 MPH and 65 MPH cycles (labelled Highway Cycles), the two approaches are close in accuracy. A statistical analysis shows that there is 90% confidence that the cycle average map is 1.7% better at matching the measurements than the steady state map. This level of difference is potentially within the variability of the engines and test locations used to create the different maps. For these relatively steady cycles the two map approaches are expected to produce similar results and they do agree within the variability of testing.

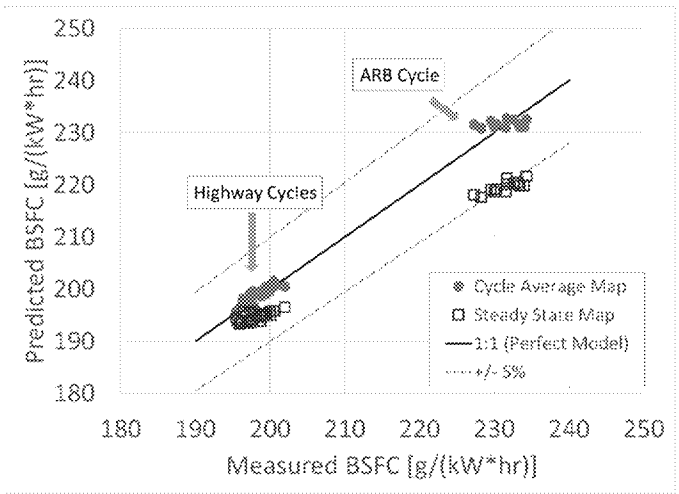

Figure 12. Comparison of cycle average map linear fit in cycle work and N/V to a steady state map interpolation

For the ARB cycle with more transient content the cycle average map does show a better match to the measured data than the steady state map approach. A statistical analysis shows that there is 90% confidence that the cycle average map is 4.9% better at matching the measurements than the steady state map. This difference is higher than expected testing variability. The larger difference on the more transient cycle is explained by the ability of the cycle average map approach to capture transient performance content.

Note that for this initial investigation of the cycle average map approach, the goal was not to precisely and completely prove capability, but rather to check for concept feasibility. For a regulation approach, it's likely that a surface fit to the cycle data would not be used. If a certification configuration matches a mapped configuration, the exact tested result is a desired output of the model. So an interpolation and extrapolation method will likely be proposed for any regulation.

The engine only testing approach is equivalent to current engine certification protocols, so repeatability is expected to be on par with current engine transient cycle certification methods. A number of repeat points on the different cycles were checked with the results shown in Figure 13 indicating good test repeatability.

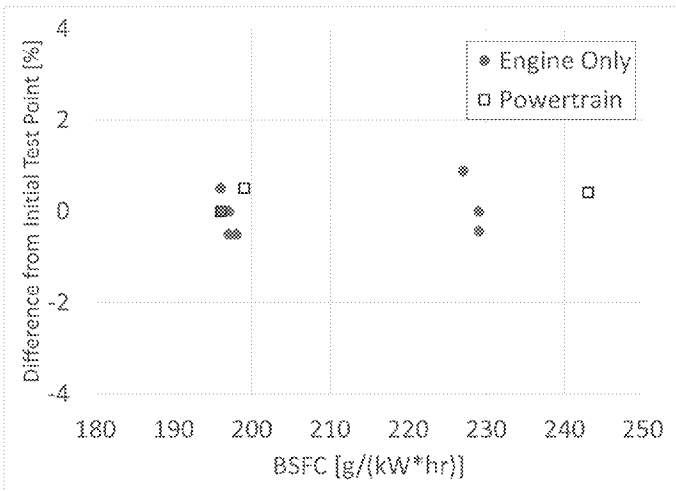

Figure 13. Repeatability of test results

Powertrain Approach

Dykes and Dorobantu [10] describe the test setup in detail. The powertrain test cell as shown in Figure 14 was sized to accommodate a powertrain from a relatively heavy-duty vehicle. The vehicle test weight was 30,391 kg [67,000 lbs.]. The powertrain tested included a Cummins 15-liter ISX engine with an Eaton 10-speed automated manual transmission. The engine maximum rated performance was 336kW (450 hp) at 1800 rpm with peak torque of 2375 Nm (1750 ft-lb) at 1000 rpm and was operated using two separate calibrations; one base calibration for testing with the 10-speed Eaton UltraShift PLUS LAS transmission and an additional calibration with SmartTorque2 (ST2) technology for testing in conjunction with the 10-speed Fuller Advantage™ (FASA) transmission. Both engine calibrations tested were emission certified for 2013 CARB and EPA. The dynamometer was sized to accommodate the engine's peak torque multiplied by the transmission's maximum gear reduction. All data collection and test procedures described for the engine only test were repeated for the powertrain testing. For the powertrain testing, the test cell ran as an HIL system with a version of the GEM vehicle model controlling the dynamometer and throttle controls so that the engine ran as if in a vehicle.

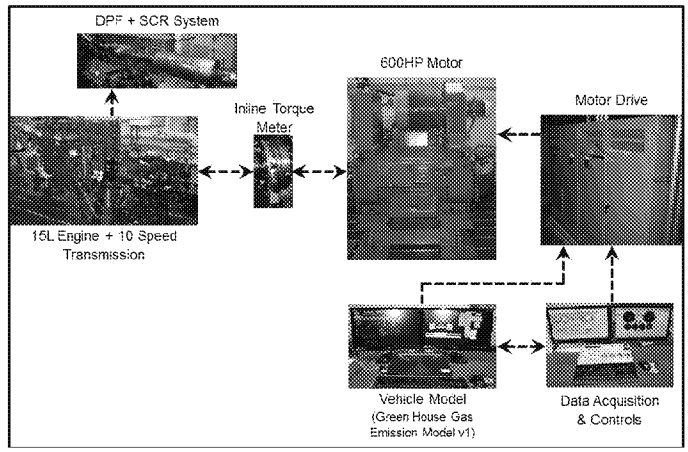

Figure 14. Powertrain test setup [10]

The same three cycles from Figure 9 were used for the powertrain testing. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle.

An example powertrain cycle average map is shown in Figure 15. As with the engine only results, the surfaces look to have a reasonable shape that can be used for interpolation and extrapolation use in a vehicle simulation for regulation purposes.

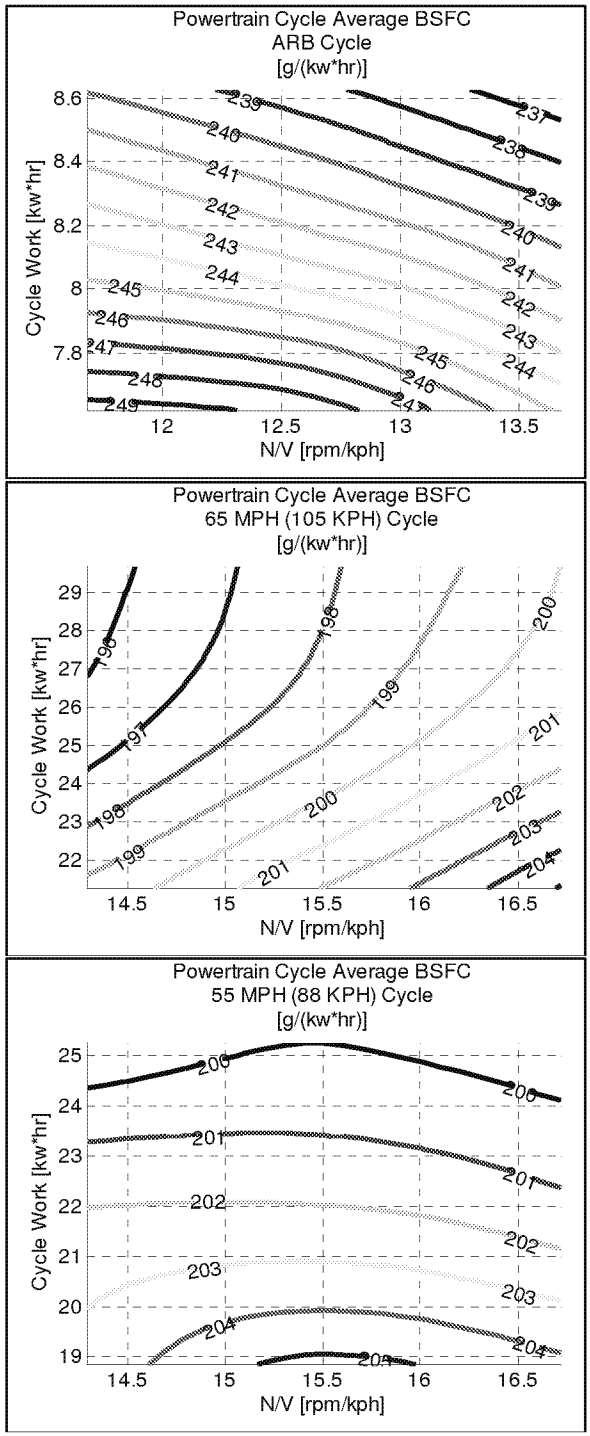

Figure 15 Powertrain cycle average BSFC maps: a) ARB Transient, b) 65 mph, c) 55 mph

Like the engine map, the predictive capability of the powertrain cycle average map was checked by fitting half of the data set and checking the prediction for the other half. In this case the fit chosen is linear in cycle work and second order in N/V. The model performance is shown in Figure 16, indicating good behavior of the model to represent truck configurations different than those tested to create the map.

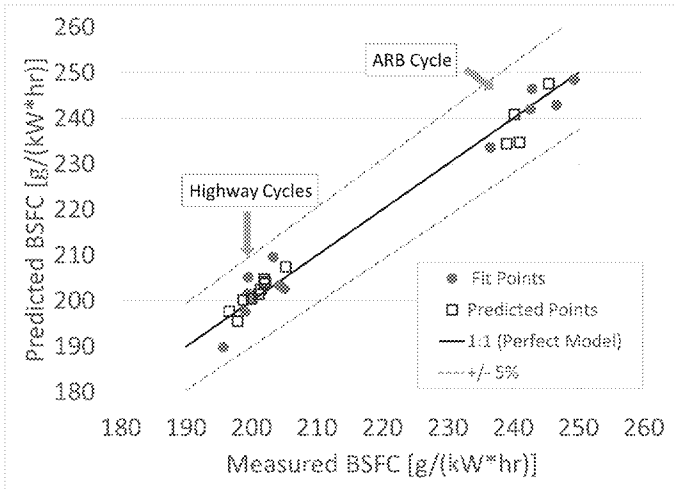

Figure 16. Powertrain cycle average map prediction capability with a linear fit in cycle work and second order fit in N/V

Repeatability of the powertrain approach was checked during the test program. An initial check of a few repeat cycles is shown in Figure 13 with the powertrain testing showing similar results to the engine cycle testing across the three different cycles. Dykes and Dorobantu [10] also show a set of six repeat points on the 55 MPH cycle to have a COV of 0.5% BSFC.

Using the Cycle Average Map in the CO_2 Regulation

With some level of validation complete, a potential procedure for utilizing a cycle average map in the vehicle CO_2 regulation can be outlined:

1. Generate engine torque and speed cycles from the vehicle certification cycles using GEM and generic vehicle configurations (Figure 17)
    a. The generic vehicles are defined based on the characteristics of the parent engine torque curve based on a pre-defined approach stipulated in the regulation protocol. This approach can be considered analogous to the de-normalization process of a normalized FTP cycle into the absolute speed and torque target cycle. This process will ensure that vehicles are chosen to match up with the engine and not force the mapping process to run the engine in a manner in which it will not be used in the field.
    b. The generic vehicles are simulated within GEM with the use of a default engine map and the torque curve and motoring curves of the parent target engine. The speed and torque profiles for the engine are recorded and then used as reference targets for the engine testing.

2. Run engine tests and tabulate cycle average CO_2 , N/V and cycle work for use in certification (Figure 17)
    a. The engine must match the target cycles with a regression requirement similar to that used for criteria emissions certification.
    b. Alternately, a hardware-in-the-loop (HIL) approach can also be used with GEM running at the test cell and creating the speed and torque targets in real time. This approach is preferred for powertrain testing or any controls features that will have a close integration with vehicle speed, road grade, or other vehicle level information.
3. Generate certification data for the specific vehicle using GEM simulation (Figure 18)
    a. The certified vehicle configuration is run in GEM with the torque and motoring curves for the specific engine rating, but with a default engine fuel consumption map.
    b. GEM calculates the engine (or powertrain) cycle work and average N/V then interpolates within the cycle average map to obtain a cycle average fuel consumption value. GEM also calculates the vehicle power demand and then multiplies the cycle average fuel consumption by the cycle cumulative power demand to arrive at the vehicle drive cycle fuel consumption as shown in Figure 4. In this manner, the use of a cycle average map is a simple post processing step in GEM and does not interact with the detailed GEM vehicle modeling calculations. Note that the only difference between use of an engine or a powertrain map is the location of the cycle work calculation. For an engine map, the cycle work is the engine cycle work. For a powertrain map, the cycle work is calculated at the transmission output.

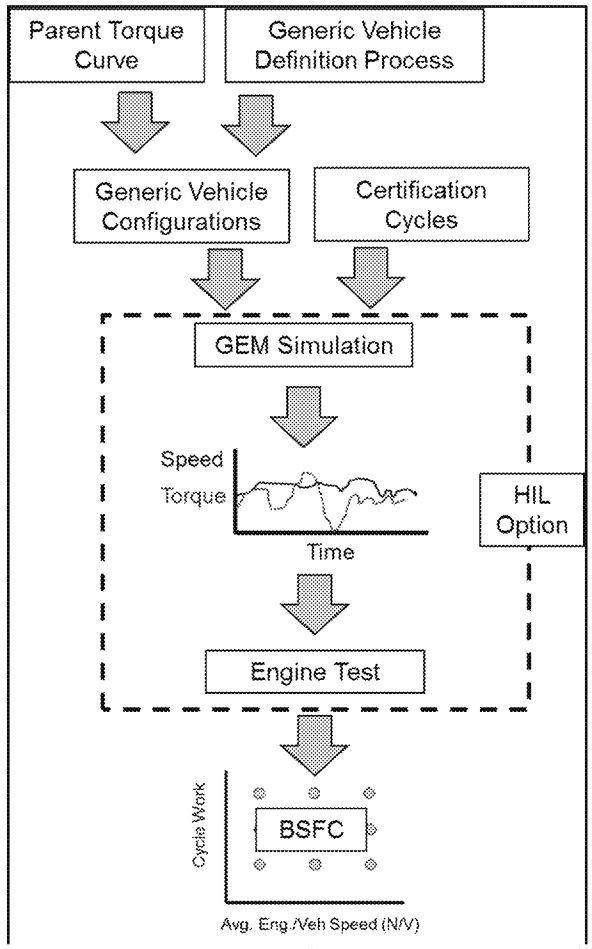

Figure 17. Process for generating the cycle average map for use in vehicle CO_2 regulation

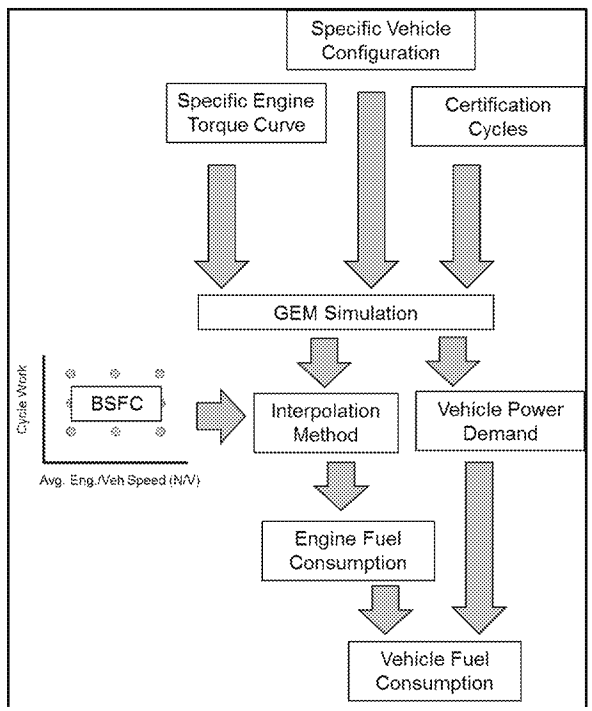

Figure 18. Process for using the cycle average map in vehicle CO_2 regulation

In work to date, nine vehicle configurations have been used and run on each of the three certification cycles, providing 27 data points. This number of cycles is a significant amount of engine testing time, but note that the expected steady state map approach of 143 operating points has a testing burden as well. A comparison of the testing time required for this approach as tested and a steady state map approach is shown in Table 1. Future work will focus on reducing the number of test cycles or streamlining the testing protocol. As shown in the table, a change in the pre-conditioning cycle strategy can reduce the test time significantly. Zhang et al. [1] have proposed a potential procedure that can reduce the testing time to the same range as the steady state map approach.

Table 1. Comparison of Testing Times for Different Approaches [10]

Cycle	Steady State Map [Hours]	Original Cycle Average Map [Hours]	Cycle Average Map New Pre-Conditioning Strategy [Hours]
Engine Warm-Up	0.3	0.3	0.3
DPF Regeneration	1.0	1.0	1.0
Emission Purge & Calibration	2.4	5.9	1.1
Pre-conditioning	3.3	5.6	1.9
Time at Test	1.2	5.6	5.6
Total Time	8.3	18.4	9.9

Summary/Conclusions

The cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation. The results obtained provide a well behaved surface for evaluation of BSFC, while also demonstrating a consistent treatment of the engine and powertrain.

Recommendation

Future work should investigate the cycle average map for use in the GHG Phase 2 program. Specifically some work should look at the behavior of the cycle average map on other engines across ratings. More work can certainly be done to choose the right number of map points, reduce cycle pre-conditioning, and to consider interpolation, extrapolation, and fit methods with a goal to reduce the number of mapping points and testing burden.

Future work should also concentrate on the number and specification of the vehicle configurations required for testing in order to generate a map that will apply to all vehicles under the same family. Zhang et al. [1] describe the principle with preliminary findings, but more work is needed.

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The authors would like to acknowledge the many conversations with others in the participating companies and around the industry to help develop the concept presented here. Houshun Zhang, James Sanchez, and Matt Spears at the EPA deserve mention for many collaborative and insightful discussions.

Definitions/Abbreviations

BSFC	Brake Specific Fuel Consumption
COV	Coefficient of Variance
GEM	Greenhouse Gas Emissions Model
N/V	Average Cycle Engine Speed Divided by Average Cycle Vehicle Speed
HIL	Hardware In the Loop

Appendix

Comparison of Typical Options to Represent Engine Performance in a Vehicle Simulation

Requirement	Form of Engine Information in the Vehicle Program			
	None	Single Value from Engine Certification Program (SET or FTP)	Steady State Engine Map	0D/1D Thermodynamic Model
Criteria Emissions Link	Good (built into Generic Map)	Good	Weak. Steady state map links to SET somewhat.	Hard to do
Accuracy	Generic Engine Map (Phase 1 GHG Approach)	Better than Generic Map	Better than Generic Map, but no transients	Depends on effort on calibration of the model
Auditability	N/A	Built into the engine certification program	Auditing each map point is a burden	Still need to audit engine?
Amount of Work	None for engine manufacturer (some for EPA)	None extra if using engine cert program value	Extra engine testing needed beyond the engine cert program	Very large to manage a detailed model
Consistency with Vehicle Operation	Reasonable	Possible if cycle represents vehicle operation well, but as powertrain configurations change maybe not	Speed and load matching but no transient content	Speed and load matching and could have transient content if controls are included
Confidentiality	N/A	No Issues	Map is confidential	Detailed model and controls logic are highly confidential
Powertrain Evaluation Capability	Generic Powertrain	Can move the transmission into the engine test	Hard to make a steady state map with the transmission included	Requires transmission controller model like the engine controller model

Message

From: Gary C Salemme [gary.c.salemme@cummins.com]
Sent: 4/24/2015 9:51:30 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Cortney.Guzlas@Navistar.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; David.Majors@Navistar.com; Matthew.Hunkler@Navistar.com; MihaiDorobantu@eaton.com; Morgan Andreae [morgan.andreae@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; david.gardner@navistar.com; debbie.gordon@allisontransmission.com; ErikDykes@eaton.com; erin.luke@paccar.com; Manik Narula [manik.narula@cummins.com]; MatthewRBusdiecker@eaton.com; michael.j.howenstein@allisontransmission.com; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Jeffrey.shultz@allisontransmission.com
Subject: Next Rev of the SAE Paper
Attachments: Alternative Approach SAE Paper Draft r15 markup.docx; Alternative Approach SAE Paper Draft r16.docx

All,

Thanks for the valuable feedback. I've tried to work it all in.

R15 is a copy with markup to see the changes from what I previously sent.
R16 is with everything incorporated. There is some clean up and 1 extra figure in R16 (figure 16) that is not in R15 (just added it last).

Let me know what you think. Please give positive confirmation to submit if you can or comments for changes. Submission deadline is Tues.

Regards,

Gary

Gary C. Salemme, P.E.
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2015-01-XXXX

An ~~Alternative~~ Engine and Powertrain Mapping Approach for Simulation of Vehicle CO2 Emissions

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

Simulations used to estimate carbon dioxide (CO_2) emissions and fuel consumption of medium- and heavy-duty vehicles over prescribed drive cycles often employ engine fuel maps consisting of engine measurements at numerous steady-state operating conditions. However, simulating the engine in this way has limitations as engine controls become more complex, particularly when attempting to use steady-state measurements to represent transient operation. This paper explores an alternative approach to vehicle simulation that uses a "cycle average" engine map rather than a steady state engine fuel map. The map contains engine CO_2 values measured on an engine dynamometer on cycles derived from vehicle drive cycles for a range of generic vehicles. A similar cycle average mapping approach is developed for a powertrain (engine and transmission) ~~tested together~~ in order to show the specific CO_2 improvements due to powertrain ~~integration and~~ optimization that would not ~~otherwise~~ be recognized in ~~other approaches simulation, engine testing, or full vehicle evaluation~~. While a related paper ~~[2] entitled "Alternative Vehicle Certification Procedure"~~ focuses primarily on simulation results, this paper summarizes the associated experimental results and ~~the~~ development of the ~~cycle average map~~ concept. Test results for an engine and a powertrain demonstrate the cycle average map is a smooth, continuous surface ~~in each case~~. The paper also compares accuracy of using the steady-state engine map versus the cycle average engine map ~~with the cycle-average map performing similarly or better, depending on drive cycle. Advantages of~~ Considerations for using the cycle average map for vehicle simulation in the context of CO_2 regulations are also discussed with the conclusion that the ~~cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation. cycle average map is a good alternative to the steady state map approach for representing engine fuel consumption and CO2 emissions performance in a vehicle certification program.~~

Introduction

~~The~~ An engine map is used to represent tested engine performance (fuel consumption, emissions, etc.) in a vehicle simulation in order to estimate drive cycle performance of the engine and vehicle [1, 2, 3]. The map is defined by triplets of engine speed, engine torque, and an engine performance parameter, for example brake specific fuel consumption. Figure 1 shows a schematic of the typical process to create such a map. An engine is run at steady speed and load conditions for some amount of time (usually minutes) for stabilization and data acquisition. After data collection at one point, the speed and load are ramped to another steady condition and the process repeated. The number of points varies depending on the intended use of the map, but can be over 100. Figure 2 shows an example map. Figure 3 shows how the map is used as part of a vehicle simulation, with each simulation time step using the map to predict instantaneous fuel consumption based on the current speed and load.

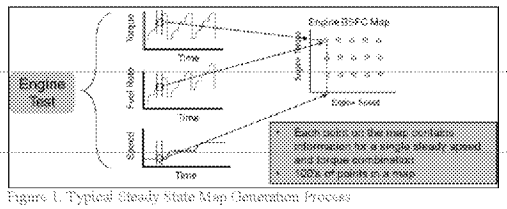

Figure 1. Typical Steady State Map Generation Process

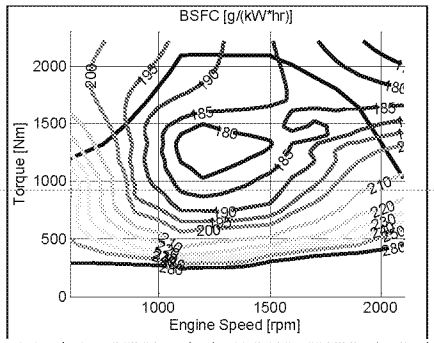

Figure 2. Steady State BSFC Map for the 2017 15 L 455 HP Engine Used in GEM

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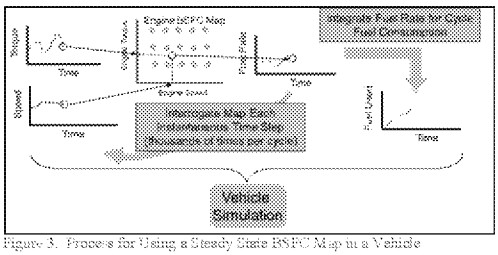

Figure 3. Process for Using a Steady State BSFC Map in a Vehicle Simulation

This map can be used in a vehicle simulation for general vehicle performance understanding as well as powertrain matching of the engine, transmission, ~~and~~ rear axle ratio and tire size to the vehicle. Historically, the engine map approach has also been a reasonable method to predict vehicle drive cycle fuel consumption [1, 2].

However, there are some inherent assumptions in using an engine map in this manner:

- The test cell engine installation mimics the vehicle installation. This assumption includes considerations such as radiator performance, charge air cooler cooling performance as well as flow restriction, combustion air inlet restriction, exhaust system restriction, and ambient cooling of the engine.
- The engine performance is closely correlated to engine speed and engine torque. These parameters are the map axes for defining the engine performance.
- The engine performance at a speed and torque in transient operation is very close to the performance at a steady state operating point of the same speed and torque.
- The engine performance is "well behaved" in the speed and torque space so interpolation or surface fitting of the map can be used to represent non-tested operating points.
- Traditionally, these assumptions have held well enough to use an engine map for relative comparisons of engine performance. For example, engine maps for two different model year engines have been used to reasonably accurately predict the change in drive cycle fuel consumption. (Reference something that shows that hopefully)

~~However f~~For modern diesel engines with aftertreatment and complex controls systems, the assumptions above are starting to be challenged. Engine performance is closely tied to aftertreatment performance, with closed loop feedback from the aftertreatment system to the engine. The aftertreatment performance is dependent on temperature, so ambient cooling differences between the test cell and the vehicle are becoming more important. Aftertreatment systems also have longer time responses than the base engine. It can take minutes for the aftertreatment to respond to engine changes [4]. So treating a speed and torque in a transient cycle the same as a steady state point becomes difficult and some model developers are looking for methods to correct the steady state map for transient behavior [5, 6].

In the past heavy duty engines set controls references based on tables that had axes of engine speed and fueling (or torque), but modern engines have much more complex control algorithms that depend on ambient conditions, temperature of the aftertreatment, or storage state of the aftertreatment (ammonia or soot for example) [6]. These control systems do not necessarily repeat performance at the same engine speed and torque in two different drive cycles. With these changes in the engine system, steady state maps can be expected to have trouble predicting the fuel consumption of a vehicle drive cycle. So a new approach to model an engine in a vehicle simulation is needed.

Development of the Concept

Vehicle CO_2 Regulation Considerations

The EPA Greenhouse Gas (GHG) Regulations ~~promulgated~~ published in 2011 [10] ~~(9)~~ ("Phase 1") ~~(Reference)~~ use vehicle simulation to regulate CO_2 emissions from heavy duty vehicles [7]. This Greenhouse Gas Emissions Model simulation program (GEM) uses engine steady state maps to represent the engine performance in the vehicle. But note that the simulation is really just used to evaluate vehicle characteristics like aerodynamics, tire rolling resistance, and weight. There is a generic map and generic powertrain specification that represents engine performance at the engine standard level which is used for all vehicle technologies. This approach essentially builds the engine map into the standard and all vehicles in a class are evaluated on the same engine.

For the next round of GHG Regulations ("Phase 2"), there is a desire to use the specific engine performance along with the specific transmission, rear axle ratio, and tire size in the vehicle certification. In this way the vehicle will receive~~get~~ credit for an engine and powertrain specification performing better than~~as~~ the standard or take the penalty for an engine performing above the standard. This approach will require some method of representing the actual engine performance in GEM. Consequently, EPA has made significant improvements over Phase 1 GEM. The detailed improvements and features of the new GEM are described by Newman et al. [7]. In the GEM, a~~A~~ steady state map representation of the engine is expected to be proposed. ~~This approach has been suggested by other [5] but with some clear qualifiers that the steady state engine map does not alone suffice to represent the engine.~~

For a regulation there are some different considerations for the engine information used in a vehicle simulation than for a product development effort. A more complete discussion of regulatory considerations is provided by Zhang et al [8]. Some key considerations relevant to the discussion in this paper are, ~~are~~

- ~~The CO_2 evaluation of the engine for use in the vehicle program should be consistent with the criteria emission regulations protocol. If the protocol for giving credit for a good CO_2 engine in the vehicle program is not consistent with the protocol for engine regulation for NO_x, HC, and PM, then manufacturers will have a large incentive to create systems that perform well on CO_2 at the expense of NO_x which may end up with solutions that do not drive both NO_x and CO_2 control to the real world.~~
- The engine information should be accurate, auditable, and relatively easy to collect. These requirements are not always consistent with each other, so trade-offs between them are likely to be needed. ~~Accuracy includes accurate representation of the engine performance as well as an accurate accounting of the benefit of vehicle technologies when used with the engine. A regulation requires compliance procedures. It seems unlikely that the GHG regulation will audit a full vehicle on the road, so auditing the inputs to the simulation becomes the compliance pathway. Consideration should be given to using common engine performance test results in the engine regulation and the~~

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~~vehicle regulation so that there is minimal extra test and auditing burden for the engine data used for the vehicle program.~~

- The engine should be evaluated in a manner consistent with how it will be used in the vehicle regulation. ~~Simply put, the engine model should be created with the expectation that it will be used in a transient cycle in simulation across a range of vehicle configurations and drive cycles.~~
- ~~Because engine manufacturers are not always the vehicle manufacturer, consideration must be given to keeping proprietary engine performance and controls information confidential.~~
- With future emphasis on recognizing the benefits of engine and transmission integration, some form of powertrain (engine and transmission) representation is desired for the vehicle regulation. A consistent approach for modeling the engine and powertrain for the vehicle regulation is desirable.

Options for Engine Model

With the above requirements in mind, it is useful to step back and consider what options exist to provide appropriate engine information to the vehicle regulatory program. Wurzenberger et al. [3] have taken a comprehensive look at engine modeling options, but for this work we want to look at some broad categories with respect to considerations for use in a regulation. Table 2~~Table 1~~ in the Appendix compares some traditional options.

Each of the options in Table 2~~Table 1~~ has some positive and negative attributes. A generic map puts no burden on the engine manufacturer but also gives no credit to the vehicle for a well performing engine. A single cycle value is simple, connected to the criteria emissions program, and auditable but depends on a single cycle operation matching the engine's operation in the vehicle. A steady state map doesn't capture engine transient behavior, but, perhaps a new type of map can be used. ~~A more detailed engine model adds a lot of complexity and confidentiality concerns.~~

~~In choosing a method, a process that relies on engine system testing is preferable. This approach avoids any of the issues with model calibration or confidentiality and leads to an auditable process. A map is needed that is based on testing, includes transient content, and is flexible to adjust the engine's performance when the vehicle configuration or drive cycle changes.~~

To consider such a map, it's worth noting that the cumulative vehicle CO_2 on any drive cycle can be considered in parts as shown in Figure 4. The ~~e~~Engine CO_2 is just the cycle cumulative brake specific emissions of the engine that is typically measured and regulated. This value is a measure of the engine efficiency. The vehicle power demand is the cycle cumulative engine work normalized by the payload and distance travelled. Another way to consider this value is the average horsepower required to move a unit of payload at a given speed. It is a measure of the efficiency of the vehicle to move payload. Mathematically, these values can be calculated from any drive cycle simulation and combined to provide the overall drive cycle vehicle CO_2 emissions.

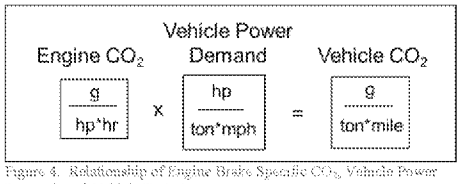

Figure 4. Relationship of Engine Brake Specific CO_2, Vehicle Power Demand, and Vehicle Emissions

The engine CO_2 part of Figure 4 can be represented by a cycle average BSFC map. The engine is tested on a cycle that matches vehicle operation well and the cycle cumulative fuel consumption is measured. The cycle can then be changed to represent slightly different vehicle operation for a new value of fuel consumption. In this way a set of cycles can be tested to "map" the engine's cumulative cycle fuel consumption response. A schematic of this approach is shown in Figure 5. An example cycle average map is shown in Figure 6. The process for using it in a vehicle simulation is shown in Figure 7. The entire cycle is simulated and then the cumulative cycle work, average engine speed, and average vehicle speed are used to interrogate the map for a cycle brake specific fuel consumption value. Then the relationship of Figure 4 is used to calculate the vehicle cycle fuel consumption or CO_2. Zhang et al. [8] describe this process as an alternative certification approach, which is supported by a large number of simulations and also the results of this paper.

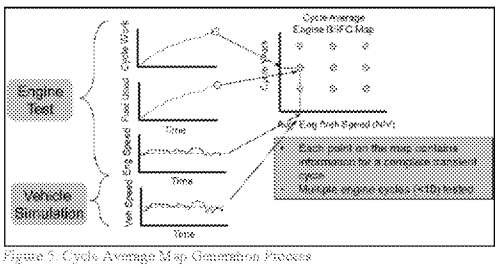

Figure 5. Cycle Average Map Generation Process

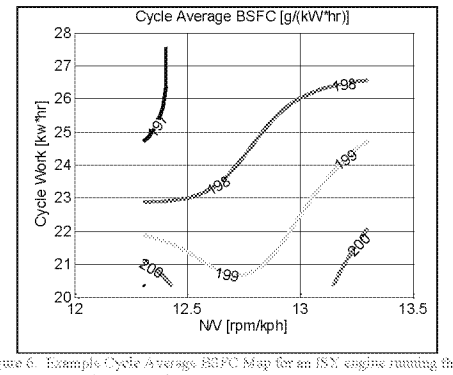

Figure 6. Example Cycle Average BSFC Map for an ISX engine running the 55 MPH (88 KPH) GEM Cycle

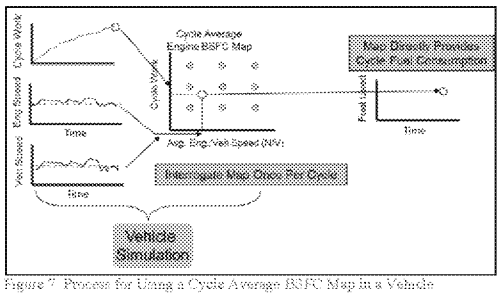

Figure 7 Process for Using a Cycle Average BSFC Map in a Vehicle Simulation

Average engine speed divided by average vehicle speed (denoted as N/V) has been used as a map axis to represent the nature of the engine speed operation on the cycle. Cycle work has been used as a second map axis to represent the engine loading on the cycle. These parameters are analogous to using engine speed and load as the axes for a steady state map. Other similarities between the steady state map and the cycle average map are:

- An engine test is completed with production controls in a CFR 1065 capable test cell
- An extra test is required beyond what is used for the engine certification
- Points on the map can be audited
- Allows evaluation of the engine at speeds and loads that the engine sees in the vehicle

Table 2 summarizes some more similarities and some differences between the two mapping approaches.

Table 2. Comparison of the Steady State and Cycle Average Maps

	Steady State Map Approach	Cycle Average Map Approach
Similarities	Actual engine with production controls in a CFR 1065 capable test cell	
	Requires an extra test beyond what is used for the engine CO_2 certification	
	Points on map can be audited	
	Provides cycle fuel consumption based on the speeds and loads the engine sees in the vehicle	
	Use speed and torque as axes to define the map	Use a Cycle Average Speed metric and Cycle Average Torque (Cycle Work) as axes to define the map
Differences	No transient performance evaluated or captured	Realistic transient performance built into each point on the map
	Not possible to consider for criteria emissions use	Possible to consider as a criteria emissions protocol for the future
	Fuel use at each point in the cycle is calculated	Fuel use is only calculated as a total cycle value
	Audit steady-state points	Audit transient cycles
	Differences in the testing burden need to be investigated	

Based on the comparisons above, the cycle average map approach is a good alternative to investigate for modeling the engine performance in the vehicle CO_2 regulation protocol.

Validation of the Concept

Validation of the concept was first conducted through simulations using GEM [8]. In that study, a test matrix based on a Class 8 Kenworth T700 tractor with a Cummins ISX engine was carefully designed. It covered 32 vehicle configurations and three transmissions together with other relevant parameters, resulting in over one thousand simulations. In this paper, a hardware based approach with both engine and powertrain testing is used to further vetting the concept. The combination of the two papers provides a complete picture of how this alternative certification concept has been developed and evaluated.

Similar to the study by Zhang et al. [8], s8ome of the key questions to consider for the cycle average map are:

1. Is the map surface well behaved so that interpolation can represent points not tested?
2. How does the accuracy compare to a steady state map approach?
2.3. Is the test procedure robust and the results repeatable?

A first check of the surface shape was performed via simulation in GEM [8] and is described in a separate paper. After reasonable results from a simulation study, two test programs were implemented to investigate the questions above. The first test program included only the engine and the second program included the powertrain (engine and transmission).

Engine Only Approach

Dekker and Dorobantu [9] describe the test setup in detail. The engine-only test cell as shown in Figure 8 was sized to accommodate a heavy-duty (HD) engine. A Cummins 15 liter ISX engine rated to 336kW (450 hp) with peak torque of 2375 Nm (1750 ft-lb) was used for the evaluation. A HD aftertreatment system was installed to meet the EPA and CARB emissions standards. The aftertreatment system utilized both a Diesel Particulate Filter (DPF) and a Selective Catalytic Reduction (SCR) system. To maintain a baseline condition for the DPF during testing, a DPF regeneration was forced prior to each set of tests to clean the DPF of stored particulates. The SCR system was operated during testing as would be witnessed in-vehicle

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operation to reduce NOx. The exhaust emissions were collected continuously using a Horiba Mexa7100D emission bench. The fuel was measured continuous during each test cycle using a ReSol RS438A-200 Fuel Flow Measurement System. The testing is completed using ultra low sulfur diesel fuel with a maximum sulfur concentration of 15 PPM. The engine intake air is temperature, humidity and pressure controlled to 25°C, 53% and 99kPa, respectively. All temperatures, pressures, fuel flow and emissions measurements were logged at a rate of 10 Hz.

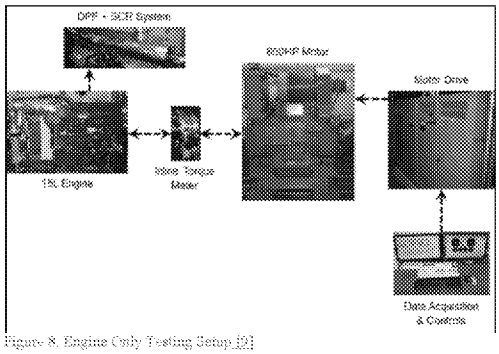

Figure 8. Engine Only Testing Setup [9]

The test cycles utilized for the engine-only mapping approach were generated using GEM. Three separate vehicle configurations were input into the GEM model to generate speed and load points for each of the regulatory cycles (ARB, 65MPH, and 55 MPH). A total of nine traces were generated for each cycle. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle. A total of 27 engine tests were run (3 vehicle configurations x 3 test cycles x 3 axle ratios). The vehicle configurations were chosen to provide a reasonably broad coverage of real-world specifications to give sufficient spread of the test points to allow an interpolation and extrapolation approach to be used for the even broader spectrum of customer vehicle specifications. The cycles run are shown in Figure 9. These are the GHG Phase 1 GEM cycles [2] with the change that the highway cycles have been modified to include grade profiles. The grade profiles were provided by the EPA [7].

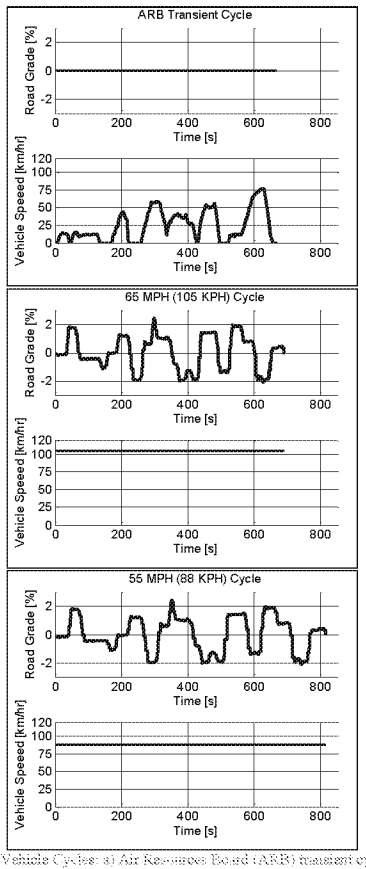

Figure 9. Vehicle Cycles: a) Air Resources Board (ARB) transient cycle, b) 65 mph [105 kph] GEM cycle with road grade, c) 55 mph [88 kph] GEM cycle with road grade.

Example engine map results are shown in Figure 10. These show a generally well-behaved surface for either surface fitting or interpolation.

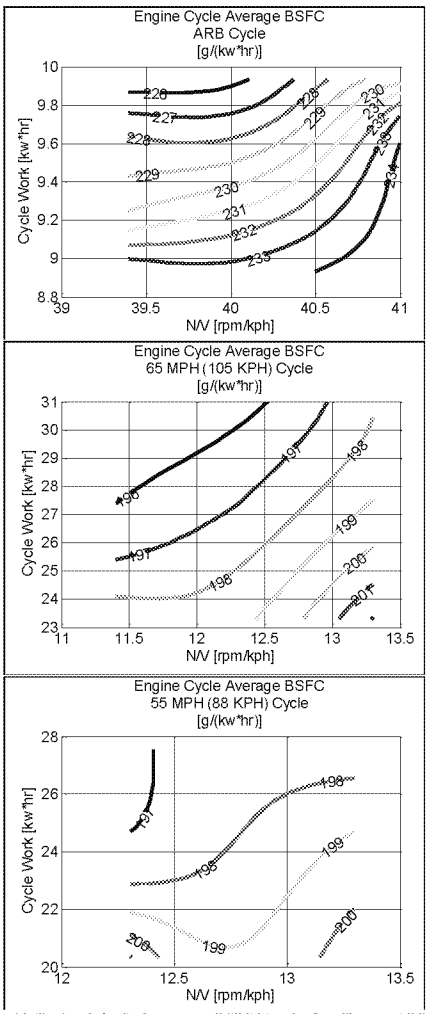

Figure 10. Engine Only Cycle Average BSFC Map Surface Plots: a) ARB Transient, b) 65 mph, c) 55 mph

To check the predictability of the map, half the data set was used to fit BSFC to a linear model in N/V and cycle work. Testing this model on the other half of the data set shows the model performance as seen in Figure 11, indicating good behavior of the model to represent truck configurations different than those tested to create the map. Additionally, some extra truck configurations were tested at a later date as independent check points for the map. Those points are also shown in Figure 11, with similar good agreement between the model and test results. These findings are consistent with the observations obtained from the simulation study [8].

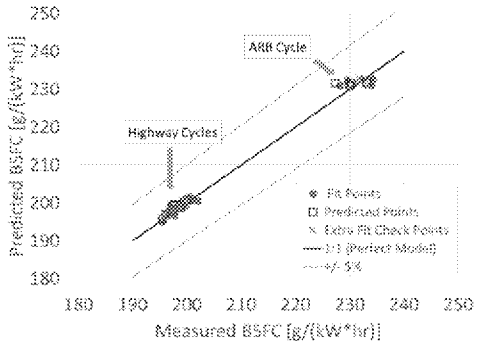

Figure 11. Cycle average map prediction capability with a linear fit in cycle work and N/V

A comparison of the cycle average map to the steady state map approach was completed and is shown in Figure 12. The steady state map results were taken directly from GEM using a steady state map for the same engine model as tested for the cycle average map [8], but it was not the identical engine. So engine to engine and test cell to test cell variability ~~on the order of 2%~~ need to be considered in comparing results. In the region of the 55 MPH and 65 MPH cycles (labelled Highway Cycles), ~~differences between the cycle average map and the steady state map can be attributed to that aforementioned variability the two approaches are close in accuracy. A statistical analysis shows that there is 90% confidence that the cycle average map is 1.7% better at matching the measurements than the steady state map. This level of difference is potentially within the variability of the engines and test locations used to create the different maps.~~ For these relatively steady cycles the two map approaches are expected to produce similar results and they do agree within the variability of testing.

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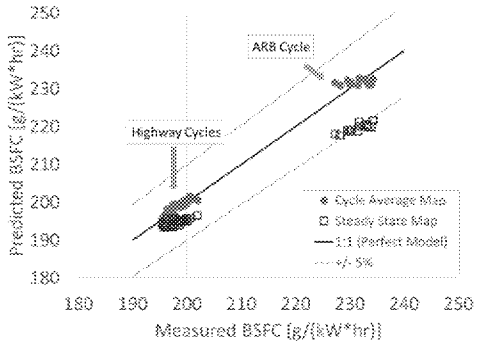

Figure 12. Comparison of cycle average map linear fit in cycle work and N/V to a steady state map interpolation

For the ARB cycle with more transient content the cycle average map does show a better match to the measured data than the steady state map approach. ~~A statistical analysis shows that there is 99% confidence that the cycle average map is 4.9% better at matching the measurements than the steady state map. This difference is higher than expected testing variability. This result~~ The larger difference

with the more transient cycle is expected from the more transient nature of the ARB cycle and the from the ability of the cycle average map approach to capture transient performance content.

Note that for this initial investigation of the cycle average map approach, the goal was not to precisely and completely prove capability, but rather to check for concept feasibility. For a regulation approach, it's likely that a surface fit to the cycle data would not be used. If a certification configuration matches a mapped configuration, the exact tested result is a desired output of the model. So an interpolation and extrapolation method will likely be proposed for any regulation.

The engine only testing approach is equivalent to current engine certification protocols, so repeatability is expected to be on par with current engine transient cycle certification methods. A number of repeat points on the different cycles were checked with the results shown in Figure 13 indicating good test repeatability.

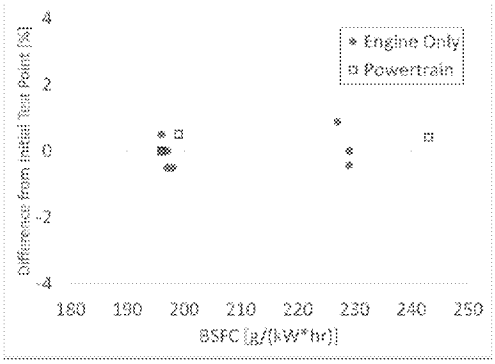

Figure 13. Repeatability of Test Results

Powertrain Approach

Dykas and Duralamy [9] describe the test setup in detail. The powertrain test cell as shown in Figure 14Figure 13 was sized to accommodate a powertrain from a relatively heavy-duty vehicle. The vehicle test weight was 30,391 kg [67,000 lbs.]. The powertrain tested included a Cummins 15-liter ISX engine with an Eaton 10-speed automated manual transmission. The engine maximum rated performance was 336kW (450 hp) at 1800 rpm with peak torque of 2375 Nm (1750 ft-lb) at 1000 rpm and was operated using two separate calibrations; one base calibration for testing with the 10-speed Eaton UltraShift PLUS LAS transmission and an additional calibration with SmartTorque2 (ST2) technology for testing in conjunction with the 10-speed Fuller Advantage™ (FASA) transmission. Both engine calibrations tested were emission certified for 2013 CARB and EPA. The dynamometer was sized to accommodate the engine's peak torque multiplied by the transmission's maximum gear reduction. All data collection and test procedures described for the engine only test were repeated for the powertrain testing. For the powertrain testing, the test cell ran as an HIL system with a version of the GEM vehicle model controlling the dynamometer and throttle controls so that the engine ran as if in a vehicle.

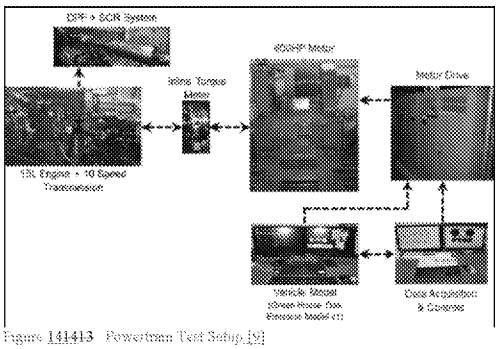

Figure 141413 Powertrain Test Setup [9]

The same three cycles from Figure 9 were used for the powertrain testing. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle.

An example powertrain cycle average map is shown in Figure 15Figure 14. As with the engine only results, the surfaces look to have a reasonable shape that can be used for interpolation and extrapolation use in a vehicle simulation for regulation purposes.

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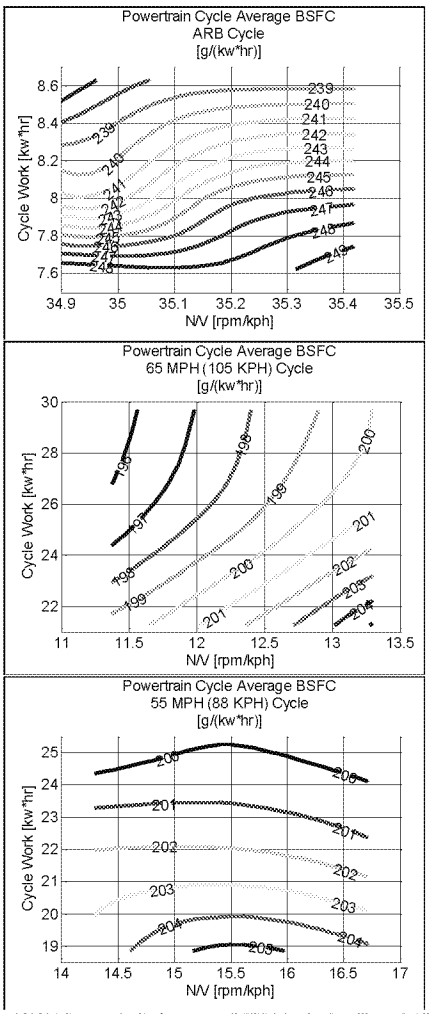

Figure ~~15~~14 Powertrain Cycle Average BSFC Map Surface Plots: a) ARB Transient, b) 65 mph, c) 55 mph

Repeatability of the powertrain approach was checked during the test program. An initial check of a few repeat cycles is shown in Figure 13 with the powertrain testing showing similar results to the engine cycle testing across the three different cycles. Dykes and Dorobantu [9] also show a set of 6 repeat points on the 55 MPH cycle to have a COV of 0.5%.

Using the Cycle Average Map in the CO_2 Regulation

~~*Process for Using in CO_2 Regulation*~~

With some level of validation complete, a potential procedure for utilizing a cycle average map in the vehicle CO_2 regulation can be outlined:

1. Generate engine torque and speed cycles from the vehicle certification cycles using GEM and generic vehicle configurations (Figure 16~~Figure 15~~)
    a. The generic vehicles are defined based on the characteristics of the parent engine torque curve based on a pre-defined approach stipulated in the regulation protocol. This approach can be considered analogous to the de-normalization process of a normalized FTP cycle into the absolute speed and torque target cycle. This process will ensure that vehicles are chosen to match up with the engine and not force the mapping process to run the engine in a manner in which it will not be used in the field.
    b. The generic vehicles are simulated within GEM with the use of a default engine map and the torque curve and motoring curves of the parent target engine. The speed and torque profiles for the engine are recorded and then used as reference targets for the engine testing.
2. Run engine tests and tabulate cycle average CO2 , N/V and cycle work for use in certification (Figure 16~~Figure 15~~)
    a. The engine must match the target cycles with a regression requirement similar to that used for criteria emissions certification.
    b. Alternately, a hardware-in-the-loop (HIL) approach can also be used with GEM running at the test cell and creating the speed and torque targets in real time. This approach is preferred for powertrain testing or any controls features that will have a close integration with vehicle speed, road grade, or other vehicle level information.
3. Generate certification data for the specific vehicle using GEM simulation (Figure 17~~Figure 16~~)
    a. The certified vehicle configuration is run in GEM with the torque and motoring curves for the specific engine rating, but with a default engine fuel consumption map.
    b. GEM calculates the engine (or powertrain) cycle work and average N/V then interpolates within the cycle average map to obtain a cycle average fuel consumption value. GEM also calculates the vehicle power demand and then multiplies the cycle average fuel consumption by the cycle cumulative power demand to arrive at the vehicle drive cycle fuel consumption as shown in Figure 4. In this manner, the use of a cycle average map ~~is~~ is a simple post processing step in GEM and does not interact with the detailed GEM vehicle modeling calculations. Note that the only difference between use of an engine or a

powertrain map is the location of the cycle work calculation. For an engine map, the cycle work is the engine cycle work. For a powertrain map, the cycle work is calculated at the transmission output.

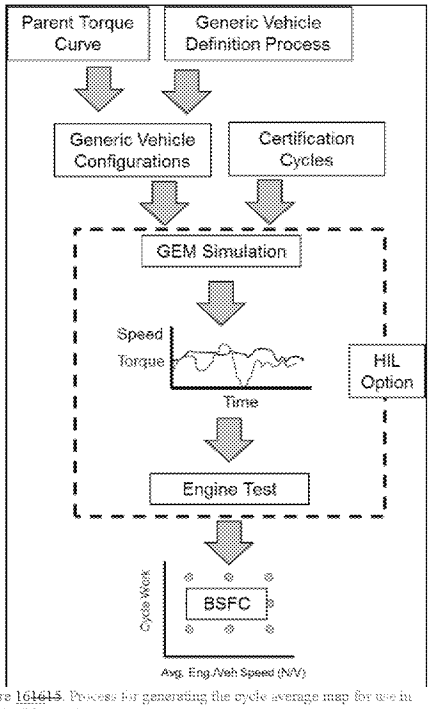

Figure 161615. Process for generating the cycle average map for use in vehicle CO_2 regulation

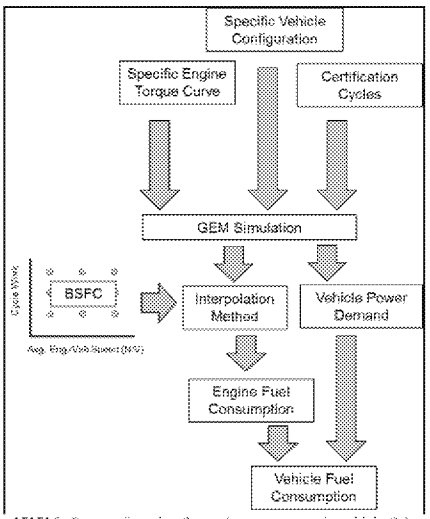

Figure 171716. Process for using the cycle average map in vehicle CO_2 regulation

In work to date, nine vehicle configurations have been used and run on each of the three certification cycles, providing 27 data points. This number of cycles is a significant amount of engine testing time, but note that the expected steady state map approach of 143 operating points has a testing burden as well. A comparison of the testing time required for this approach as tested and a steady state map approach is shown in Table 1~~Table 3~~. Future work will focus on reducing the number of test cycles or streamlining the testing protocol. As shown in the table, a change in the pre-conditioning cycle strategy can reduce the test time significantly. Zhang et al. [8] have proposed a potential procedure that can reduce the testing time to the same range as the steady state map approach.

Table 13. Comparison of Testing Times for Different Approaches [9]

Cycle	Steady State Map [Hours]	Original Cycle Average Map [Hours]	Cycle Average Map New Pre-Conditioning Strategy [Hours]
Engine Warm-Up	0.3	0.3	0.3
DPF Regeneration	1.0	1.0	1.0
Emission Purge & Calibration	2.4	5.9	1.1
Pre-conditioning	3.3	5.6	1.9
Time at Test	1.2	5.6	5.6
Total Time	8.3	18.4	9.9

Future Regulatory Considerations

In the current work, the cycle average map has been utilized to represent engine fuel consumption performance for use in the vehicle CO_2 regulation. But in the future, this concept could be used for other purposes.

The engine cycles tested for the cycle average map are inherently linked to the vehicle configurations expected to be using the engines. So these cycles are good real-life cycles that could be considered for criteria emissions certification for the engine. By using the same cycles, the criteria emissions program and the GHG program would be linked so that one cannot be compromised in favor of the other. This approach can also simplify the engine certification program. Figure 17 shows the expected GHG phase 2 engine regulatory structure with 3 pathways of regulation on the engine. Figure 18 shows that a future structure based on a cycle average map could simplify this picture.

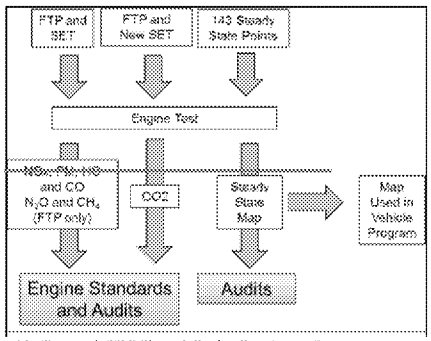

Figure 17. Expected GHG Phase 2 Engine Regulatory Structure

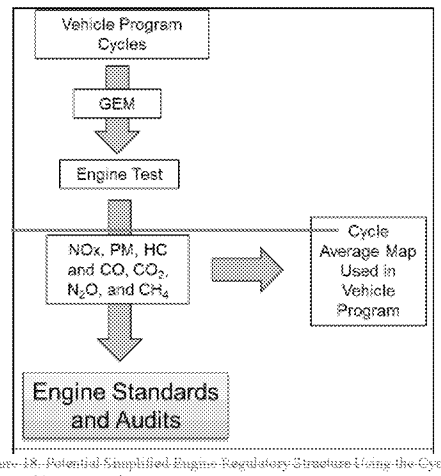

Figure 18. Potential Simplified Engine Regulatory Structure Using the Cycle Average Map Approach

The consistent treatment of the powertrain and engine with a cycle average map approach allow it to be considered for regulating criteria emissions at the powertrain level. The powertrain test results for criteria emissions could be directly regulated, allowing the benefits of the transmission and engine integration to be recognized for optimizing fuel consumption and emissions.

Also, if there is ever a desire to give credit to a lower power demand vehicle in reducing criteria emissions, the cycle average map approach could be used. Because transient cycles are tested to create the map, it is possible criteria emissions could be treated in the same manner as fuel consumption.

Summary/Conclusions

The cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation. The results obtained provide a well behaved surface for evaluation of BSFC, while also demonstrating a consistent treatment of the engine and powertrain. First indications are that the accuracy is comparable or better than a steady state map. It also allows a consistent treatment of the engine and the powertrain in the same approach and has potential to simplify and link the criteria emissions and CO_2 programs in the future.

Recommendation

Future work should investigate the cycle average map for use in the GHG Phase 2 program. Specifically some work should look at the behavior of the cycle average map on other engines across ratings. More work can certainly be done to choose the right number of map points, reduce cycle pre-conditioning, and to consider interpolation, extrapolation, and fit methods, especially with a goal to reduce the number of mapping points and testing burden.

Future work should also concentrate on the number and specification of the vehicle configurations required for testing in order to generate a map that will apply to all vehicles under the same family. Zhang et al. [8] describe the principle with preliminary findings, but more work is needed.

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Definitions/Abbreviations

N/V	Average Cycle Engine Speed Divided by Average Cycle Vehicle Speed
GEM	Greenhouse Gas Emissions Model

Appendix

Table 24. Comparison of Typical Options to Represent Engine Performance in a Vehicle Simulation

Requirement	Form of Engine Information in the Vehicle Program			
	None	Single Value from Engine Certification Program (SET or FTP)	Steady State Engine Map	0D/1D Thermodynamic Model
Criteria Emissions Link	Good (built into Generic Map)	Good	Weak. Steady state map links to SET somewhat.	Hard to do
Accuracy	Generic Engine Map (Phase 1 GHG Approach)	Better than Generic Map	Better than Generic Map, but no transients	Depends on effort on calibration of the model
Auditability	N/A	Built into the engine certification program	Auditing each map point is a burden	Still need to audit engine?
Amount of Work	None for engine manufacturer (some for EPA)	None extra if using engine cert program value	Extra engine testing needed beyond the engine cert program	Very large to manage a detailed model
Consistency with Vehicle Operation	Reasonable	Possible if cycle represents vehicle operation well, but as powertrain configurations change maybe not	Speed and load matching but no transient content	Speed and load matching and could have transient content if controls are included
Confidentiality	N/A	No Issues	Map is confidential	Detailed model and controls logic are highly confidential
Powertrain Evaluation Capability	Generic Powertrain	Can move the transmission into the engine test	Hard to make a steady state map with the transmission included	Requires transmission controller model like the engine controller model

2015-01-XXXX

An Engine and Powertrain Mapping Approach for Simulation of Vehicle CO2 Emissions

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

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Abstract

Simulations used to estimate carbon dioxide (CO_2) emissions and fuel consumption of medium- and heavy-duty vehicles over prescribed drive cycles often employ engine fuel maps consisting of engine measurements at numerous steady-state operating conditions. However, simulating the engine in this way has limitations as engine controls become more complex, particularly when attempting to use steady-state measurements to represent transient operation. This paper explores an alternative approach to vehicle simulation that uses a "cycle average" engine map rather than a steady state engine fuel map. The map contains engine CO_2 values measured on an engine dynamometer on cycles derived from vehicle drive cycles for a range of generic vehicles. A similar cycle average mapping approach is developed for a powertrain (engine and transmission) in order to show the specific CO_2 improvements due to powertrain optimization that would not be recognized in other approaches. While a related paper [1] focuses primarily on simulation results, this paper summarizes the associated experimental results and development of the concept. Test results for an engine and a powertrain demonstrate the cycle average map is a smooth, continuous surface. The paper also compares accuracy of using the steady-state engine map versus the cycle average engine map. Considerations for using the cycle average map for vehicle simulation in the context of CO_2 regulations are also discussed with the conclusion that the cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation.

Introduction

An engine map is used to represent tested engine performance (fuel consumption, emissions, etc.) in a vehicle simulation in order to estimate drive cycle performance of the engine and vehicle [2, 3, 4]. The map is defined by triplets of engine speed, engine torque, and an engine performance parameter, for example brake specific fuel consumption. Figure 1 shows a schematic of the typical process to create such a map. An engine is run at steady speed and load conditions for some amount of time (usually minutes) for stabilization and data acquisition. After data collection at one point, the speed and load are ramped to another steady condition and the process repeated. The number of points varies depending on the intended use of the map, but can be over 100. Figure 2 shows an example map. Figure 3 shows how the map is used as part of a vehicle simulation, with each simulation time step using the map to predict instantaneous fuel consumption based on the current speed and load.

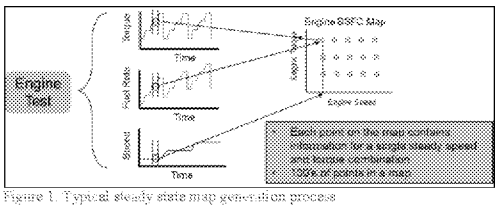

Figure 1. Typical steady state map generation process

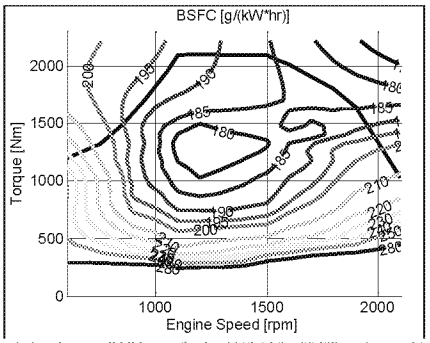

Figure 2. Steady state BSFC map for the 2017 15 L 455 HP engine used in GEM

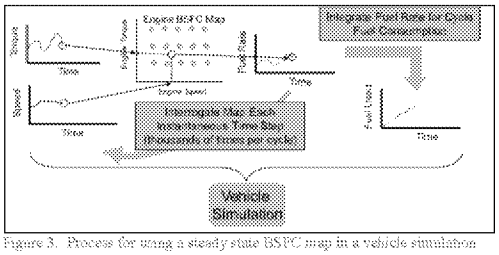

Figure 3. Process for using a steady state BSFC map in a vehicle simulation

This map can be used in a vehicle simulation for general vehicle performance understanding as well as powertrain matching of the engine, transmission, rear axle ratio, and tire size to the vehicle. Historically, the engine map approach has also been a reasonable method to predict vehicle drive cycle fuel consumption [2, 3].

However, there are some inherent assumptions in using an engine map in this manner:

- The test cell engine installation mimics the vehicle installation. This assumption includes considerations such as radiator performance, charge air cooler cooling performance as well as flow restriction, combustion air inlet restriction, exhaust system restriction, and ambient cooling of the engine.
- The engine performance is closely correlated to engine speed and engine torque. These parameters are the map axes for defining the engine performance.
- The engine performance at a speed and torque in transient operation is very close to the performance at a steady state operating point of the same speed and torque.
- The engine performance is "well behaved" in the speed and torque space so interpolation or surface fitting of the map can be used to represent non-tested operating points.

Traditionally, these assumptions have held well enough to use an engine map for relative comparisons of engine performance. However for modern diesel engines with aftertreatment and complex controls systems, the assumptions above are starting to be challenged. Engine performance is closely tied to aftertreatment performance, with closed loop feedback from the aftertreatment system to the engine. The aftertreatment performance is dependent on temperature, so ambient cooling differences between the test cell and the vehicle are becoming more important. Aftertreatment systems also have longer time responses than the base engine. It can take minutes for the aftertreatment to respond to engine changes [5]. So treating a speed and torque in a transient cycle the same as a steady state point becomes difficult and some model developers are looking for methods to correct the steady state map for transient behavior [6, 7].

In the past, heavy duty engines set controls references based on tables that had axes of engine speed and fueling (or torque), but modern engines have much more complex control algorithms that depend on ambient conditions, temperature of the aftertreatment, or storage state of the aftertreatment (ammonia or soot for example) [7]. These control systems do not necessarily repeat performance at the same engine speed and torque in two different drive cycles. With these changes in the engine system, steady state maps can be expected to have trouble predicting the fuel consumption of a vehicle drive cycle. So a new approach to model an engine in a vehicle simulation is needed.

Development of the Concept

Vehicle CO_2 Regulation Considerations

The EPA Greenhouse Gas (GHG) Regulations published in 2011 [8] ("Phase 1") use vehicle simulation to regulate CO_2 emissions from heavy duty vehicles [3]. This Greenhouse Gas Emissions Model simulation program (GEM) uses engine steady state maps to represent the engine performance in the vehicle. But note that the simulation is really just used to evaluate vehicle characteristics like aerodynamics, tire rolling resistance, and weight. There is a generic map and generic powertrain specification used for all vehicle technologies. This approach essentially builds the engine map into the standard and all vehicles in a class are evaluated on the same engine.

For the next round of GHG Regulations ("Phase 2"), there is a desire to use the specific engine performance along with the specific transmission, rear axle ratio, and tire size in the vehicle certification. In this way the vehicle will receive credit for an engine and powertrain specification performing better than the standard or take the penalty for an engine performing above the standard. This approach will require some method of representing the actual engine performance in GEM. Consequently, EPA has made significant improvements over Phase 1 GEM. The detailed improvements and features of this new GEM are described by Newman et al. [9] In this GEM, a steady state map representation of the engine is expected to be proposed. For a regulation there are some different considerations for the engine information used in a vehicle simulation than for a product development effort. A more complete discussion of regulatory considerations is provided by Zhang et al. [1] Some key considerations relevant to the discussion in this paper are:

- The engine information should be accurate, auditable, and relatively easy to collect. These requirements are not always consistent with each other, so trade-offs between them are likely to be needed.
- The engine should be evaluated in a manner consistent with how it will be used in the vehicle regulation.
- With future emphasis on recognizing the benefits of engine and transmission integration, some form of powertrain (engine and transmission) representation is desired for the vehicle regulation. A consistent approach for modeling the engine and powertrain for the vehicle regulation is desirable.

Options for Engine Model

With the above requirements in mind, it is useful to step back and consider what options exist to provide appropriate engine information to the vehicle regulatory program. Wurzenberger et al. [4] have taken a comprehensive look at engine modeling options, but for this work we want to look at some broad categories with respect to considerations for use in a regulation. The table in the Appendix compares some traditional options.

Each of the options in the table has some positive and negative attributes. A generic map puts no burden on the engine manufacturer but also gives no credit to the vehicle for a well performing engine. A single cycle value is simple, connected to the criteria emissions program, and auditable but depends on a single cycle operation matching the engine's operation in the vehicle. A steady state map doesn't capture engine transient behavior, but perhaps a new type of map can be used.

To consider such a map, it's worth noting that the cumulative vehicle CO_2 on any drive cycle can be considered in parts as shown in Figure 4. The engine CO_2 is just the cycle cumulative brake specific emissions of the engine that is typically measured and regulated. This value is a measure of the engine efficiency. The vehicle power demand is the cycle cumulative engine work normalized by the payload and distance travelled. Another way to consider this value is the average horsepower required to move a unit of payload at a given speed. It is a measure of the efficiency of the vehicle to move payload. Mathematically, these values can be calculated from any

drive cycle simulation and combined to provide the overall drive cycle vehicle CO_2 emissions.

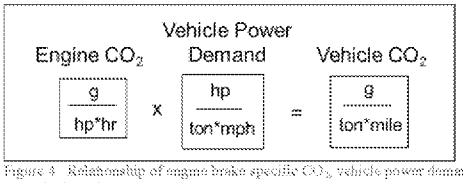

Figure 4. Relationship of engine brake specific CO_2, vehicle power demand, and vehicle emissions

The engine CO_2 part of Figure 4 can be represented by a cycle average BSFC map. The engine is tested on a cycle that matches vehicle operation well and the cycle cumulative fuel consumption is measured. The cycle can then be changed to represent slightly different vehicle operation for a new value of fuel consumption. In this way a set of cycles can be tested to "map" the engine's cumulative cycle fuel consumption response. A schematic of this approach is shown in Figure 5. An example cycle average map is shown in Figure 6. The process for using it in a vehicle simulation is shown in Figure 7. The entire cycle is simulated and then the cumulative cycle work, average engine speed, and average vehicle speed are used to interrogate the map for a cycle brake specific fuel consumption value. Then the relationship of Figure 4 is used to calculate the vehicle cycle fuel consumption or CO_2. Zhang et al. [1] describe this process as an alternative certification approach, which is supported by a large number of simulations and also the results of this paper.

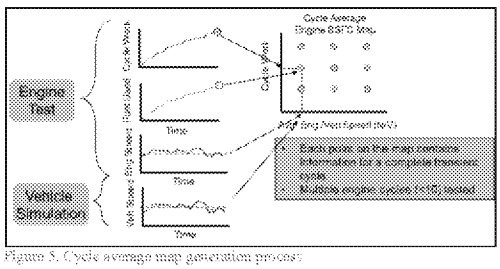

Figure 5. Cycle average map generation process

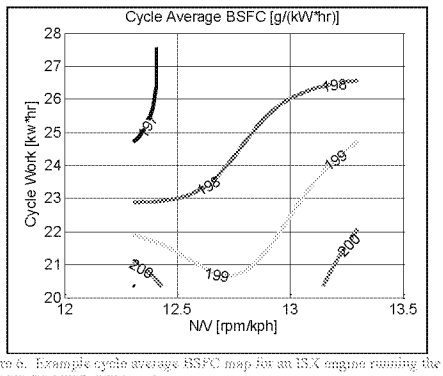

Figure 6. Example cycle average BSFC map for an ISX engine running the 55 MPH (88 KPH) GEM cycle

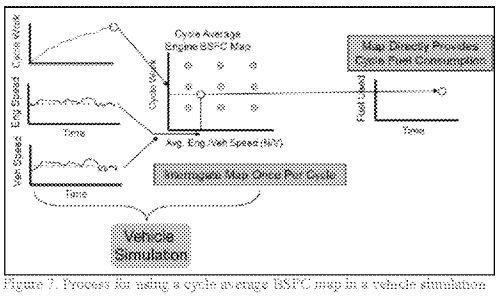

Figure 7. Process for using a cycle average BSFC map in a vehicle simulation

Average engine speed divided by average vehicle speed (denoted as N/V) has been used as a map axis to represent the nature of the engine speed operation on the cycle. Cycle work has been used as a second map axis to represent the engine loading on the cycle. These parameters are analogous to using engine speed and load as the axes for a steady state map. Other similarities between the steady state map and the cycle average map are:

- An engine test is completed with production controls in a CFR 1065 capable test cell
- An extra test is required beyond what is used for the engine certification
- Points on the map can be audited
- Allows evaluation of the engine at speeds and loads that the engine sees in the vehicle

Based on the comparisons above, the cycle average map approach is a good alternative to investigate for modeling the engine performance in the vehicle CO_2 regulation protocol.

Validation of the Concept

Validation of the concept was first conducted through simulations using GEM [1]. In that study, a test matrix based on a Class 8 Kenworth T700 tractor with a Cummins ISX engine was carefully designed. It covered 32 vehicle configurations and three transmissions together with other relevant parameters, resulting in over one thousand simulations. In this paper, a hardware based approach with both engine and powertrain testing is used to further prove the concept. The combination of the two papers provides a complete picture of how this alternative certification concept has been developed and evaluated.

Similar to the study by Zhang et al. [1], some of the key questions to consider for the cycle average map are:

1. Is the map surface well behaved so that interpolation can represent points not tested?
2. How does the accuracy compare to a steady state map approach?
3. Is the test procedure robust and the results repeatable?

A first check of the surface shape was performed via simulation in GEM [1]. After reasonable results from a simulation study, two test programs were implemented to investigate the questions above. The first test program included only the engine and the second program included the powertrain (engine and transmission).

Engine Only Approach

Dykes and Dorobantu [10] describe the test setup in detail. The engine-only test cell as shown in Figure 8 was sized to accommodate a heavy-duty (HD) engine. A Cummins 15 liter ISX engine rated to 336kW (450 hp) with peak torque of 2375 Nm (1750 ft-lb) was used for the evaluation. A HD aftertreatment system was installed to meet the EPA and CARB emissions standards. The aftertreatment system utilized both a Diesel Particulate Filter (DPF) and a Selective Catalytic Reduction (SCR) system. To maintain a baseline condition for the DPF during testing, a DPF regeneration was forced prior to each set of tests to clean the DPF of stored particulates. The SCR system was operated during testing as would be witnessed in-vehicle operation to reduce NOx. The exhaust emissions were collected continuously using a Horiba Mexa7100D emission bench. The fuel was measured continuous during each test cycle using a ReSol RS438A-200 Fuel Flow Measurement System. The testing is completed using ultra low sulfur diesel fuel with a maximum sulfur concentration of 15 PPM. The engine intake air is temperature, humidity and pressure controlled to 25°C, 53% and 99kPa, respectively. All temperatures, pressures, fuel flow and emissions measurements were logged at a rate of 10 Hz.

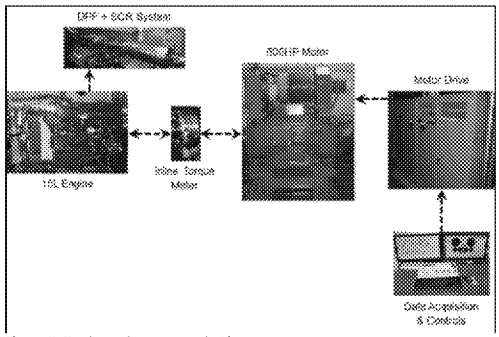

Figure 8. Engine only test setup [10]

The test cycles utilized for the engine only mapping approach were generated using GEM. Three separate vehicle configurations were input into the GEM model to generate speed and load points for each of the regulatory cycles (ARB, 65MPH, and 55 MPH). A total of nine traces were generated for each cycle. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle. A total of 27 engine tests were run (3 vehicle configurations x 3 test cycles x 3 axle ratios). The vehicle configurations were chosen to provide a reasonably broad coverage of real-world specifications to give sufficient spread of the test points to allow an interpolation and extrapolation approach to be used for the even broader spectrum of customer vehicle specifications. The cycles run are shown in Figure 9. These are the GHG Phase 1 GEM cycles [3] with the change that the highway cycles have been modified to include grade profiles. The grade profiles were provided by the EPA [11].

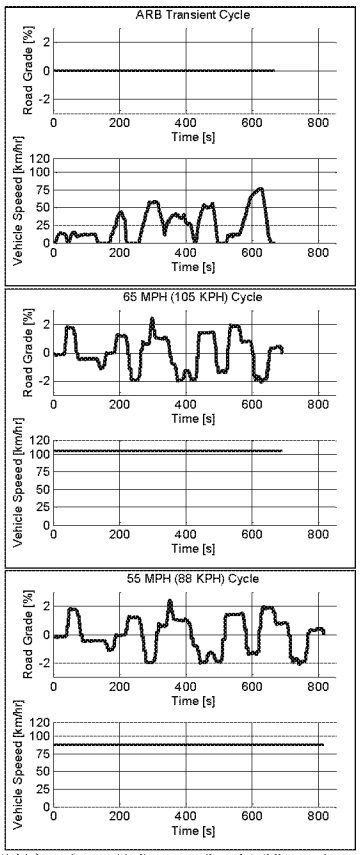

Figure 9. Vehicle cycles: a) Air Resources Board (ARB) transient cycle, b) 65 mph [105 kph] GEM cycle with road grade, c) 55 mph [88 kph] GEM cycle with road grade

Example engine map results are shown in Figure 10. These show a generally well behaved surface for either surface fitting or interpolation.

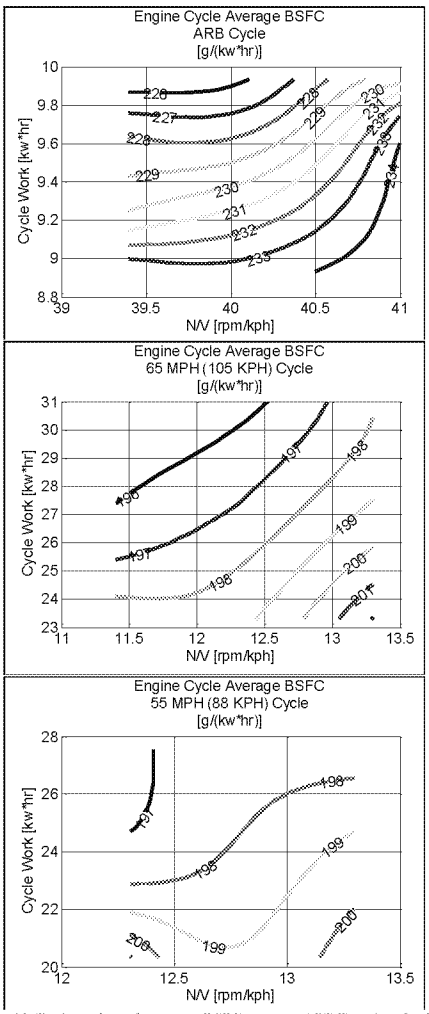

Figure 10. Engine only cycle average BSFC maps: a) ARB Transient, b) 65 mph, c) 55 mph

To check the predictive capability of the map, half the data set was used to fit BSFC to a linear model in N/V and cycle work. Testing this model on the other half of the data set shows the model performance as seen in Figure 11, indicating good behavior of the model to represent truck configurations different than those tested to create the map. Additionally, some extra truck configurations were tested at a later date as independent check points for the map. Those points are also shown in Figure 11, with similar good agreement between the model and test results. These findings are consistent with the observations obtained from the simulation study [1].

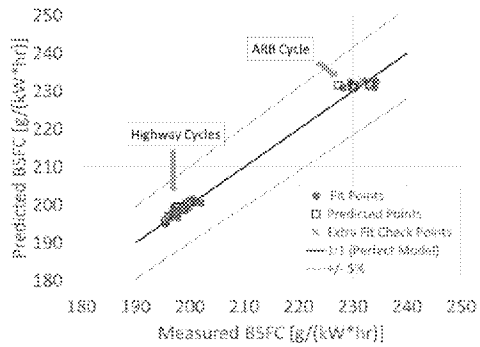

Figure 11. Engine cycle average map prediction capability with a linear fit in cycle work and N/V

A comparison of the cycle average map to the steady state map approach was completed and is shown in Figure 12. The steady state map results were taken directly from GEM [1] using a steady state map for the same engine model as tested for the cycle average map, but it was not the identical engine. So engine to engine and test cell to test cell variability need to be considered in comparing results. In the region of the 55 MPH and 65 MPH cycles (labelled Highway Cycles), the two approaches are close in accuracy. A statistical analysis shows that there is 90% confidence that the cycle average map is 1.7% better at matching the measurements than the steady state map. This level of difference is potentially within the variability of the engines and test locations used to create the different maps. For these relatively steady cycles the two map approaches are expected to produce similar results and they do agree within the variability of testing.

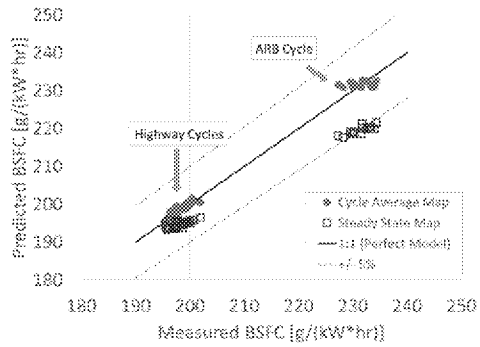

Figure 12. Comparison of cycle average map linear fit in cycle work and N/V to a steady state map interpolation

For the ARB cycle with more transient content the cycle average map does show a better match to the measured data than the steady state map approach. A statistical analysis shows that there is 90% confidence that the cycle average map is 4.9% better at matching the measurements than the steady state map. This difference is higher than expected testing variability. The larger difference on the more transient cycle is explained by the ability of the cycle average map approach to capture transient performance content.

Note that for this initial investigation of the cycle average map approach, the goal was not to precisely and completely prove capability, but rather to check for concept feasibility. For a regulation approach, it's likely that a surface fit to the cycle data would not be used. If a certification configuration matches a mapped configuration, the exact tested result is a desired output of the model. So an interpolation and extrapolation method will likely be proposed for any regulation.

The engine only testing approach is equivalent to current engine certification protocols, so repeatability is expected to be on par with current engine transient cycle certification methods. A number of repeat points on the different cycles were checked with the results shown in Figure 13 indicating good test repeatability.

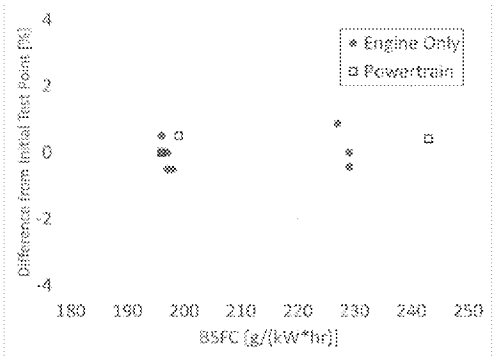

Figure 13. Repeatability of test results

Powertrain Approach

Dykes and Dorobantu [10] describe the test setup in detail. The powertrain test cell as shown in Figure 14 was sized to accommodate a powertrain from a relatively heavy-duty vehicle. The vehicle test weight was 30,391 kg [67,000 lbs.]. The powertrain tested included a Cummins 15-liter ISX engine with an Eaton 10-speed automated manual transmission. The engine maximum rated performance was 336kW (450 hp) at 1800 rpm with peak torque of 2375 Nm (1750 ft-lb) at 1000 rpm and was operated using two separate calibrations; one base calibration for testing with the 10-speed Eaton UltraShift PLUS LAS transmission and an additional calibration with SmartTorque2 (ST2) technology for testing in conjunction with the 10-speed Fuller Advantage™ (FASA) transmission. Both engine calibrations tested were emission certified for 2013 CARB and EPA. The dynamometer was sized to accommodate the engine's peak torque multiplied by the transmission's maximum gear reduction. All data collection and test procedures described for the engine only test were repeated for the powertrain testing. For the powertrain testing, the test cell ran as an HIL system with a version of the GEM vehicle model controlling the dynamometer and throttle controls so that the engine ran as if in a vehicle.

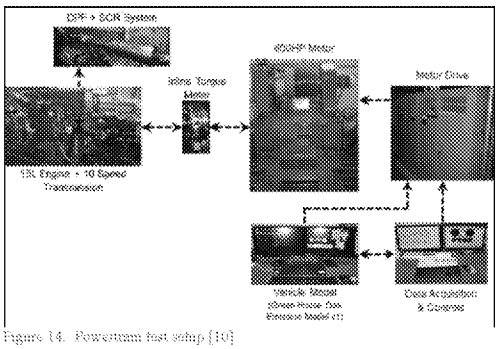

Figure 14. Powertrain test setup [10]

The same three cycles from Figure 9 were used for the powertrain testing. Each individual cycle was repeated two times consecutively and emission data sampled during the second cycle.

An example powertrain cycle average map is shown in Figure 15. As with the engine only results, the surfaces look to have a reasonable shape that can be used for interpolation and extrapolation use in a vehicle simulation for regulation purposes.

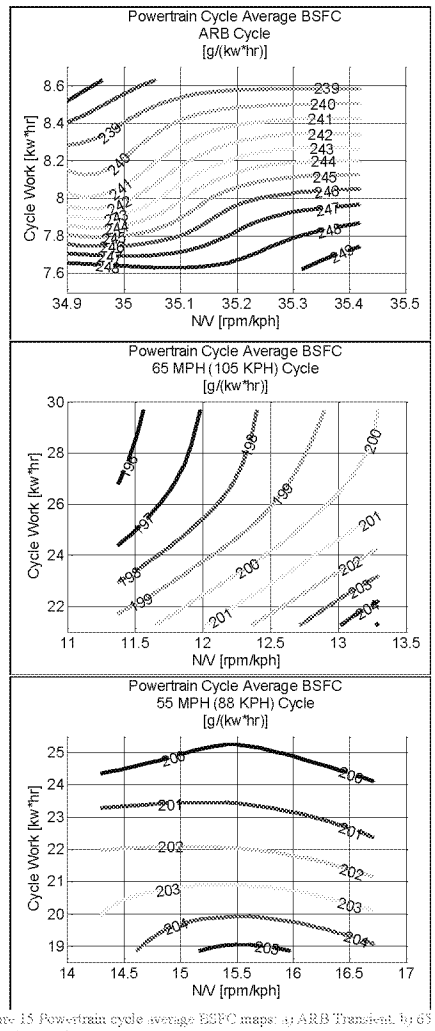

Figure 15 Powertrain cycle average BSFC maps: a) ARB Transient, b) 65 mph, c) 55 mph

Like the engine map, the predictive capability of the powertrain cycle average map was checked by fitting half of the data set and checking the prediction for the other half. The model performance is shown in Figure 16, indicating good behavior of the model to represent truck configurations different than those tested to create the map.

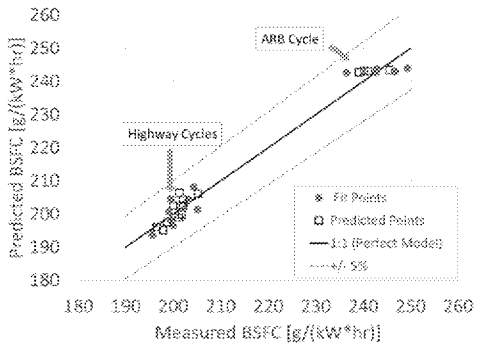

Figure 16 Powertrain cycle average map prediction capability with a linear fit in cycle work and N/V

Repeatability of the powertrain approach was checked during the test program. An initial check of a few repeat cycles is shown in Figure 13 with the powertrain testing showing similar results to the engine cycle testing across the three different cycles. Dykes and Dorobantu [10] also show a set of six repeat points on the 55 MPH cycle to have a COV of 0.5% BSFC.

Using the Cycle Average Map in the CO_2 Regulation

With some level of validation complete, a potential procedure for utilizing a cycle average map in the vehicle CO_2 regulation can be outlined:

1. Generate engine torque and speed cycles from the vehicle certification cycles using GEM and generic vehicle configurations (Figure 17)
    a. The generic vehicles are defined based on the characteristics of the parent engine torque curve based on a pre-defined approach stipulated in the regulation protocol. This approach can be considered analogous to the de-normalization process of a normalized FTP cycle into the absolute speed and torque target cycle. This process will ensure that vehicles are chosen to match up with the engine and not force the mapping process to run the engine in a manner in which it will not be used in the field.
    b. The generic vehicles are simulated within GEM with the use of a default engine map and the torque curve and motoring curves of the parent target engine. The speed and torque profiles for

the engine are recorded and then used as reference targets for the engine testing.

2. Run engine tests and tabulate cycle average CO_2 , N/V and cycle work for use in certification (Figure 17)
    a. The engine must match the target cycles with a regression requirement similar to that used for criteria emissions certification.
    b. Alternately, a hardware-in-the-loop (HIL) approach can also be used with GEM running at the test cell and creating the speed and torque targets in real time. This approach is preferred for powertrain testing or any controls features that will have a close integration with vehicle speed, road grade, or other vehicle level information.
3. Generate certification data for the specific vehicle using GEM simulation (Figure 18)
    a. The certified vehicle configuration is run in GEM with the torque and motoring curves for the specific engine rating, but with a default engine fuel consumption map.
    b. GEM calculates the engine (or powertrain) cycle work and average N/V then interpolates within the cycle average map to obtain a cycle average fuel consumption value. GEM also calculates the vehicle power demand and then multiplies the cycle average fuel consumption by the cycle cumulative power demand to arrive at the vehicle drive cycle fuel consumption as shown in Figure 4. In this manner, the use of a cycle average map is a simple post processing step in GEM and does not interact with the detailed GEM vehicle modeling calculations. Note that the only difference between use of an engine or a powertrain map is the location of the cycle work calculation. For an engine map, the cycle work is the engine cycle work. For a powertrain map, the cycle work is calculated at the transmission output.

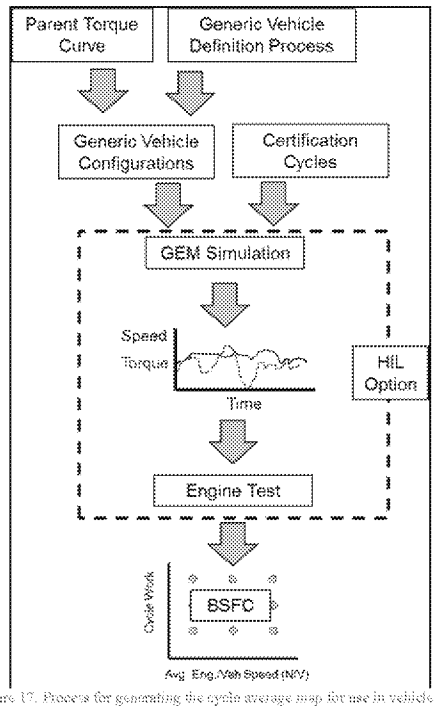

Figure 17. Process for generating the cycle average map for use in vehicle CO_2 regulation

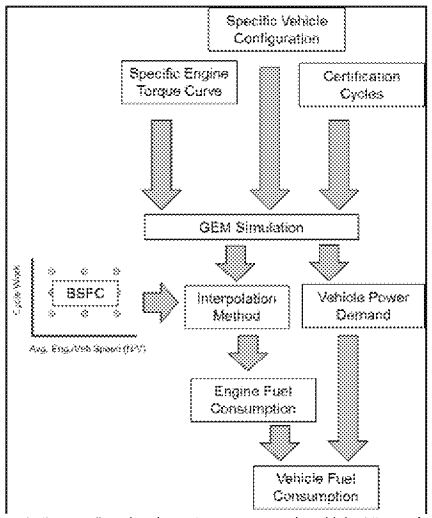

Figure 18. Process for using the cycle average map in vehicle CO_2 regulation

In work to date, nine vehicle configurations have been used and run on each of the three certification cycles, providing 27 data points. This number of cycles is a significant amount of engine testing time, but note that the expected steady state map approach of 143 operating points has a testing burden as well. A comparison of the testing time required for this approach as tested and a steady state map approach is shown in Table 1. Future work will focus on reducing the number of test cycles or streamlining the testing protocol. As shown in the table, a change in the pre-conditioning cycle strategy can reduce the test time significantly. Zhang et al. [1] have proposed a potential procedure that can reduce the testing time to the same range as the steady state map approach.

Table 1. Comparison of Testing Time for Different Approaches [10]

Cycle	Steady State Map [Hours]	Original Cycle Average Map [Hours]	Cycle Average Map New Pre-Conditioning Strategy [Hours]
Engine Warm-Up	0.3	0.3	0.3
DPF Regeneration	1.0	1.0	1.0
Emission Purge & Calibration	2.4	5.9	1.1
Pre-conditioning	3.3	5.6	1.9
Time at Test	1.2	5.6	5.6
Total Time	8.3	18.4	9.9

Summary/Conclusions

The cycle average map appears to be a technically viable approach to utilizing engine fuel consumption performance in a vehicle regulation. The results obtained provide a well behaved surface for evaluation of BSFC, while also demonstrating a consistent treatment of the engine and powertrain.

Recommendation

Future work should investigate the cycle average map for use in the GHG Phase 2 program. Specifically some work should look at the behavior of the cycle average map on other engines across ratings. More work can certainly be done to choose the right number of map points, reduce cycle pre-conditioning, and to consider interpolation, extrapolation, and fit methods with a goal to reduce the number of mapping points and testing burden.

Future work should also concentrate on the number and specification of the vehicle configurations required for testing in order to generate a map that will apply to all vehicles under the same family. Zhang et al. [1] describe the principle with preliminary findings, but more work is needed.

References

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3. Lee PhD, S., Lee, B., Zhang PhD, H., Sze PhD, C. et al., "Development of Greenhouse Gas Emissions Model for 2014-2017 Heavy- and Medium-Duty Vehicle Compliance," SAE Technical Paper 2011-01-2188, 2011, doi:10.4271/2011-01-2188.
4. Wurzenberger, J., Heinzle, R., Deregnaucourt, M., and Katrasnik, T., "A Comprehensive Study on Different System Level Engine Simulation Models," SAE Technical Paper 2013-01-1116, 2013, doi:10.4271/2013-01-1116.
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9. Newman, K., Dekraker, P., Zhang, H. Sanchez, J. and Gururaja, P., "Development of Greenhouse Gas Emissions Model (GEM) for Heavy- and Medium-Duty Vehicle Compliance", SAE Paper 2015-01-xxxx, submitted to SAE COMVEC, Chicago, October, 2015
10. Dykes, E. and Dorobantu, M., "Certification Test Approach for the Phase II Greenhouse Gas Regulations", Eaton Technical Report, Jan. 2015.
11. Zhang, H., EPA, Personal Communication, May 2014.

Commented [GCS1]: Will need to check all the references and order of references once the content is finalized.

Contact Information

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Acknowledgments

The authors would like to acknowledge the many conversations with others in the participating companies and around the industry to help develop the concept presented here. Houshun Zhang, James Sanchez, and Matt Spears at the EPA deserve mention for many collaborative and insightful discussions.

Definitions/Abbreviations

BSFC	Brake Specific Fuel Consumption
COV	Coefficient of Variance
GEM	Greenhouse Gas Emissions Model
N/V	Average Cycle Engine Speed Divided by Average Cycle Vehicle Speed
HIL	Hardware In the Loop

Appendix

Comparison of Typical Options to Represent Engine Performance in a Vehicle Simulation

Requirement	Form of Engine Information in the Vehicle Program			
	None	Single Value from Engine Certification Program (SET or FTP)	Steady State Engine Map	0D/1D Thermodynamic Model
Criteria Emissions Link	Good (built into Generic Map)	Good	Weak. Steady state map links to SET somewhat.	Hard to do
Accuracy	Generic Engine Map (Phase 1 GHG Approach)	Better than Generic Map	Better than Generic Map, but no transients	Depends on effort on calibration of the model
Auditability	N/A	Built into the engine certification program	Auditing each map point is a burden	Still need to audit engine?
Amount of Work	None for engine manufacturer (some for EPA)	None extra if using engine cert program value	Extra engine testing needed beyond the engine cert program	Very large to manage a detailed model
Consistency with Vehicle Operation	Reasonable	Possible if cycle represents vehicle operation well, but as powertrain configurations change maybe not	Speed and load matching but no transient content	Speed and load matching and could have transient content if controls are included
Confidentiality	N/A	No Issues	Map is confidential	Detailed model and controls logic are highly confidential
Powertrain Evaluation Capability	Generic Powertrain	Can move the transmission into the engine test	Hard to make a steady state map with the transmission included	Requires transmission controller model like the engine controller model

A-2001-28
IV-E-04

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
NATIONAL VEHICLE AND FUEL EMISSIONS LABORATORY
2565 PLYMOUTH ROAD
ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

MEMORANDUM

Date: August 13, 2003

From: Don Kopinski Personal Address / Ex. 6

To: Air Docket A-2001-28

Subject: Phone Meetings with EMA

Chet France, Bill Charmley and I met by teleconference with Jed Mandel of EMA on July 14 and 16, 2003 to discuss engine manufacturers' issues connected with EPA's proposal for nonroad diesel standards, particularly those covering engines over 750 hp.

2003

Printed on Recycled Paper

March 26, 2004

MEMORANDUM

TO: EPA Air Docket OAR-2003-0012

FROM: William Charmley
Engineer
Office of Transportation and Air Quality
U.S. EPA

SUBJECT: Summary of Conference Calls with the Engine Manufacturers Association on July 1, 14, and 17, 2003 regarding Nonroad Tier 4 Proposal

---

On July 1, July 14, and July 17, 2003, representatives from EPA and the Engine Manufacturers Association (EMA) participated in a series of conference calls to discuss EPA's nonroad diesel Tier 4 proposal. A list of the participants for each of these calls is attached.

The following topics were discussed during the meeting;

July 1, 2003 Conference Call
- not-to-exceed standard and implementation requirements
- emission standards for nonroad engines >750 hp
- implementation dates for Tier 4 standards for the 75-175 hp category
- optional Tier 4 emission standards for the 50-75 hp range

July 14, 2003 Conference Call (all topics were specific to engines >750 hp)
- transient test cycle requirements and standards
- NTE requirements
- NOx emission standards and implementation dates
- PM emission standards and implementation dates
- Differences between >750 mobile machines and generators

July 17, 2003 Conference Call (all topics were specific to engines >750 hp)
- NOx emission standards and implementation dates
- PM emission standards and implementation dates
- Differences between >750 mobile machines and generators

attachments: Attendees List

Attachment: Attendees List

EPA Conference Call with Engine Manufacturers Association, July 1, 2003
EMA Participants
Jed Mandel, EMA

EPA Participants
Chet France, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, July 14, 2003
EMA Participants
Jed Mandel, EMA
Bill Passie, Caterpillar
John Gladden, Caterpillar
Bob Jorgenson, Cummins Inc.
Todd Hendricks, Cummins Inc.
John Duerr, Detroit Diesel Corp.

EPA Participants
Chet France, Assessment & Standards Division, Office of Transportation & Air Quality
Don Kopinski, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, July 17, 2003
EMA Participants
Jed Mandel, EMA
John Gladden, Caterpillar
Bob Jorgenson, Cummins Inc.
Todd Hendricks, Cummins Inc.
John Duerr, Detroit Diesel Corp.

EPA Participants
Don Kopinski, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

March 26, 2004

MEMORANDUM

TO: EPA Air Docket OAR-2003-0012

FROM: William Charmley
Office of Transportation and Air Quality
U.S. EPA

SUBJECT: Summary of Conference Calls with the Engine Manufacturers Association, November 4, 6, and 21, 2003 regarding Nonroad Tier 4 Proposal for Engine Labeling Requirements

---

On November 4, 6, and 21, 2003, representatives from EPA and the Engine Manufacturers Association (EMA) participated in a series of conference call to discuss EPA's nonroad diesel Tier 4 proposal. A list of the participants for each of these calls is attached.

The following topics were discussed during each conference call;

November 4, 2003 Conference Call

During this meeting, EPA and EMA members discussed the Tier 4 proposal for engine labeling requirements as well as EMA's comments on the Tier 4 proposal regarding engine labels.

November 6, 2003 Conference Call

- Implementation time frame for engine standards in the 75-175hp category
- Optional 2008 PM standards for engine in the 50-75hp range
- Averaging, banking and trading provisions for nonroad diesel engines
- Standards and implementation time frame for engines >750 hp
- Transient testing requirements for engines >750 hp

November 21, 2003 Conference Call

- Standards and implementation time frame for engines >750 hp
- Cold start testing requirements for nonroad diesel engines
- Constant speed, variable load transient testing requirements for nonroad diesel engines
- Defect reporting requirements
- Engine labeling requirements
- Replacement engine provisions

attachments: Attendees List

Attachment: Attendees List

EPA Conference Call with Engine Manufacturers Association, November 4, 2003
EMA Member Attendees
Kevin Korkada, EMA
Rick Bishop, John Deere

EPA Attendees
Alan Stout, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, November 6, 2003
EMA Member Attendees
Jed Mandel, EMA
Rick Bishop, John Deere
Ted Breidenbach, John Deere
Jim Green, Caterpillar Inc.
Al Scheigert, Caterpillar Inc.
Bill Passie, Caterpillar Inc.
Tim Tindall, Detroit Diesel Corp.
Bob Jorgensen, Cummins Inc.

EPA Attendees
Margo Oge, Office of Transportation & Air Quality
Karen Orehowsky, Office of Transportation & Air Quality
John Hannon, Office of General Counsel
Chet France, Assessment & Standards Division, Office of Transportation & Air Quality
Cle Jackson, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, November 21, 2003
EMA Member Attendees
Jed Mandel, EMA

EPA Attendees
Chet France, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

March 31, 2004

MEMORANDUM

TO: EPA Air Docket OAR-2003-0012

FROM: William Charmley
Engineer
Office of Transportation and Air Quality
U.S. EPA

SUBJECT: Summary of Conference Calls with the Engine Manufacturers Association on December 10, 2003, January 16, 2004 and January 27, 2004 regarding Nonroad Tier 4 Proposal

---

On December 10, 2003, January 16, 2004 and January 27, 2004, representatives from EPA and the Engine Manufacturers Association (EMA) participated in a series of conference calls to discuss EPA's nonroad diesel Tier 4 proposal. A list of the participants for each of these calls is attached.

The following topics were discussed during the meeting;

<u>December 10, 2003 Conference Call</u>

- Diesel fuel lubricity
- Diesel fuel cetane
- >750 hp engine transient testing provisions
- 75-175 hp engine standards options
- 50-75 hp engine standard options
- NOx phase-in requirements for 75-750 hp engines
- Transition Program for Equipment Manufacturers
- In-use add-on factors for in-use compliance
- averaging, banking and trading provisions for Tier 4, including family emission limit caps and averaging sets
- not-to-exceed standards and requirements
- crankcase emission standard provisions
- measurement provisions for non-methane hydrocarbons
- cold start testing provisions
- engine test speed definition
- definition of maximum power
- smoke testing requirements
- engine labeling requirements
- provisions for the separate shipment of aftertreatment devices and engines
- deterioration factor provisions

- non-conformance penalties
- definition of engine family
- criteria for selecting the certification engine within an engine family
- labeling requirements for stationary engines
- trailer-refrigeration unit optional test cycle

January 16, 2004 Conference Call

- not-to-exceed standards (NTE) for Tier 4 engines and the NTE multiplier inflection point value

January 27, 2004 Conference Call

- use of Tier 2 emission credits under the averaging, banking and trading program for engines in the 50-75 hp range
- definition of an equipment manufacturer for purposes of the Transition Program for Equipment Manufacturers
- family emission limit caps under the averaging, banking and trading provisions
- temporary compliance adjustment factors
- engine labeling provisions
- defect reporting requirements

attachments: Attendees List

Attachment: Attendees List

EPA Conference Call with Engine Manufacturers Association, December 10, 2003
EMA Participants
Kevin Korkada, EMA
Rich Bishop, John Deere

EPA Participants
Alan Stout, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality
Chuck Moulis, Assessment & Standards Division, Office of Transportation & Air Quality
Cle Jackson, Assessment & Standards Division, Office of Transportation & Air Quality
Don Kopinski, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, January 16, 2004
EMA Participants
Kevin Korkada, EMA
Todd Hendricks, Cummins Inc.

EPA Participants
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, January 27, 2004
EMA Participants
Jed Mandel, EMA
Kevin Korkada, EMA

EPA Participants
Cle Jackson, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

March 31, 2004

MEMORANDUM

TO: EPA Air Docket OAR-2003-0012

FROM: William Charmley
Office of Transportation and Air Quality
U.S. EPA

SUBJECT: Summary of Conference Calls with the Engine Manufacturers Association, March 4 and 12, 2004 regarding Nonroad Tier 4 Proposal

---

On March 4 and March 12, 2004, representatives from EPA and the Engine Manufacturers Association (EMA) participated in a series of conference call to discuss EPA's nonroad diesel Tier 4 proposal. A list of the participants for each of these calls is attached.

The following topics were discussed during each conference call;

March 4, 2004 Conference Call

- averaging, banking and trading provisions for nonroad diesel engines;
- carry-over provisions for under the averaging, banking, and trading program's alternative family emission limit caps;
- defect reporting requirements for engine companies

March 12, 2004 Conference Call

- defect reporting requirements for engine companies

attachments: Attendees List

Attachment: Attendees List

EPA Conference Call with Engine Manufacturers Association, March 4, 2004
EMA Member Attendees
Jed Mandel, EMA

EPA Attendees
Chet France, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, March 12, 2004
EMA Member Attendees
Jed Mandel, EMA

EPA Attendees
Alan Stout, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

April 5, 2004

MEMORANDUM

TO: EPA Air Docket OAR-2003-0012

FROM: William Charmley
Engineer
Office of Transportation and Air Quality
U.S. EPA

SUBJECT: Summary of Meeting with the Engine Manufacturers Association, March 23, 2004, and Conference Call on April 2, 2004

On March 23, 2004, representatives from EPA and the Engine Manufacturers Association (EMA), met at the Westin Hotel inside the Detroit Metropolitan Airport to discuss the nonroad diesel Tier 4 proposal. A conference call regarding the same topics was also held between EPA and EMA on April 2, 2004. A list of the attendees for these two meeting is attached.

The following topics were discussed during the meetings;

- defect reporting provisions
- engine labeling provisions
- use of good engineering judgement in the regulations
- provisions to account for engines sold in the State of California under the averaging, banking and trading program
- Fuel specifications for NR Tier 4 program, and opportunities for harmonization with the European Commissions nonroad diesel fuel specifications
- reporting of CO2 emissions as part of the certification process
- steady-state certification test procedures

attachments: Attendees List

Attachment: Attendees List

EPA Meeting with Engine Manufacturers Association, March 23, 2004

EMA Member Attendees:
Kevin Korkada, EMA
Jed Mandel, EMA
Rick Bishop, John Deere
John Duerr, Detroit Diesel Corp.
Bill Passie, Caterpillar
Todd Hendrickson, Cummins Inc.
Bob Jorgenson, Cummins Inc.

EPA Attendees
Cle Jackson, Assessment & Standards Division, Office of Transportation & Air Quality
Don Kopinski, Assessment & Standards Division, Office of Transportation & Air Quality
Alan Stout, Assessment & Standards Division, Office of Transportation & Air Quality
Chuck Moulis, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality
John Guy, Certification and Compliance Division, Office of Transportation & Air Quality

EPA Conference Call with Engine Manufacturers Association, April 2, 2004

EMA Member Attendees:
Jed Mandel, EMA

EPA Attendees
Don Kopinski, Assessment & Standards Division, Office of Transportation & Air Quality
Alan Stout, Assessment & Standards Division, Office of Transportation & Air Quality
Chuck Moulis, Assessment & Standards Division, Office of Transportation & Air Quality
Bill Charmley, Assessment & Standards Division, Office of Transportation & Air Quality

Message

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 2/4/2016 9:31:17 AM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]
Subject: Fwd: HD oems meeting with NHTSA political leadership on Friday

Sent from my iPhone

Begin forwarded message:

From: <charmley.william@epa.gov>
Date: February 4, 2016 at 9:59:41 AM GMT+1
To: Jed Mandel <jmandel@emamail.org>, "Timothy A. Blubaugh" <tblubaugh@emamail.com>
Subject: HD oems meeting with NHTSA political leadership on Friday

Jed

The folks at Navistar reached out to me to let us know that the HD OEMs will be meeting with the NHTSA political leadership on Friday.

I really appreciate Navistar letting me know, and I will try to catch up with David Majors later today when o get back to the US.

One thing I am uncertain on is what message the OEMs may give on vocational.

I think it is fine for the OEMs to explain their concerns, but I am worried that they not get to far out front of me and my staff with the event EMA concept.

If they tell NHTSA that EMA has presented the agencies with a proposal, NHTSA will have no idea what they are talking about, as we only just heard about this from you and Tim on Monday, and I did not invite NHTSA or carb to that meeting.

So, if they want to say that EMA has a new concept/proposal, and they are working through the trade association (EMA) to arrange a meeting with EPA and NHTSA soon to discuss the concept that would be ok, but I hope they won't go to far down that path yet, as we have not had a chance to catch up with the NHTSA career staff since our Monday discussion with you and Tim.

Thanks
Bill

Sent from my iPhone

Message

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 1/29/2016 3:38:35 PM
To: jmandel@emamail.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=28f042dc168644178af3ea00b35336f4-jmandel@emamail.org]
CC: Iffland, JoNell [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=269c8731e7c6417482f8a8ddccfc4887-Iffland, JoNell]
Subject: Vocational dialogue

Jed,

We are looking at Monday afternoon as maybe possible, 3-5pm. Still not sure if it will work for us but wanted to get your feedback asap.

I am on travel to Europe Tuesday-Thursday, so other option of next week on Friday

Thanks
Bill

Sent from my iPhone

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 3/13/2015 9:49:09 PM
To: EMA [ema@emamail.org]

Subject: Declined: EMA - EMTC, CARB, EPA & Others - April 1-2, 2015, EMTC Meeting Notice and Agenda - Live Meeting Link
Location: EPA Offices, 2000 Traverwood Drive, Ann Arbor, Michigan

Start: 4/1/2015 1:00:00 PM
End: 4/2/2015 6:00:00 PM
Show Time As: Free

Recurrence: (none)

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 1/28/2016 11:14:41 AM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]

Subject: Declined: Phase 2 Collaboration Meeting
Location: US toll-free Conference Code / Ex. 6 nd Skype Meeting

Start: 1/28/2016 8:00:00 PM
End: 1/28/2016 9:00:00 PM

Recurrence: (none)

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 3/10/2015 3:05:48 PM
To: EMA [ema@emamail.org]

Subject: Declined: EMA - EMTC, CARB, EPA & Others - April 1-2, 2015, EMTC Meeting Notice and Agenda
Location: EPA Offices, 2000 Traverwood Drive, Ann Arbor, Michigan

Start: 4/1/2015 1:00:00 PM
End: 4/2/2015 6:00:00 PM
Show Time As: Free

Recurrence: (none)

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 3/9/2015 2:09:26 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]

Subject: Accepted: EPA/ARB Visit to Cummins - Bill arrives 2:00, Erik arrives 4:00
Location: CTC (1900 McKinley Avenue, Columbus, IN 47201), Columbus, Indiana Customer Visit Room A

Start: 3/23/2015 6:00:00 PM
End: 3/23/2015 9:30:00 PM
Show Time As: Busy

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 1/25/2016 11:17:15 AM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]

Subject: Accepted: Cummins/EPA meeting
Location: 2000 Traverwood Drive, Ann Arbor, MI

Start: 1/29/2016 2:00:00 PM
End: 1/29/2016 5:00:00 PM

Recurrence: (none)

Message

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 7/15/2015 5:55:11 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: Follow-up to our discussion earlier this week regarding the Cummins/EPA/NHTSA/CARB meeting on July 28: WHR cost estiamtes
Attachments: Tetra Tech MDHD Tech Cost Report_Docket Version.pdf; 812146-CommercialMDHD-TruckFuelEfficiencyTechStudyReport1.pdf

Brian,

During our call earlier this week we discussed the EPA/NHTSA estimates for the cost of WHR for the HD Phase 2 NPRM.

In the Draft RIA for the proposal you will find in Section 2.12.2.15 "Waster heat recovery", the text and table I have copied to the bottom of this email.

We have cited for the underlying source a report that NHTSA contracted with a firm called Tertra Tech for. I have attached a copy of those reports, which are also available in the public docket for the HD Phase 2 rule.

Note that in the attached "Tech Cost Report", on page 136 is a table of TetraTech's sources for the WHR cost estimates

Note, in the attached "TechStudyReport1" on page D-1 (p.297 of the pdf) is TetraTech's description of the WHR system they have provided cost estimates for.

As you and I discussed, I would like to have the topic of WHR cost estimation on our agenda for the meeting for next week, as we would like to receive any comments/information Cummins can provide regarding the WHR cost estimates contained in the NPRM.

Best regards,
Bill

==========

2.12.2.15 Waste heat recovery

We have estimated the cost of waste heat recovery based on the estimate from Tetra Tech showing it at $12,000 (retail, 2013$). Using that $12,000 estimate and dividing by a 1.36 RPE (see Chapter 2.12.1.2 of this draft RIA) and converting to 2012$, we arrive at our estimated DMC of $8,692 (DMC, 2012$, in 2018). We consider this technology to be on the flat portion of the learning curve (curve 12) because although waste heat recovery is a new technology and in the 2015 to 2017 timeframe remains, perhaps, on the steeper portion of the learning

curve, applying such rapid learning effects to the cost estimate we have would result in costs too low in the MY2024 to 2027 timeframe. We have applied a medium complexity ICM with short term markups through 2025. The resultant technology costs, adoption rates and total cost applied to the package are shown in Table 2-136 for tractor engines.

Table 2-136 Costs for Waste Heat Recovery HDD Tractor Engines (2012$)

ITEM		2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Waste heat recovery	DMC	$8,692	$8,431	$8,179	$7,933	$7,775	$7,619	$7,467	$7,317	$7,171	$7,028
Waste heat recovery	IC	$2,628	$2,615	$2,602	$2,589	$2,581	$2,574	$2,566	$2,558	$1,908	$1,903
Waste heat recovery	TC	$11,320	$11,046	$10,780	$10,523	$10,356	$10,193	$10,032	$9,876	$9,079	$8,931
Waste heat recovery	Alt 1a										
Waste heat recovery	Alt 3				1%	1%	1%	5%	5%	5%	15%
Waste heat recovery	TCp	$0	$0	$0	$105	$104	$102	$502	$494	$454	$1,340

Notes: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost; TCp=total cost applied to the package; alt=alternative; empty cells for adoption rates denote 0% adoption

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U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

NHTSA
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DOT HS 812 146

June 2015

Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study – Report #1

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15. Supplementary Notes

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16. Abstract

This research project is to inform NHTSA and EPA's development of Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (Class 2b – 8). A literature review is used to identify potential fuel saving technologies and review the state of the art. A large number of engine and vehicle technologies are selected for additional analysis, and their fuel saving performance is simulated to project the fuel savings potential of each technology over a wide range of duty cycles. Wherever possible, experimental data is used to inform and validate the simulation results. All baseline engine and vehicle models are validated against experimental data. Trade-offs between engine-out NOx levels and fuel consumption are reviewed. There is a review of fuel consumption, fuel economy, and GHG metrics, and of test and analysis procedures. The existing international truck fuel consumption and GHG regulations are compared and contrasted. Certification issues are explored, including the potential for including trailers in future regulations.

Note: This report was subjected to external peer review per OMB guidelines for a Highly Influential Scientific Assessment (HISA). Materials from the peer review process are publicly available in accompanying documents.

17. Key Words Fuel Consumption, GHG Emissions, Medium Duty, Heavy Duty, Engine Simulation, Vehicle Simulation		18. Distribution Statement Document is available free of charge from the National Technical Information Service www.ntis.gov	
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EXECUTIVE SUMMARY

In 2011, the National Highway Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) jointly issued a first phase of fuel efficiency and greenhouse gas (GHG) standards that apply to medium- and heavy-duty on-highway engines and vehicles for model years (MY) 2014 to 2018 and beyond. These regulations are commonly referred to as "Phase 1" of the Heavy-Duty National Program. The standards cover all vehicles in weight classes 2b through 8, which encompasses most vehicles with gross vehicle weight ratings (GVWR) over 8,500 pounds except for a limited number of passenger vehicles covered under the light duty corporate average fuel economy (CAFE) standards, and recreational vehicles, which were included in EPA's GHG standards but not NHTSA's fuel efficiency standards. Phase 1 has two implementation stages. EPA's greenhouse gas emission standards are mandatory beginning with model year 2014. NHTSA's fuel consumption standards are voluntary in model years 2014 and 2015, becoming mandatory with model year 2016 for most regulatory categories. Commercial trailers were not regulated in Phase 1. The Phase 1 GHG and fuel consumption standards were developed using input from a number of studies that evaluated the fuel saving technologies that are available, such as the NESCCAF 2009 report [1] and the NHTSA and NAS 2010 reports [2, 3].

The research project described in this report has been completed for NHTSA to help to inform the next phase ("Phase 2") of the regulations, which would set standards in coordination with EPA for model years beyond 2018. In order to prepare for Phase 2, NHTSA directed SwRI to update prior research on fuel saving technologies to reflect the effects of the Phase 1 regulations, as well as to include technical progress that has been made over the last few years. In particular, SwRI was tasked with assessing the current commercial fleet technology baseline at the time of contract award (MY 2011/2012) and assessing the effectiveness and cost of potential fuel efficiency/GHG improving technologies for the Phase 2 timeframe (post MY 2018).

When considering potential fuel efficiency/GHG-reducing technologies, NHTSA directed SwRI to include a range of factors: design, functionality, duty cycle, use (type of work done by the vehicle), and factors that can influence the effectiveness, feasibility, and cost. Vehicle utility and performance are also to be considered. The content of report sections is summarized below.

After an introduction (Section 1), Section 2 provides a literature review covering the following topics:

- Fuel saving technologies for MD and HD engines and vehicles
- Market segmentation of fleets
- Current and planned fuel economy regulations in markets around the world

Four references were found regarding vehicle segmentation. This is a challenge in the medium- and heavy-duty vehicle world, where there are hundreds of applications, and where any given vehicle type may be exposed to a wide range of different drive cycles. SwRI determined that the most promising segmentation approach has been developed by CalHEAT in California. Calheat breaks the Class 2b through Class 8 market into six segments:

1. Heavy duty pickups and vans
2. Long haul tractors
3. Short and regional haul tractors
4. Work site vocational trucks such as dump trucks, concrete truck, utility service trucks, etc.
5. Urban vocational trucks such as refuse haulers, busses, delivery trucks, transit bus, school bus, etc.
6. Rural vocational trucks, including motor coach, forestry, petroleum, heavy haulers, etc.

Nineteen references were found regarding government regulations of truck fuel consumption and GHG emissions around the world. A review of the literature shows that the world is moving towards quite different fuel consumption / GHG regulations in different markets. The differences in national regulations reflect the unique characteristics and needs of each market, as well as variation in regulatory philosophy. Japan has the first regulation to go into effect. Its regulations use a simple vehicle simulation model where factors such as vehicle weight, aerodynamic drag, and rolling resistance are held constant. The Japanese regulation effectively targets engine brake specific fuel consumption (BSFC) and transmission match.

China is implementing a regulatory approach based on a combination of chassis dynamometer testing and simulation. Vehicles are assigned a target fuel consumption based on vehicle type and Gross Vehicle Weight (GVW) rating. A modified version of the World Harmonized Vehicle Cycle (WHVC) is specified for the drive cycle, with different weightings of the urban, rural, and motorway cycles as a function of vehicle application.

At the end of the literature review task in January 2013, NHTSA, EPA, and SwRI agreed on a list of vehicle and engine technologies that form the main subject of this project.

Section 3 addresses the heart of the project, which is a performance analysis of technologies that could be used to comply with a future Phase 2 fuel consumption / GHG regulation, for the time frame beyond 2018. The analysis included both engine technologies and vehicle technologies, using a technology list described in Section 3.1 that was developed during the literature review. Four basic engines and four vehicles were selected for simulation. All of these vehicles and engines had experimental data available from other projects, and full use of experimental data was made to calibrate the models before additional technologies were evaluated. The following baseline engine models were created and calibrated using available experimental data:

Engine Type	**Displacement, liters**	**Configuration**	**Rating**	**Applications**
Gasoline	3.5	V-6 Turbo	355 HP @ 5500 RPM	MD and Pickup Trucks
Gasoline	6.2	V-8	380 HP @ 6000 RPM	MD and Pickup Trucks
Diesel	6.7	Inline 6	300 HP @ 2500 RPM	Medium Duty Truck
Diesel	6.7	Inline 6	385 HP @ 3000 RPM	Pickup Truck
Diesel	15	Inline 6	485 HP @ 1800 RPM	Long Haul Truck

The following vehicle models were built and calibrated using experimental data:

Vehicle Type	Model	Empty Wt.	Payload	GVWR	Applications
Pickup Truck	Ram 2500	6,876 lb.	3,124 lb.	10,000 lb.	HD Pickup Truck
Straight Truck	Ford F-650	15,640 lb	6,360 lb	22,000 lb.	Tow Truck
Straight Truck	KW T270	17,140 lb.	8,860 lb.	26,000 lb.	Box Delivery Truck
Tractor-Trailer	KW T-700	33,960 lb.	46,040 lb.	80,000 lb.	Long Haul (OTR)

Each engine and vehicle technology was exercised over a range of drive cycles at zero payload, 50% payload, and 100% payload. For the pickup truck, the 100% payload point included pulling a trailer with a total combined vehicle weight of 25,000 pounds. The range of drive cycles is critical, in order to exercise the technologies over a range of speeds, loads, and grades. The table below summarizes which drives cycles were used for each truck model. The Greenhouse gas Emissions Model (GEM) cycles include an urban stop-and-go cycle developed by California Air Resources Board (CARB), a 55 MPH steady-state cruise, and a 65 MPH steady-state cruise. The cruise cycles do not include any grade, so they effectively represent a single operating point for the engine. The World Harmonized Vehicle Cycle (WHVC) cycle includes urban, rural, and European-style motorway segments. The Combined International Local and Commuter Cycle (CILCC) and Parcel delivery cycles are stop-and-go cycles meant to reflect delivery truck operation. The Northeast States Center for a Clean Air Future (NESCCAF) cycle includes a small portion of urban driving, but most operation is on the highway at target speeds of 65 to 68 MPH. This cycle does include grades of +/- 1% and +/- 3%. Section 3.2 describes the analysis approach used in this study.

Vehicle Type	Drive Cycles
Ram Pickup	FTP City, FTP Highway, US06, SC03, WHVC, 65 MPH Cruise
T270 Box Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
F-650 Tow Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
T-700 Tractor	GEM Cycles, WHVC, NESCCAF Long Haul Cycle

Section 3.3 describes the results from an evaluation of both engine and vehicle level technologies. The baseline 15-liter truck engine is the MY 2011 Detroit DD15. This engine uses a turbocompound for waste heat recovery, a feature that has been on the engine since its launch in 2008. One surprising result is that removing this feature actually provided a modest *reduction* in fuel consumption. This result was confirmed when Detroit started offering a non-turbocompound version of the DD15 in 2013, with claims of better fuel consumption than the 2011 turbocompound engine used as our baseline. When SwRI tried to model all the changes that Detroit implemented in 2013, it resulted in a benefit of 1 to 1.5%, similar to their claims. These results do not match previous published work on other engines, which showed a 2% to 3% benefit for turbocompound. Turbocompound systems work best when the engine runs at high load, so a smaller displacement engine or a more heavily loaded truck would produce a better result with turbocompound. There are also other forms of waste heat recovery such as a Rankine cycle (or bottoming cycle), and this will be discussed later.

Reduced engine friction provides a benefit of 2% to nearly 5% on the long haul T-700 truck, with the actual benefit depending on payload and drive cycle. As expected, more highly loaded cycles show a smaller benefit. Downspeeding and downsizing also both provide benefits

in the 2% to 4% range. A water-based bottoming cycle shows a potential benefit of 4% to 5% for long haul drive cycles, while an R245-based cycle provides about a 3% benefit.

Vehicle related changes on the long haul tractor T-700 offer the potential for larger fuel savings. Ranges were evaluated for aerodynamic drag reduction, tire rolling resistance, and reductions in vehicle empty weight for the T700. For example, a 25% reduction in drag coefficient lowers fuel consumption by approximately 12% on a high-speed cycle, while a 30% reduction in tire rolling resistance provides benefits of 4% to 9%, depending on drive cycle and payload. However, this study did not examine potential trade-offs with tire traction, durability, and other performance characteristics. Evaluating empty vehicle weight reduction only (and not changes in payload), a vehicle mass reduction of 2,200 pounds only provides about a 1% fuel savings on high-speed cycles, but about a 2% benefit on stop-and-go cycles. A 6 X 2 drive axle configuration offers savings of around 1.5% on all operating cycles and payloads. Setting a lower speed limit on the vehicle speed controller is worth about 1.5% fuel savings for every 1 MPH reduction in cruise speed. The savings only accrue when driving conditions would normally allow a higher speed, and these fuel savings are offset by lower truck productivity, which would require a larger fleet and a higher vehicle miles traveled (VMT) to deliver the same freight volume. Automated manual transmissions appear to offer a significant fuel savings benefit in transient operation, although their impact at the steady-state maximum cruising speed is effectively zero. Increasing the number of transmission ratios from 10 to 18 provided no benefit.

It should be noted that the benefits of aerodynamic drag, tire rolling resistance, and weight reduction improvements are very linear. For example, if a 25% coefficient of drag (Cd) reduction provides a 12% fuel savings, then a 12.5% Cd reduction will be worth about 6% fuel savings. Not all technologies have such a linear behavior.

On the two baseline medium-duty trucks, the Ford F-650 and Kenworth T270, three different engines were evaluated: the medium-duty version of the 6.7-liter diesel, the 6.2-liter naturally aspirated gasoline V-8, and the 3.5-liter turbocharged, direct injection V-6. On all drive cycles and payloads but one (65 MPH at full GCW), the V-6 performed better than the V-8. The biggest benefits were at light loads on low speed drive cycles. The diesel provided up to 30% lower fuel consumption than the 6.2 V-8 on higher speed and load drive cycles, but on the Combined International Local and Commuter Cycle (CILCC) cycle, which has a high amount of time at idle and very gentle accelerations, the gasoline V-6 actually outperformed the diesel at light and moderate payloads. The cause of this result was tracked to the high idle fuel consumption of the diesel, which in turn was caused by the tighter torque converter match that is required by the low speed, high torque diesel. Future work will evaluate a feature to unload the torque converter at idle.

A collection of low friction engine features including fuel, water, and oil pumps, reduced piston cooling, as well as improved bearings, rings, and liners, offers significant potential for improving diesel engine efficiency in medium trucks. Benefits of 2.4% to 8.5% were found, with the larger benefits occurring on lightly loaded vehicles on low speed drive cycles. A high engine-out NOx approach (no exhaust gas recirculation (EGR) and a more efficient turbo) can

also provide a significant benefit. This approach assumes future technical advances in aftertreatment that would mitigate the effects of higher engine-out NOx.

For the 3.5 liter V-6, adding variable valve actuation and lift (VVA/VVL) to reduce pumping work provides a benefit of about 3%. Cylinder deactivation can provide up to a 2% benefit on very lightly loaded drive cycles, but zero at high speed. Lean gasoline direct injection (GDI) offers significant benefits (2% to 13%), with bigger benefits at low speeds and light loads. Note that there are issues that need to be overcome to make production implementation of a lean burn gasoline engine feasible. The largest issue is the lack of a suitable NOx aftertreatment system that can work with the exhaust temperatures of a lean GDI engine. A stoichiometric EGR approach has benefits of 4 to 6% for most drive cycles and payloads. The combination of EGR and downspeeding provides benefits of 2% to 10%, again with the larger benefits at higher speeds and loads. Downspeeding hurts fuel consumption on cycles with significant idle time, such as the Parcel cycle, which is over 50% idle. The lower speed, higher torque engine requires a tighter torque converter match, which in turn hurts idle fuel consumption. Engine friction and turbocharger efficiency are minor factors on this relatively small displacement engine.

The 6.2-liter V-8 shows larger benefits from VVA/VVL and cylinder deactivation, compared to the V-6. This is because the larger displacement results in higher pumping losses that these technologies can address. VVA/VVL provides 3.5 to almost 7% benefits, while cylinder deactivation provides zero to 7% benefits. In both cases, the larger benefits are for light payloads and low vehicle speeds. Stoichiometric EGR is worth about a 4% fuel savings on most drive cycles, but it offers up to 10% on the large, heavy T270 at 65 MPH.

Vehicle technologies were all evaluated using the baseline 6.7-liter diesel engine. The medium-duty trucks have less potential for aerodynamic improvement than the long haul trucks, for two reasons. First, they are less amenable to aerodynamic treatments. Second, many medium-duty trucks spend a lot of their life in lower speed urban traffic, where aerodynamic drag is not a major factor. However, there is still some potential for improvement from aerodynamic improvements. Rolling resistance reduction can provide benefits from 3% to 10%, depending on the drive cycle and payload. However, this study did not address potential trade-offs with tire traction, durability, or other performance characteristics. The benefit is larger with increased payload. A substantial 1,100-pound weight reduction provides modest benefits ranging from 1% to just under 3%, depending on payload and drive cycle.

An improved efficiency 8-speed automatic (compared to the 5-speed baseline) provides benefits ranging from 1% to 6%. Only the CILCC cycle had benefits over 3%, however. Switching from the baseline automatic transmission to an automated manual transmission (AMT) offers benefits ranging from 3% to over 10%. The large benefits for AMTs occur in drive cycles with a significant amount of idle time. At idle, the parasitic drag of the torque converter is very high compared to a manual or AMT transmission in neutral, which has essentially zero torque drag from the transmission. Follow-up work is planned to see how an idle neutral feature affects the relative performance of AMT and automatic transmissions. It should be noted that AMTs come with two significant disadvantages in highly transient operation: the frequent power interrupts for shift events cause significantly slower acceleration

times, and drivability suffers from the power interruptions. These penalties must be weighed against the performance advantages.

The baseline Ram pickup truck used the same two gasoline engines as the medium-duty trucks, along with a modified version of the 6.7 liter diesel with higher power, torque and speed range. In comparing the 3.5 V-6 to the 6.2 V-8, benefits of -1% to 25% in fuel consumption were found for the V-6, with the largest benefits coming on the most lightly loaded drive cycles. The 3.5 V-6 had lower fuel consumption than even the diesel in a few cases. On the lightest drive cycle (FTP City) at zero payload, the 3.5 V-6 was 7.5% better than the diesel. On the other hand, on highly loaded drive cycles at 25,000-pound GCW, the small V-6 was up to 36% worse than the diesel, despite offering lower performance. This result shows the diesel engine is better for applications where heavy loads are towed.

The diesel performs 15% to 28% better than the 6.2 V-8 at 50% payload, with the biggest advantages coming on the higher speed, more aggressive drive cycles. Lean GDI, VVA/VVL, reduced engine friction, and cylinder deactivation all provide more benefit in the pickup application than in the larger, heavier medium duty applications, except in the case where the pickup is towing a loaded trailer. The benefit of exhaust gas recirculation (EGR) on the gasoline engines is 3% to over 6% in the Ram, which is about the same as the benefits observed in the medium trucks.

The diesel engine shows a 4% to 8% benefit for reduced engine friction (only including components required to run the engine) at 50% payload, which is more than the benefit observed in medium trucks. Removing EGR and increasing turbocharger efficiency has an effect similar to that in medium trucks. A 4-cylinder diesel version, derived from the 6.7 liter 6-cylinder, was evaluated in the pickup. This engine is downsized by 33% both in size and in power, so performance is reduced (while still being significantly more powerful than pickup diesels of 20 years ago). The downsized engine provides results ranging from zero benefit on some cycles at 25,000 pounds GCW up to 12% better on the gentle FTP City cycle at zero payload. The 4-cylinder provides a 3.9% fuel savings on the aggressive US06 drive cycle at 50% payload.

The table below summarizes the fuel consumption reductions described above. Values in the table are for fuel savings of individual technologies, not for any combination of technologies. Technology combinations will be covered by a separate report.

Engine / Vehicle	Range of Fuel Savings	Notes
DD15 w/o WHR	0 – 5.7%	Downspeeding provided the largest benefits, mainly on low speed cycles
DD15 with WHR	2.7 – 6.0%	Largest benefit at high speed and payload. Includes asymmetric turbo + WHR
ISB Diesel	0 – 13%	Friction reduction and downsizing give largest benefits, both mainly at low speed, light load
6.2 L Gasoline V8	0 – 15%	Lean GDI gives the largest benefit, and works best at light load, but there are implementation issues
3.5 L Gasoline V6	0 – 15%	Lean GDI gives the largest benefit, and works best at light load, but there are implementation issues

T700 Tractor	0 – 15%	Reduced Cd gives the largest benefit at high speed, reduced Crr at 55 MPH
T270 Box Truck	0 – 11%	Reduced Crr and AMT transmission provide the largest benefit
F-650 Tow Truck	0 – 11%	Reduced Crr and AMT transmission provide the largest benefit
Ram Pickup	0 – 7%	Reduced Crr and high efficiency 8-speed automatic provide the largest benefits

Section 3.4 addresses the trade-offs between engine-out NOx and fuel consumption. Diesel engines have always had a strong relationship between these two key parameters. Over time, the trade-off has been improving, with a better NOx / BSFC trade-off possible today than in the past. The addition of selective catalytic reduction (SCR) by nearly all diesel engine manufacturers beginning in MY2010 has greatly reduced the trade off in fuel consumption caused by the requirement to reduce NOx emissions to 2010 levels, by allowing higher engine-out NOx. Further improvements in air handling and controls refinements should provide some additional improvement of the trade-off of fuel consumption against engine out NOx in the future, but the fact remains that low engine-out NOx (below 2 g/bhp-hr, and especially near 0.2 g/bhp-hr) extracts a significant fuel consumption and CO_2 penalty. Potential future lower NOx regulations are likely to require a reduction in engine-out NOx from current levels, and thus are likely to extract a fuel consumption penalty.

As stated above, SCR systems with high conversion efficiency can reduce the need for low engine-out NOx. However, in this case, fuel consumption is traded for urea (Diesel Exhaust Fluid - DEF) consumption. Typically, each gram of engine-out NOx requires the use of a volume of DEF equal to 1.4% of fuel. Thus, an engine running 2g/hp-hr engine-out NOx will consume DEF at a rate of about 2.8% of fuel burn. At early 2015 fuel prices, this DEF will cost about 2.4% of fuel cost. If minimum fuel consumption and GHG values are the goal, a high engine-out NOx level can be combined with a very efficient SCR system and high DEF consumption. This drives up the total fluid cost to the operator, however, so OEMs are likely to prefer lower engine-out NOx levels that offer the lowest total fluid consumption.

Section 4 evaluates testing and simulation approaches. The first subsection covers fuel efficiency metrics. Current regulations use fuel consumption in gallons per ton-mile. Other units that can be considered include fuel consumption per passenger-mile (for busses) and fuel consumption per unit volume-mile (for trucks that normally operate fully loaded, but at less than the legal weight limit (cubed-out). Longer, heavier truck combinations can provide large increases in the denominator (tons or cubic volume) for a relatively modest increase in the numerator (fuel consumption), with the potential for large increases in freight efficiency.

Section 4.2 assesses the ability of test and simulation procedures to quantify fuel consumption effects for individual technologies. Some technologies can be readily quantified by testing or simulating a complete vehicle or engine. Many smaller opportunities for increased efficiency, however, produce benefits too small to be reliably measured in a full engine or vehicle test. For these technologies, laboratory rig tests, combined with duty cycle data from actual vehicle use, can provide an accurate picture of benefits. Another issue that is discussed is

technologies such as downspeeding, where the benefit may not be fully realized on an engine test cycle. A combination of engine test and vehicle drive cycle simulation may be needed to fully quantify the benefit of certain technologies. The section contains a list of technologies that may not be fully captured by the existing GEM model and engine certification protocol.

Section 4.3 looks at regulatory approaches in China, Japan, and Europe. Each of the countries and regions is adopting a different regulatory approach. To the extent that these different regulations work in ways that assign different benefits to a given technology, this can have the effect of driving different technical solutions in different markets, and increasing complexity for manufacturers. Some of the variation in regulatory approach is driven by differences in local market factors such as fuel price or length and weight regulations, but some differences are due to different regulatory philosophies.

Section 4.4 addresses certification of tractor-trailer vehicles. Trailers represent about 30% of the overall vehicle rolling resistance, so including trailer tire rolling resistance in the regulation will cover the 30% of rolling resistance not covered by current regulations. Requirement of SmartWay level aerodynamic features on a trailer provides about 5% fuel savings on highway operation. A portion of today's fleet already uses trailer aerodynamic features and low rolling resistance tires, and the share of these features in the fleet is growing. As a result, regulatory analysis should not claim all of the benefits from adding these features to the regulatory requirement.

Sections 4.4 and 4.5 provides data comparing the current regulatory cycles for certifying engines (the SET and FTP cycles) to actual truck fleet duty cycle data. There is a significant mismatch, which suggests that better regulatory cycles could be developed. There is a discussion of the potential for extending regulations for vocational trucks beyond the current parameters of engine efficiency and tire rolling resistance.

Section 4.6 describes how different technologies perform over a range of duty cycles. Some technologies perform best on drive cycles that emphasize low speed, light load engine operation, while others prefer high speeds and loads. A few technologies have performance that is almost independent of duty cycle.

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LIST OF ABBREVIATIONS AND ACRONYMS

6X2.....Tractor with a front axle, a drive axle, and a non-driven axle
6X4.....Tractor with a front axle and dual drive axles (tandem)
A/C.....Air Conditioning
AES.....Automatic Engine Shutdown
AFR.....Air/Fuel Ratio
ALVW.....Vehicle test weight for pickup trucks equal to the empty weight plus half of the payload that can go in the bed, with no trailer
AMT.....Automated Manual Transmission
APU.....Auxiliary Power Unit
BMEP.....Brake Mean Effective Pressure (A unit to compare the relative load on engines of different size)
BSFC.....Brake Specific Fuel Consumption
CAFE.....Corporate Average Fuel Economy
CARB.....California Air Resources Board
Cd.....Coefficient of Drag (Aerodynamic drag)
CFD.....Computational Fluid Dynamics
CH_4.....Methane
CILCC.....Combined International Local and Commuter Cycle
CNG.....Compressed Natural Gas
CO.....Carbon Monoxide
CO_2.....Carbon Dioxide
Crr.....Coefficient of Rolling Resistance (Tire rolling resistance)
DD15.....Detroit 15 liter heavy duty truck engine (formerly Detroit Diesel)
DEF.....Diesel Exhaust Fluid (Urea mixture used in SCR catalysts)
DPF.....Diesel Particulate Filter
E10.....Gasoline with 10% ethanol content
ECM.....Engine Control Module
EGR.....Exhaust Gas Recirculation
EPA.....United States Environmental Protection Agency
EVO.....Exhaust Valve Opening (Valve timing)
F-650.....Ford Class 5 and 6 truck model
FMEP.....Friction Mean Effective Pressure (Unit for comparison of friction between different engines)
GDI.....Gasoline Direct Injection
GEM.....Greenhouse gas Emissions Model (EPA tool for determining compliance with truck GHG regulations)
GCW.....Gross Combination Weight (Weight of the vehicle and trailer combined)
GHG.....Greenhouse Gas (CO_2, N_2O, CH_4, and others. In this report, CO_2 is the focus)
GT-POWER....Commercial 1-dimensional engine simulation code. Part of GT-SUITE.
GVW.....Gross Vehicle Weight
GVWR.....Gross Vehicle Weight Rating (Vehicle mass with maximum allowed payload)

LIST OF ABBREVIATIONS AND ACRONYMS (CONT'D)

HCCI .....Homogeneous Charge Compression Ignition
HD.....Heavy Duty (Typically refers to Class 8 trucks with engine of 10 liters or more displacement)
HPCR .....High Pressure Common Rail (Diesel fuel system)
ICCT.....International Council on Clean Transportation
IEA .....International Energy Agency
ISB.....Cummins 6.7 liter diesel engine (also available as a 4.5 liter 4-cylinder)
IVC .....Intake Valve Closing (Valve timing)
LD.....Light Duty (Typically refers to Class 2b and 3 trucks. Note that to passenger car manufacturers, Class 2b and 3 are called "Heavy Duty". This leads to considerable confusion between people with car and truck backgrounds.
LTC .....Low Temperature Combustion
MD.....Medium Duty (Typically refers to Class 4 through "Baby 8" trucks with engine displacements below 10 liters)
mm.....millimeter
MY.....Model Year
N_2 .....Nitrogen
N_2O .....Nitrous Oxide
NOx.....Nitrogen Oxides
NAS.....National Academy of Science
NESCCAF.....Northeast States Center for a Clean Air Future
NH_3 .....Ammonia
NHTSA.....National Highway Traffic Safety Administration (Responsible for fuel economy regulations)
NREL .....National Renewable Energy Laboratory
NMHC.....Non-Methane Hydrocarbons
NO.....Nitric Oxide
NO_2 .....Nitrogen Dioxide
NOX.....Oxides of Nitrogen
O_2 .....Oxygen
DOC.....Diesel Oxidation Catalyst
ppm.....Parts per Million
PFI .....Port Fuel Injection
PM .....Particulate Matter
RCCI .....Reactivity Controlled Compression Ignition
rpm .....revolutions per minute
SCR.....Selective Catalytic Reduction
SwRI .....Southwest Research Institute
T270.....Kenworth Class 6 truck model
T-700.....Kenworth Class 8 long haul tractor model
TCPD.....Turbocompound
VIUS .....Census Bureau Vehicle Inventory and Use Survey
VSL.....Vehicle Speed Limiter (also called road speed governor)
VVA/VVL .....Variable Valve Actuation/Lift (Variable lift and duration)

LIST OF ABBREVIATIONS AND ACRONYMS (CONT'D)

VVT .....Variable Valve Timing (Typically cam phasing, but constant lift & duration)
WHR.....Waste Heat Recovery
WHSC .....World Harmonized Steady-State Cycle (An engine dyno test cycle)
WHTC.....World Harmonized Transient Cycle (An engine dyno test cycle)
WHVC.....World Harmonized Vehicle Cycle (Truck test cycle with urban, rural, and motorway segments)

1.0 INTRODUCTION

In 2011, the National Highway Traffic Safety Administration (NHTSA) and Environmental Protection Agency (EPA) jointly issued a first phase of fuel efficiency and greenhouse gas (GHG) standards that apply to medium- and heavy-duty on-highway engines and vehicles for model years (MY) 2014 to 2018 and beyond. These regulations are commonly referred to as "Phase 1" of the Heavy-Duty National Program. The standards cover all vehicles in weight classes 2b through 8, which encompasses most vehicles with gross vehicle weight ratings (GVWR) over 8,500 pounds except for a limited number of passenger vehicles covered under the light duty corporate average fuel economy (CAFE) standards, and recreational vehicles, which were included in EPA's GHG standards but not NHTSA's fuel efficiency standards. Phase 1 has two implementation stages. EPA's greenhouse gas emission standards are mandatory beginning with model year 2014. NHTSA's fuel consumption standards are voluntary in model years 2014 and 2015, becoming mandatory with model year 2016 for most regulatory categories. Commercial trailers were not regulated in Phase 1. The Phase 1 GHG and fuel consumption standards were developed using input from a number of studies which evaluated the fuel saving technologies that are available, such as the NESCCAF 2009 report [1] and the NHTSA and NAS 2010 reports [2, 3].

The research project described in this report has been completed for NHTSA to help to inform the next phase ("Phase 2") of the regulations, which would set standards in coordination with EPA for sometime beyond model year 2018. In order to prepare for Phase 2, NHTSA directed SwRI to update prior research on fuel saving technologies to reflect the effects of the Phase 1 regulations, as well as to include technical progress that has been made over the last few years. In particular, SwRI was tasked with assessing the current commercial fleet technology baseline at the time of contract award (MY 2011/2012), projecting the post-Phase 1 technology baseline (MY 2018), and assessing the effectiveness and cost of potential fuel efficiency/GHG improving technologies for the Phase 2 timeframe (post MY 2018).

When considering potential fuel efficiency/GHG-reducing technologies, NHTSA directed SwRI to include a range of factors: design, functionality, duty cycle, use (type of work done by the vehicle), and factors that can influence the effectiveness, feasibility, and cost. Vehicle utility and performance are also to be considered.

NHTSA issued two requests for proposal (RFP) documents via the General Services Administration (GSA) in 2012. The first document, DTNH22-12-R-00599, was issued on August 9, 2012. A revised version, with the same name plus the suffix CAFE-9-1-2012, was released on September 1, 2012. In the RFP documents, NHTSA described two main purposes for doing a new study. First, the work should update the key findings of the prior NHTSA and NAS studies (which provided technology projections up to MY 2020) so that it could help the agency to develop standards beyond MY 2020. Secondly, the work should provide updated findings and analysis that could be used to inform the following regulatory considerations:

- Appropriate test procedures and methodologies for measuring fuel efficiency of MD and HD vehicles
- Appropriate metrics for measuring and expressing fuel efficiency
- The range of factors, including, but not limited to, design, functionality, use, duty cycle, infrastructure, and total overall energy consumption and operating costs, that affect MD and HD vehicle fuel efficiency
- Other factors and conditions that could impact a program to improve MD/HD fuel efficiency

Since the regulation of MD/HD engine and vehicle fuel efficiency/GHG emissions is relatively new, a "learning curve" to some extent is to be expected. One of the goals of this research project is to use the Phase 1 regulations to look for and evaluate areas for improvement for the Phase 2 program. Certain aspects of the Phase 1 regulations may provide learning opportunities for Phase 2. For instance, there is the possibly that the existing regulations do not fully capture significant fuel saving opportunities that exist and can be cost-effectively achieved. An example of this would be the potential fuel savings from aerodynamic and rolling resistance improvements to trailers, use of special low friction lubricants, or the use of automated manual transmissions.

The project has been divided into tasks. The first task was a literature survey, covering the following topics:

- Fuel saving technologies for MD and HD engines and vehicles
- Market segmentation of fleets
- Current and planned fuel economy regulations in markets around the world

At the end of the literature review task in January 2013, NHTSA, EPA and SwRI agreed on a list of vehicle and engine technologies that form the main subject of this project. The parties also agreed on the selection of engines and vehicles to be used in the project. The selection was constrained to include only engines and vehicles for which extensive experimental data was available. One vehicle type that was not included as a result of this criteria was a Class 8 straight truck. This is a tandem axle straight truck typical of dump trucks, concrete trucks, and waste haulers, among other applications.

The second task requires an analysis of the range of fuel efficiency and GHG reduction performance for technologies that were selected at the end of the literature review task. SwRI used the SwRI Vehicle Simulator tool, a vehicle simulation tool developed in-house, to model vehicle performance over a range of drive cycles. A range of vehicle models has been created to cover the range of Class 2b through Class 8b. There was an increased emphasis on vocational truck applications, since less information is available on the performance of these vehicles as compared to larger segments such as long haul. The commercial software GT-POWER (Gamma Technologies, Inc.) was used to model engine performance, fuel consumption, and CO_2 emissions over the full speed-load range. A range of two gasoline and two diesel engines have been simulated, with additional permutations to cover gaps in the engine size range. Note that GT-POWER is not an appropriate tool for evaluating other greenhouse gas emissions, such as N_2O or CH_4, so these are not addressed by this project.

The third task is a cost effectiveness analysis of the efficiency and emissions reduction technologies for the Phase 2 timeframe. A subcontractor, Tetra Tech, Inc. performed the cost analysis, and their results are to be provided in a separate report. The cost analysis also includes indirect costs and benefits that may occur with the various technologies.

A fourth task includes a review of fuel efficiency metrics that take vehicle work and use into account. It also includes a review of engine efficiency test procedures, vehicle efficiency test procedures (whole vehicle on-road, chassis dyno tests, etc.), and efficiency simulation approaches.

The final task calls for post-report support of NHTSA, including the provision of presentations, meeting support, and documents. This task will not be included in either final report. The remaining tasks will be covered by Final Report #2, which is due to NHTSA in early 2015.

2.0 LITERATURE REVIEW

Several researchers were involved in the literature review. There was no specific search methodology prescribed, so each section author used his own background and favorite search approach. The goal is to have a representative overview of literature related to the topics of concern, but not to have every possible paper included.

The scope of this review has included literature pertaining to light, medium, and heavy trucks. Passenger car studies have been included only in cases where the technologies and fuel economy benefits could be directly applied to light truck applications as well. Transit bus and motor coach applications were not included.

The majority of this work was done in calendar years 2012 and early 2013. As a result, the majority of references are through 2012. A few later references are included based on specific topics added during document review and revision. These have been added by exception, and do not consider the full scope of 2013 and 2014 publications.

2.1 Market Segmentation

Several approaches were considered in the development of market segmentation for commercial vehicles. The National Research Council, which is a part of the National Academy of Sciences, used an approach based primarily on weight class [VS-1].* The U.S. Census Bureau formerly provided detailed vehicle inventory data with populations by weight class and application. The information contained in the Census Bureau Vehicle Inventory and Use Survey (VIUS) study is excellent. It includes detailed information about the fleet size, types of operations, annual vehicle miles traveled, and more. Unfortunately, the final year for which such data was compiled was 2002 [VS-2]. After reviewing the various possible approaches, SwRI and NHTSA agreed to use the market segmentation approach developed by CalHEAT [VS-3, VS-4]. CalHEAT agreed to provide technical support, and the segmentation used in this project is as detailed in references VS-3 and VS-4. The segmentation was developed by CalHEAT in conjunction with industry representatives during a series of web meetings, the results of which are documented in VS-3 and VS-4.

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* Designations in brackets indicate the references used in the study, and summarized in this literature review. The references are organized by section, using the following prefixes:

VS	Vehicle Segmentation
R	Regulations
ET	Engine Technology
VT	Vehicle Technology

The CalHEAT approach to Class 2b – 8 vehicle segmentation involves 6 truck categories, which are listed below:

1. Class 2b/3 Pickups and Vans
2. Class 3-8 Urban Vocational Work Trucks
3. Class 3-8 Rural/Intracity Work Trucks
4. Class 3-8 Work Site Support Trucks
5. Class 7-8 Short and Regional Haul Tractors
6. Class 7-8 Over the Road Tractors

2.2 Regulations

The emission and CO_2 regulatory requirements provide a necessary framework from which the project was conducted. The regulatory standards studied, and the sources used, are summarized in this section. In the following subsections, the terms fuel *economy* and fuel *efficiency* may both be used. Fuel *economy* is measured in distance traveled per unit of fuel consumed, such as miles per gallon. Fuel *efficiency* is inversely proportional to fuel *economy*, and is expressed in terms of units of fuel consumed per distance traveled, such as gallons per 100 miles. If a change is introduced that increases efficiency by 25%, this means that a given transport task can be completed using 25% less fuel. Units of fuel *economy* overstate the benefit. A 25% increase in *efficiency* (25% decrease in fuel consumption) equates to a 33% increase in fuel *economy*. Figure 2.1 shows the relationship between fuel economy changes and fuel consumption / GHG emissions changes. For small changes, the values for change in fuel economy and fuel consumption are almost equal, but for larger changes, the values diverge rapidly. A 10% increase in fuel economy equals a 9.1% reduction in fuel consumption, but a 100% increase in fuel economy only represents a 50% reduction in fuel consumption. Some of the results described in sections below will be in terms of fuel economy, while others are in terms of fuel consumption.

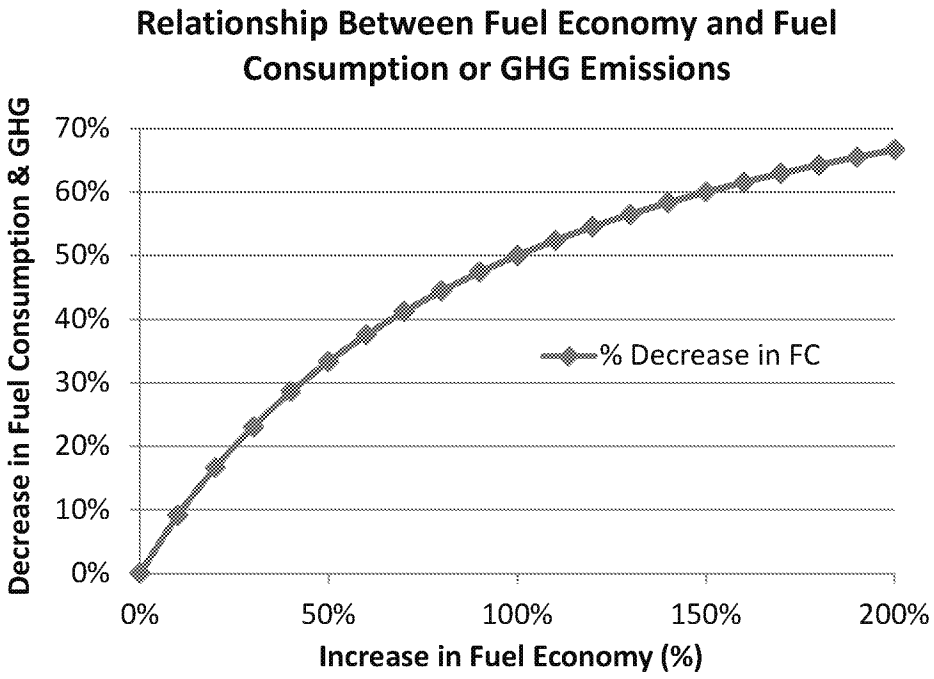

FIGURE 2.1 RELATIONSHIP BETWEEN CHANGES IN FUEL ECONOMY AND CHANGES IN FUEL CONSUMPTION AND GHG EMISSIONS

2.2.1 North American Fuel Economy Regulations

Central to the project are the current U.S. medium- and heavy-duty vehicle fuel efficiency and greenhouse gas (GHG) regulations, developed jointly by the NHTSA and the U.S. Environmental Protection Agency (EPA), and available at the web site, www.regulations.gov [R-1]. Supporting documentation, including the Regulatory Impact Analysis and further background studies, is also available on the NHTSA web site [R-2]. A NRC report provided independent technical recommendations for NHTSA to consider when developing the regulatory approach for Phase 1 [R-3], with supporting NRC data [R-4]. Canadian regulations are aligned with the U.S. 2014-2018 regulations, but are expressed only in terms of GHG limits, and not fuel consumption limits [R-18].

2.2.2 Worldwide Fuel Efficiency Regulations

The work being done in this study was also placed in the context of worldwide regulations and regulatory trends. A review was conducted of studies evaluating fuel efficiency regulations worldwide as part of this literature review. An overview of worldwide current and proposed regulations was presented in slides by Bandivadekar of the International Council on Clean Transportation (ICCT) [R-10]. A more recent slide summary was presented by Muncrief, from the same organization [R-19].

The challenges facing implementation of fuel efficiency standards, and the intended timeline were summarized in a slide presentation by Wang [R-9]. A more recent publication that provides the best available reference regarding development of the Chinese heavy-duty vehicle fuel efficiency test procedure was prepared by Zheng and co-authors from several agencies [R-14]. Fuel consumption regulations and test procedures in China are briefly summarized in a three-page document produced by the Chinese Ministry of Industry and Information Technology (MIIT) [R-5]. Base vehicle models are tested on a chassis dynamometer, using the Chinese low power variation of the World Harmonized Vehicle Cycle (C-WHVC) [R-15]. Variants of the base model have the option of being tested using a chassis dynamometer or by using simulation. Further test details are reported regarding parallel test standards administered by another Chinese government agency [R-16], and further details of current and proposed standards have been summarized [R-17].

Information regarding the 2015 Japanese regulations is summarized in the report of activities chaired by Ikegami [R-11]. The "Top Runner" program was instituted by Japan's Ministry of Economy, Trade and Industry, Agency for Natural Resources and Energy, with the stated objective of "developing the world's best energy-efficient appliances." It addresses a wide range of industries and appliances, with freight vehicles covered in Section 7.2 of the summary report [R-12]. Test procedures for fuel consumption calculation are summarized in a slide presentation from Japan's National Traffic Safety and Environment Laboratory [R-13]. The two driving cycles, JE05 and the Interurban driving mode are combined using weighting factors, and fuel consumption is calculated based on engine fuel maps. The overall impact of the Top Runner regulation is to drive improvement in engine efficiency, but not in vehicle efficiency or power demand.

It would be very useful to have a comparison of world-wide regulations in the same terms, so that the relative stringency of different regulations could be evaluated. Unfortunately, regulations are, in practice, very hard to compare. The US Phase 1 regulations, for example, cover engines and vehicles separately. There is a CO_2 and fuel consumption standard for engines, and a separate standard for vehicles. US engine standards are in units of emissions per unit of work. The vehicle standard assumes a generic engine fuel map provided by the regulators, and are in terms of emissions per unit of distance traveled. The Chinese standard, on the other hand, measures vehicle fuel consumption on a given cycle, at a payload determined by the regulation. The vehicle fuel consumption is influenced by the engine used, the transmission and driveline, and all other aspects of the vehicle. It is impossible to separate out engine and vehicle requirements in the Chinese standard, because there are no separate requirements.

The European Union is in the process of developing an approach to future regulation of truck fuel consumption and CO_2 emissions. The EU approach will use a sophisticated vehicle simulation model to project emissions over a range of drive cycles.

2.2.3 Fuel Efficiency Test and Analysis Methodology

The primary methodology for this study was to use engine and vehicle simulation approaches and drive cycles to estimate the fuel efficiency improvements of different technologies across applicable vehicles, loads, and drive cycles. This project is based on

simulation, with experimental validation where existing test results are available. SwRI made an effort to include simulation methods and drive cycles that have been validated by previous researchers. For instance, SwRI is conducting a parallel project for EPA that includes developing a correlation between full vehicle on-road tests, chassis dynamometer tests of full vehicles, and powertrain tests conducted in a test cell. The work by Sharpe and Lowell [R-6] provides a good, high-level overview comparing the drive cycle fuel efficiency methodologies.

In setting the stage for a more detailed assessment of specific engine and vehicle technologies, the International Energy Agency prepared a technology roadmap [R-7]. Pages 23 through 28 of [R-7] discuss heavy-duty vehicles, and Table 8 lists the available technologies, estimated fuel efficiency improvements, technology costs, and provides an assessment of technology readiness. Table 9 estimates technology payback times in various applications. In a related publication, the IEA presents a proposed policy plan in support of vehicle fuel efficiency improvement [R-8].

2.3 Engine Technologies

This section summarizes the findings of the literature search on efficiency gains resulting from engine and aftertreatment development. It is divided into five sub-sections: Engine Systems, Air Handling, Combustion, Aftertreatment, and Friction/Parasitics. The first sub-section begins with a look at spark-ignition engines and the transition from spark-ignition to diesel engines. It is applicable only to light-duty applications (Class 2b/3). The remainder of the Engine Systems sub-section and the sub-sections that follow address diesel engines, in light, medium, and heavy-duty applications.

2.3.1 Engine System

2.3.1.1 Direct-Injection

The transition from port-injection to direct-injection in spark-ignition engines began several years ago, and is expected to continue, with most new engines following this trend. Attractions include a two to three percent volumetric efficiency improvement and the ability to increase the compression ratio by one to two numbers, or around 10 to 20 percent [ET-14]. These capabilities are utilized primarily to increase specific output, but the latter may provide a one to two percent fuel efficiency improvement.

2.3.1.2 Lean Direct-Injection

Another approach to direct injection spark-ignition engines that was taken in its early development is that of the lean burn, stratified charge combustion system. This approach held the promise of greater efficiency gains, but the lean NO_X aftertreatment requirements negated most of the gains, especially under light duty cycle conditions, when the exhaust temperature was insufficient for NO_X trap regeneration.

Several researchers have demonstrated the fuel economy improvement potential of the lean burn direct-injection engine. Stovel and his colleagues ran back-to-back fuel economy tests over five driving cycles, using a 1998 Toyota equipped first with its production port-injected engine, and then with lean direct-injection. Fuel economy improvements ranged from 3.7 percent on the U.S. highway cycle to 16.5 percent on the New York City Cycle and 17.2 percent on the Japan 10-15 cycle [ET-26]. Alkidas obtained similar results, and identified the primary source of the fuel economy improvement as reduced pumping at part load; this explains the far greater benefit seen in urban driving cycles as compared to highway driving. Further benefits were attributed to the higher compression ratio achievable with direct injection, and the reduced heat transfer of a stratified charge engine [ET-27].

Most of the work on stratified charge direct injection engines was done from the late 1990s, when several engines of this type were introduced to production in Europe and Japan, through the early 2000s. At that point the emphasis shifted to stoichiometric direct injection engines as it was concluded that the lean NOx aftertreatment systems could not be made sufficiently efficient for light duty cycle applications. Baumgarten and his colleagues demonstrated a 22 percent fuel consumption improvement over the European city driving cycle, but concluded that "New technologies and strategies in the field of exhaust gas aftertreatment are required" [ET-28]. Stovel and his colleagues continued their studies with evaluation of aftertreatment efficiencies versus duty cycle, and concluded that only by adding grade loads to the duty cycles could they gain sufficient aftertreatment efficiency [ET-29].

Another approach to lean, or dilute combustion is utilizing exhaust gas recirculation under not only part-load but also full-load operation. Researchers at Southwest Research Institute have developed this concept in the form of High Efficiency Dilute Gas Engines (HEDGE), and more recently as Dedicated Exhaust Gas Recirculation (D-EGR). An early modeling study projected diesel-like fuel efficiency in light and medium truck applications [ET-37]. More recent studies have reported fuel efficiency improvements of between five and 30 percent over the engine operating map [ET-38, ET-39]. Under most operating conditions the reported gains are on the order of five percent, while the larger gains are seen under full-load conditions, where air-fuel ratio enrichment would normally be utilized.

2.3.1.3 Cylinder Deactivation

This technology has been included only as a spark-ignition technology as it is difficult to implement in highly turbocharged engines due to turbocharger surge problems [ET-18]. The fuel consumption improvement in spark-ignition engines is estimated at 5 to 6.5 percent [ET-21]. This is achieved through the reduced pumping losses associated with firing only a portion of cylinders under part-load conditions, and thus working the remaining cylinders at a higher load, lower pumping-loss condition. The benefit of cylinder deactivation depends on factors including engine size, the maximum BMEP where a benefit can be obtained, vehicle power demand, and drive cycle. Results presented in Section 5 below will show that smaller engines in heavier vehicles achieve smaller benefits, and that for highly loaded duty cycles, the benefit can be zero.

2.3.1.4 Throttle-Free Operation

Another technology that has been used to reduce light-load throttling losses in spark-ignition engines is "throttle-free" operation. Variable valve event lift and timing are used to control engine load in lieu of intake throttling. This system has been developed by BMW, and they report a 20 percent specific fuel consumption reduction under very light load operating conditions. A ten percent tank mileage improvement is reported over passenger car driving cycles. The mileage improvement drops as vehicle duty cycle increases [ET-35].

2.3.1.5 Downsizing and Boosting

Simultaneously downsizing and turbocharging a direct-injected spark-ignition engine is widely seen as an important fuel efficiency improvement strategy. The Ford EcoBoost engine is a well developed example, and Ford reports a twelve percent fuel economy improvement as compared to a larger displacement port-fuel-injected engine in the same application [ET-23]. The result is reported over the FTP-75 light-vehicle test cycle. Note that actual results for this approach will vary from engine to engine, and are highly sensitive to drive cycle. Boggs reports a 17 percent fuel consumption improvement through downsizing, but this is a research trends presentation, and it is not clear how much of the reported gain is proven [ET-3].

2.3.1.6 PFI to Diesel

A 25 to 30 percent fuel economy improvement (20 to 23% fuel *efficiency* improvement) is generally accepted as the magnitude attributable to replacing a port-injected gasoline engine with a direct-injected diesel engine. Cummins reports a 30 percent fuel economy improvement versus gasoline in a light truck/SUV chassis [ET-5]. This study was done using a direct comparison between the two drivetrains over the North American driving cycle.

The remaining items listed in this section pertain to further efficiency improvements that are believed achievable through diesel engine optimization. Overall gains are quite consistently reported as between twenty and twenty-five percent, with the latter number including idle-off and parasitic reductions. It is important to note that the individual improvements listed below are not completely additive as the result may include combined effects (VVA and/or Miller Cycle and turbocharging, for example), or technologies may be ones that cannot be applied together without reducing the efficiency gain of each (turbocompounding and a bottoming cycle, for example). The DOE newsletter presents an overall summary of diesel efficiency objectives, highlighting the twenty percent improvement goal (from 42 to 50 percent brake thermal efficiency (BTE)) of the SuperTruck program [ET-6]. Note that the SuperTruck program engine goal focuses on achieving 50% brake thermal efficiency (BTE) at a single operating point, and that many of the technologies used in this program may not be commercially viable in the 2015 timeframe.

2.3.1.7 Idle Reduction

Idle shutdown technology is covered in the Vehicle Technologies section, but one study is listed here. A line-haul fleet field study, with idle shut-down and an APU, was conducted on a fleet comprised of 16 trucks. An override system was used that would not allow the APU to stay on when the engine was running. The result was an almost 16 percent fleet fuel economy improvement, from 6.04 to 6.99 MPG. This result was reported for the actual use of the sixteen trucks (not for a single, defined duty cycle). Percent idle time for each vehicle, before and after the idle shut-down feature was installed is reported. Prior to installation, the percent idle time ranged from 25 percent to nearly 70 percent. After installation the percentage ranged from less than one to 20 percent, with the majority of vehicles idling less than five percent of the time [ET-25].

2.3.1.8 Bottoming Cycle

Organic Rankine Cycle waste heat recovery (WHR) systems have been studied for many years. Their basic approach is to use engine exhaust waste heat to evaporate a working fluid in a boiler unit. The gas is passed through a turbine to create mechanical or electrical power, whereupon it is re-condensed prior to pumping it again into the boiler unit. Cost and complexity remain high, and along with package size and transient response challenges that limit the application to line haul vehicles only. In EGR engines they offer the benefit of eliminating the EGR cooler. To the extent that WHR systems use exhaust heat, they increase the overall cooling system heat rejection requirement, which can have negative impacts on cooling fan power needs, as well as on vehicle aerodynamics. Eckerle and Koberlein report potential efficiency gains from WHR on the order of six percent [ET-10, ET-16]. de Ojeda reports three to five percent gains [ET-7]. Greszler reports four to five percent [ET-12]. Sisken reports 4.5 percent [ET-18].

2.3.2 Air Handling

2.3.2.1 Exhaust Gas Recirculation (EGR)

At low levels EGR is close to fuel efficiency neutral in a diesel engine, but as EGR level is increased it has a negative impact on fuel efficiency through two mechanisms – increased back pressure, adversely impacting pumping work, and slowing down the combustion heat release rate. Taking a typical EGR system map as the baseline, Eckerle reports the potential for approximately three percent BSFC improvement through further system optimization [ET-10]. This is primarily through improved system effective flow area, reducing the adverse impact on back pressure.

It should be noted that even as aftertreatment becomes more effective, the most efficient solution in practice may retain some EGR, as noted by Koberlein [ET-16]. He also reports less opportunity for improvement through reduced EGR restriction (about 0.5 percent).

2.3.2.2 Turbocharger Efficiency Improvement

Both Czarnowski and de Ojeda estimate that further advances and optimization in turbocharger efficiency provide on the order of two percent fuel efficiency improvement potential [ET-4, ET-8]. Koeberlein reports about 0.5 percent over a driving cycle [ET-16].

2.3.2.3 Engine Breathing Improvements

The combined result of various breathing improvements may be estimated as the sum total of intake and exhaust pressure drop reductions divided by brake mean effective pressure (BMEP). Koeberlein reports 1.4 percent through optimization [ET-16]. Sisken projects a two percent fuel efficiency improvement through air handling system development [ET-18]. Jadin predicts almost four percent through a combination of variable intake valve closing timing (IVC), turbocharger efficiency and match improvements [ET-15]. A few plots in this reference show another four percent, but these are not explained.

2.3.2.4 Variable Valve Event Timing

The primary gain in diesel engines is achieved by varying the exhaust valve opening (EVO) event versus engine speed and load, in conjunction with turbocharger optimization to minimize blowdown losses. de Ojeda reports a 1.25 percent fuel consumption improvement [ET-8].

The Miller Cycle is sometimes considered to improve specific engine output, but there are no definitive studies that quantify its fuel consumption impacts. Attractions include its potential role in engine downsizing, but the technology requires a greater portion of the compression process to be conducted in the turbocharger compressor, at lower isentropic efficiency. Similarly, the Atkinson Cycle may be considered in its integration with hybrid drivetrains, and fuel efficiency benefits are reported as part of the impact of hybridization.

2.3.2.5 Turbocompound – Mechanical

On-highway demonstrations of this technology began in the early 1980s. Results are duty cycle dependent, and require significant time at high load to see a fuel efficiency improvement. Light load factor vehicles can expect little or no benefit. Greszler reports two to four percent fuel consumption improvement in line haul applications [ET-12].

2.3.2.6 Turbocompound – Electric

Further gains over the mechanical turbocompound system might be available by using a turbo-generator instead of conventional power turbine. These are attained through better vehicle integration and lower backpressure impacts. The power turbine speed is no longer linked to crankshaft speed, which allows more efficient operation of the turbine. De Ojeda reports on the

order of a 1 to 1.5 percent efficiency improvement over mechanical turbocompound systems at 0.5 to 0.7 gm/hp-hr engine-out NOx levels, but dropping at lower engine-out NOx [ET-8]. Zero benefit is reported at 0.3 to 0.4 gm/hp-hr engine-out NOx, due to lower available temperature. Jadin reports a 1.6 percent fuel efficiency improvement, again as compared to a mechanical turbocompound system [ET-15].

2.3.2.7 Asymmetric Turbocharging

Detroit Diesel Corporation has recently replaced a mechanical turbocompounding system with an asymmetric turbocharger. This approach uses a twin entry turbocharger in which one portion is sized smaller than the other. The more restrictive side provides the back pressure required for EGR operation, while reducing the overall exhaust restriction. Fuel economy improvements have been reported relative to their earlier turbocompound engine. The fuel economy is reported as equivalent throughout the load range from full load to approximately 25 percent load. At lighter loads the fuel consumption is reduced, with a maximum reported reduction of five percent at ten percent load and below [ET-36].

2.3.3 Combustion

2.3.3.1 Low Temperature Combustion

While combustion efficiency drops slightly with lower combustion temperature, this is more than offset by a more favorable specific heat ratio during expansion, and reduced heat transfer, allowing greater work extraction during the expansion process. A significant increase in closed-cycle (gross indicated) efficiency has been demonstrated by several researchers. The remaining question is how much these gains might be negated by increased pumping work. The paper by Teetz provides a detailed evaluation of an HCCI engine in a multi-cylinder configuration; interestingly, fuel consumption changes go unreported [ET-20]. Zhang reports a 7.4 percent fuel consumption improvement at best operating conditions when using a dual fuel (E85/diesel) RCCI engine as compared to a baseline diesel engine [ET-24]. Jadin reports an improvement of greater than three percent at 5.8 bar [ET-15]. Jadin's presentation predicts overall 50 percent brake thermal efficiency with diesel fuel and 55 percent as a "bold goal" with dual-fuel engines. Wagner reports a 7.1 percent brake thermal efficiency improvement in a light duty (1.9 liter) engine at best operating point [ET-22]. Each of these researchers point out that low temperature combustion also comes with downsides, such as difficult control of combustion during transient operation, and increased combustion noise caused by high rates of heat release at the beginning of combustion and under high load conditions.

2.3.3.2 In-Cylinder Optimization

It's difficult to quantify efficiency improvements through combustion system optimization, since this is closely coupled with aftertreatment technology. For example, allowing higher in-cylinder NOx as SCR efficiency improves is an important avenue. The biggest lever for further optimization is rate shape control and injection split optimization as

common rail technology advances. In an attempt to separate SCR from in-cylinder optimization one can look at specific fuel consumption changes at constant in-cylinder NOx. Eckerle reports between 3 and 3.5 percent specific fuel consumption improvement at constant NOx through fuel system rate shape optimization [ET-10]. Jadin reports on the order of four percent improvement through a combination of in-cylinder optimization approaches (CFD optimization, injection pressure and fuel system losses) [ET-15].

Another important aspect of in-cylinder optimization is the impact of combustion temperature on reaction kinetics. Two fundamental studies are included in the references that demonstrate limiting parameters regarding in-cylinder NOx control. The work of Hu explains a significant slowing of energy release as combustion temperature drops [ET-30]. Flynn's paper demonstrates the impact of the slowed reaction rates on in-cylinder efficiency [ET-31].

2.3.3.3 Increased Peak Cylinder Pressure

Continued development of cylinder head, piston, and head gasket technology allows increased peak cylinder pressure. This can be taken advantage of for efficiency improvements through increased compression ratio and increased rate of heat release. de Ojeda reports a one percent improvement of fuel efficiency resulting from compression ratio increase as reasonable in the projected timeframe [ET-7]. Koeberlein reports just under one percent in a driving cycle [ET-16]. de Ojeda reports a compression ratio impact of two percent at higher engine speeds [ET-8]. Sisken projects a fuel consumption improvement of just under five percent in HD applications through "downsizing" [ET-18]. This is later defined as running at higher BMEP. Sisken also projects a 1.5 percent improvement through compression ratio increase [ET-18]. It should be pointed out that increasing cylinder pressure often requires an extensive or complete redesign of the engine, and reliability/durability of the engine also becomes an issue.

2.3.3.4 Model-Based Control

A topic that is receiving attention as an aid to diesel combustion system calibration is model-based control. This approach replaces look-up tables in collecting transient engine test data and using it in "desk-top" calibration optimization. Several recent papers have demonstrated its efficacy in resource reduction and system optimization when developing diesel combustion system calibrations [ET-32 through ET-34]. It is important to recognize that there is no inherent fuel consumption improvement resulting from model-based control. Its ability to improve the optimization process may result in improved calibrations in some cases.

2.3.4 Aftertreatment

Two approaches involving aftertreatment systems can be applied to improve fuel efficiency: better combustion system optimization through increased aftertreatment efficiency, and reduced backpressure through further development of the devices themselves. de Ojeda reports a seven to eight percent improvement projected through a combination of higher cylinder pressure, injection optimization, and engine/aftertreatment optimization [ET-8]. Koeberlein

reports a 0.5 percent improvement through improved aftertreatment flow (catalyst size optimization and improved NOx surface utilization) [ET-16]. Sisken projects a two percent fuel efficiency improvement through reduced EGR. Thinner wall DPF, improved SCR cell density, and catalyst material optimization allow greater NOx conversion efficiency in the aftertreatment, reducing the amount of EGR required. [ET-18].

2.3.5 Friction and Parasitic Losses

Piston, ring, and bearing friction are not separated in most studies. de Ojeda identifies a combined improvement of up to two percent through reduced bearing friction, reduced piston and ring friction, and unspecified lube pump improvements [ET-7]. In his 2012 follow-up paper he reports 5.5 percent through a combination of friction reduction and both lube and cooling system improvements [ET-8]. Later in the same presentation he specifies 0.45 percent demonstrated through water pump improvements and 0.3 percent through lube pump improvements. The total number of 5.5 percent seems optimistic, but is a projection of further improvements. Koeberlein reports a combined number of 3 percent [ET-16]. Sisken reports a combined number of two percent, with 0.5 percent coming from improved water pump efficiency [ET-18]. de Ojeda reported a 1.3 percent improvement in HD diesel fuel efficiency over the NA HD on-highway cycle [ET-17]. Jadin shows a 0.9% benefit for a variable speed water pump and variable displacement oil pump; piston/ring/liner friction reduction as 0.5 percent; bearing friction reduction as 0.6 percent [ET-15]. It should be noted that water pump improvements include both pump efficiency improvement, and variable speed or on/off controls. Lube pump improvements are primarily achieved using variable displacement pumps and may also include efficiency improvement.

Engine downspeeding is mentioned by Sisken but without description or quantification [ET-18]. The challenges to downspeeding include: higher driveshaft and axle torques, maintaining drivability and grade capability at lower cruise RPM, and engine durability when running at higher BMEP. Downspeeding is identified by both Cummins and Volvo as holding fuel economy advantages on their current web sites:

http://cumminsengines.com/smartadvantage?%20-%20overview#overview
http://www.volvotrucks.com/trucks/na/en-us/products/powertrain/xe/Pages/xe.aspx

2.3.5.1 Variable Displacement Lube Pump / Variable Speed Water Pump

Sliding-vane, variable displacement lube pumps are just starting to see production in new European diesel passenger cars. Analysis shows lube pump driving power to be cut in half at highest engine speeds. This in itself is reported by Excell as reducing pump power demand by two to three kilowatts at rated speed in a heavy-duty diesel engine (approximately one percent) [ET-11]. Larger improvements are seen if the engine also uses piston cooling nozzle cut-outs for light load, high speed operation. Large gains are reported under cold start conditions (six to eight percent) [ET-1, ET-17, ET-19].

One reference reported a 2.2 percent fuel efficiency improvement through piston, ring pack, and bearing optimization, and the addition of a variable displacement oil pump. The

results were over the European passenger car driving cycle [ET-2]. The DD15 water pump uses a variable speed viscous clutch controlled by the engine management system based on engine load and coolant temperature [ET-9].

2.3.5.2 Flow Circuit and Thermostat Advances

An interesting approach to flow circuit and thermostats is taken in the new Volkswagen TSI gasoline engine. Two thermostats were used, with separate flow circuits around the cylinder walls, and through the oil cooler and cylinder head. Flow around the cylinder walls is separately regulated to keep wall temperatures at a more uniform (and generally higher) temperature, and to reduce cylinder wall lubricant viscosity. While this is a small gasoline engine, the same concept could be applied in small, lower duty cycle diesel engines [ET-13].

2.4 Vehicle Technologies

An extensive study of reference material pertaining to vehicle technologies was conducted on this project. Vehicle technologies include those affecting aerodynamics, rolling resistance, transmission and driveline after the engine, and vehicle auxiliary loads are included in this section. Because many of the potential improvements are highly dependent on both the vehicle type and its application or duty cycle, specific fuel efficiency projections are for the most part not summarized in this section. Examples from specific applications can be found in many of the references, and information from these references was applied to the analyses reported elsewhere in this project.

2.4.1 Identification of Vehicle Technologies

The National Research Council [VT-1, VT-2] and Department of Energy [VT-3] summaries provide recent evaluations of the technologies available for vehicle efficiency improvement. These reports provide a starting point to gain perspective on the work being done through such programs as the 21st Century Truck Partnership. The final rule for medium and heavy duty fuel efficiency includes a further listing of fuel efficiency improvement technologies [VT-5]. Also addressed [VT-5] are questions pertaining to alternative standards that may better include vehicle technologies not accounted for in the current rules.

A CalHEAT study [VT-4] identifies further vehicle technology pathways including electrification, low carbon and alternative fuels, powertrain efficiency, hybridization, mass and drag reduction. Also considered in this study is improving the efficiency of truck utilization. Annual vehicle mileage and ton-mpg values for medium and heavy duty applications are addressed in several of the studies [VT-11, VT-14].

A 2009 NESCCAF study focused specifically on engine and vehicle technologies for long haul applications [VT-6]. It was further summarized, including technologies anticipated through the 2017 requirements in a study led by Cooper [VT-7]. Projections toward further, future technology implementation are provided by Kobayashi [VT-9]. The timeframe to 2050 is

addressed in the Kobayashi study. An IEA study provided projections to the year 2050 that included especially useful graphical depictions of the impact of fuel efficiency improvement technologies by vehicle type and expected implementation date on fuel usage and GHG mitigation [VT-12].

Emphasizing cost/benefit analysis, Harrington identified problems capturing and quantifying the vast array of vehicle fuel efficiency improvement technologies with the current fuel consumption standards. These problems are driven by the wide range of applications and duty cycles encountered in the field. The work covered the vehicle range from Class 2B through Class 8 [VT-8]. Alternative approaches are presented with an emphasis on capturing improvements resulting from further vehicle technologies.

In a study by Saricks and colleagues, potential market penetration of various technologies is considered [VT-10]. A base case, in which innovation proceeds at its current pace, and an accelerated implementation pace, are considered and compared through the year 2020. Both engine and vehicle technologies are considered.

A particular medium duty vehicle was evaluated in an Argonne study [VT-13]. Technologies including aerodynamic drag reduction, rolling resistance reduction, transmission improvements, and vehicle weight reduction were applied to a baseline vehicle. Each technology was considered individually, and then various technology groupings were studied.

An Oregon state government study was previously cited for its consideration of vehicle utilization efficiency [VT-14]. This extensive study also covers a wide range of vehicle technologies including auxiliary power units, automatic engine shut-down, automated transmissions and speed governors, low rolling resistance and single-wide tires, automated tire inflation and nitrogen tire inflation, as well as an array of aerodynamic devices. The impacts of management policies including driver education, idle time reduction, and service practices are addressed. The study also includes information system technologies such as wireless transport management, on-board fuel system monitoring, and advanced routing and scheduling systems. Each of these technologies, and several others, are identified with an initial discussion of their potential, but this is not a detailed study.

Several light duty studies were also considered, especially if the findings could be applied to medium or heavy duty vehicles. An ICCT study focused on Class 2B and 3 pickup trucks and vans, and included cost information [VT-15]. An EPA study that included cost analysis for light duty vehicles provided a costing approach that was identified as applicable to medium and heavy duty vehicles [VT-26]. A roadmap on fuel efficiency prepared by the International Energy Agency (IEA) included vehicles from two-wheeled through cars and light trucks [VT-16]. This study also outlined the roles of various stakeholders, and ways they can work together in achieving fuel consumption reduction goals.

The interaction between emission factors and fuel efficiency was addressed in a university study [VT-17]. Vehicle classification was addressed in this study, and various engine and vehicle technologies were included.

2.4.2 Evaluations of Specific Vehicle Technologies

Each of the technologies described in this section were identified in some of the references cited in the previous section on Vehicle Technology Identification [VT-1 through VT-17]. The publications summarized in this section are detailed studies of the specific technologies listed under each heading, often including measured or calculated fuel economy improvements. Included as an important reference is the users' guide to EPA's GEM model [VT-25]. It is a tool for evaluation of the GHG reduction potential of specific technologies.

2.4.2.1 Low Resistance and Wide-Based Tires

Several studies have documented the role of rolling resistance reduction in improving vehicle fuel economy. These include both modeling [VT-34, VT-36] and experimental [VT-35], and both passenger car [VT-35, VT-36] and heavy-duty [VT-34]. While this plays out in various efforts to improve tire technology, the most visible changes being seen are the wide-based tires now seeing increased application in Class 8 trucks.

As a well-developed technology, now seeing increased implementation, there are numerous studies quantifying the potential benefits of wide-based single tires in heavy duty applications [VT-18 through VT-21]. In an oral presentation from Michelin, wide-based singles were reported to reduce rolling resistance by ten percent compared to conventional dual tire heavy-truck installations and to reduce vehicle weight by about 800 pounds (363 kg) including the effect of the spare tire on the trailer [VT-30].

A study by the International Energy Agency [VT-18] emphasizes European truck applications, and provides specific recommendations regarding the use of low resistance tires. The study led by Lascurain at Oak Ridge National Lab included measured fuel economy benefits when comparing new generation single wide-based tires to standard dual tires on a Class 8 long haul truck [VT-19]. A nine to ten percent fuel economy improvement was recorded, over actual duty cycles. The improvement increased as vehicle weight was increased.

Hausberger and his colleagues developed specific coast down and constant speed tests, and included low resistance tires, trailer aerodynamics, and trailer weight in their measurements [VT-20]. Over this defined test the reduced rolling resistance tires alone resulted in a 4.5 percent fuel consumption reduction. In combination with improved aerodynamics the improvement was 6.5 percent. Reducing the trailer weight by 800 kg, combined with the rolling resistance and aerodynamic improvements, brought the total fuel consumption improvement to eight percent.

In a study led by the American Truck Association (ATA), a two to three percent fuel economy improvement is reported, with a maximum improvement of eight percent [VT-21]. This report also includes driver feedback comments on the pros and cons of wide-based tires.

2.4.2.2 Aerodynamic Improvements

As identified in the previous sub-section, trailer aerodynamics was among the factors tested by Hausberger and his colleagues [VT-20]. An ICF International study provides a comprehensive look at a variety of aerodynamic devices [VT-22]. Fuel economy gains attributed to each are reported over various duty cycles. Also reported are current and projected market penetration for the various devices.

As part of the DOE-sponsored SuperTruck program, one of the technology groups being studied is Class 8 vehicle aerodynamics. Tractor improvements, trailer improvements, and integrated, tractor/trailer system improvements have been studied, with results reported in terms of drag coefficient reduction. The most recent presentations at the time of this writing were presented at the May 2014 National Research Council Phase 3 Review of the SuperTruck partnership. The three presentations are summarized here. Koberlein reported a 46 percent drag coefficient reduction when comparing the SuperTruck tractor/trailer combination to today's baseline. This was improved to 49 percent when camera cab mirrors replaced the conventional mirrors. A further improvement (49.6 percent drag coefficient reduction from the baseline) was reported for an advanced concept tractor [VT-31]. Greszler presented a breakdown, beginning from a 2009 "best in class" baseline. The drag coefficient was reduced to 80 percent of the baseline through trailer add-on devices, and to 76 percent of the baseline through tractor modifications. Co-optimizing the tractor and trailer combination reduced the drag coefficient to 70 percent of the baseline, with the longer-term integrated SuperTruck design reducing the drag coefficient to 58 percent that of the 2009 baseline [VT-32]. Finally, Kayes reported on the order of a 15 percent drag coefficient reduction with several trailer modifications. Two tractor design concepts were evaluated, each resulting in a further 15 percent drag coefficient reduction. Scale model wind tunnel tests of the full vehicle (integrated tractor and trailer concepts) resulted in a 39 percent lower drag coefficient than that of their baseline truck [VT-33].

2.4.2.3 Hybrid Drivetrains

A projection of hybrid and plug-in hybrid cost effectiveness over a range of duty cycles is included in an especially useful reference on hybrid drivetrains [VT-23]. The study focused on medium duty parcel delivery vehicles, and explored various cost scenarios pertaining to fuel, batteries, and drivetrain components.

2.4.2.4 Weight Reduction

Regarding vehicle weight reduction, a study by the Environmental Defense Fund looked at the effect of vehicle tare weight in Class 3 through 6 medium duty trucks [VT-24]. It included considerations regarding truck class downsizing on fleet operating costs. The Hausberger study cited previously [VT-20] included the impact of reducing trailer weight in heavy duty vehicles.

2.4.2.5 Improved Drivetrain Lubricants

A study conducted by researchers at Shell Global Solutions on a Mercedes Benz OM 460LA heavy-duty diesel engine run under the World Harmonized Transient Cycle (WHTC) and World Harmonized Stationary Cycle (WHSC), used a combination of a SAE 5W-30 engine oil, SAE 75W-80 gearbox oil and SAE 75W-90 axle oil. The combination yielded average fuel economy improvements of 1.8 percent over the WHTC and 1.1 percent over the WHSC, relative to a SAE 15W-40 engine oil, SAE 80W gearbox and SAE 90 axle oil [VT-27]. The baseline lubricants represent current mainstream products, and the new lubricants were top-tier formulations focusing on modified viscometric effects. Using the WHSC cycle, significant variations in the individual lubricant contribution under different speed and load conditions within the cycle were identified. Additionally, an average fuel economy improvement of 1.8 percent was observed using medium-duty trucks under a range of typical European driving conditions in a controlled field trial.

2.4.2.6 Improved Transmission Shifting

A report by Stanton describes the Cummins High Efficiency, Clean Combustion program (HECC) for the 15L ISX engine and the 6.7L ISB engine [VT-28]. Among the technologies assessed, an additional two to three percent fuel economy improvement was achieved through engine down speeding, transmission shift pattern, and proper selection of axle ratio.

2.4.2.7 Electrified Accessories

In a Hyundai heavy duty vehicle study, various cooling system improvements were assessed. One of the improvements was that of replacing the engine-driven fan with a variable speed electric fan. The authors reported a nearly ten percent fuel economy improvement through reduced fan speed and the ability to shut the fan off over a driving cycle [VT-29].

2.5 References

Note that where available, web links to the referenced documents have been included. These links were active at the time the document was written, but web addresses may change or be eliminated over time.

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3.0 PERFORMANCE ANALYSIS OF TECHNOLOGIES FOR BEYOND MODEL YEAR 2018

This section contains an evaluation of fuel saving technologies that are expected to be available for implementation beyond model year 2018. Engine, vehicle, and trailer technologies are included in the evaluation. SwRI used Polk data to determine popular engine and vehicle models in the various segments when benchmarking/testing engines and vehicles for prior programs. As a result, data from these engines and vehicles was available to inform the current simulation effort. In one case, the Ford F-650 tow truck, the vehicle was selected despite being a relatively low volume vehicle for two reasons: because it extended the range of vocational trucks towards the smaller, lighter end of the market, and because extensive test data was available to input to the simulation model.

With information from NRC 2010, the literature review, and meetings with industry stakeholders, the staffs at SwRI, NHTSA, EPA, and CARB used their engineering judgment to select feasible engine and vehicle technologies for performance analysis. In a few cases, potentially promising technologies such as hybrids or RCCI technologies could not be simulated as they were beyond the technical capabilities of the software and/or the program lacked access to physical test data (prior engine/vehicle testing) from which to develop models. Other technologies such as continuously variable transmissions and variable compression ratio gasoline engines were left out because they have not yet been demonstrated for the vehicle classes under consideration, and are not expected to be commercially viable in the time frame for this study.

Engine technologies have been evaluated for both diesel engines and gasoline engines. Due to their low market penetration and the need for extensive experimental data to calibrate the simulation models, natural gas engines, other alternative fuels, and dual fuel engines are beyond the scope of this study. The engine technology evaluations were conducted using GT-Power, which is a commercially available one dimensional (1-D) engine modeling tool. GT-Power models of the engines were built and calibrated using actual engine test data. The GT models were then used to explore a range of potential engine technologies.

Two basic diesel engine models were selected for the project. The 6.7 liter Cummins ISB engine is used at high volume in ¾ ton Class 2b and one ton Class 3 Ram pickup trucks, and is also the most popular engine in medium-duty trucks through Class 7 and into the low end of Class 8. The ratings of this engine are quite different between medium-duty trucks and pickup trucks, so we modeled two different calibrations. The medium-duty rating is 300 HP @ 2500 RPM, while the pickup rating is 385 HP @ 3000 RPM. The pickup rating is chassis certified, so it does not use EGR at full load.

The 14.8 liter Detroit DD15 is a popular heavy-duty truck engine for Class 8 long haul operation, and the 2011 version that serves as our baseline met the 2014 GHG requirements in SwRI's benchmarking tests. To cover the range of displacements used in Class 2b through Class 8, we developed some derivatives of these base engines. We created a 4.5 liter 4-cylinder version of the ISB. We also generated a 12.3 liter 5-cylinder version of the DD15. Because of the level of effort involved in creating and calibrating GT-Power models, we used derivatives of our two basic diesel engines rather than creating entirely new GT models of different engines to

cover the desired displacement range. There is a 4-cylinder version of the ISB in production, so our model of that engine matches an actual production engine. The 12.3 liter version of the DD15 does not exist, however. Instead of this version, we could have modeled the 12.8 liter DD13, but we lacked the design data required to build GT models of this engine. We also lacked the test data required to calibrate GT models of this engine. We believe our approach of doing a smaller version of the DD15 provide realistic approximations of the true performance of engines in their size range, which can achieve the same objective of evaluating downsizing impact.

Gasoline engines are used today by all OEMs in Class 2b and 3 vehicles. Ford currently offers a gasoline engine in Class 4 through 7 trucks up to 30,000 pounds GVWR. Gasoline engines have one huge advantage in the Class 2b to Class 7 market: initial cost. In a heavy-duty pickup, the diesel engine option typically costs the customer about $8,000 above the base gasoline engine. In a model year 2014 Ford F-650 Class 6 truck, the diesel engine is a $9,216 option. Other advantages of gasoline engines include a wider operating speed range, lower price fuel, lighter weight, and, in many cases, higher horsepower ratings.

The disadvantages of gasoline engines in Class 2b – 7 trucks include higher fuel consumption (measured on a fuel volume basis, e.g. MPG). Gasoline engines also have lower maximum torque values and reduced durability compared to diesel engines. This section will explore technologies that could reduce the fuel consumption disadvantage of gasoline engines. Turbocharging can reduce the torque disadvantage of gasoline engines. The durability disadvantage stems from two primary sources: gasoline engines operate at higher temperatures, and existing medium-duty gasoline engines were originally designed for Class 2b and 3 applications, not for heavier Class 4 - 8 applications.

The fuel consumption penalty is inherent in the operating cycle of gasoline engines, and in the lower energy content per unit volume of gasoline compared to diesel fuel. A gallon of diesel fuel contains about 16% more chemical energy than a gallon of E10 gasoline [Energy.gov, 2014]. The same reference states that the CO_2 emissions from a gallon of gasoline are about 14% lower than for a gallon of diesel, so energy content and CO_2 emissions are very tightly linked for these two fuels. The combination of lower peak torque, higher peak power, and a wider operating speed range are typical features of gasoline engines. High peak power and a wide operating speed range can be advantages, but many heavy-duty applications require a higher peak torque than currently available gasoline engines can deliver.

The durability issue faced by gasoline engines is largely based on two factors. The first is the higher temperatures experienced in a stoichiometric combustion engine. The second factor is that the engines used in these trucks are derived from engines originally developed for light duty applications. It is possible to design a more durable gasoline engine, although that would erode the price advantage to some degree. High levels of cooled EGR can be used to reduce the temperatures experienced in stoichiometric combustion, although it is generally not possible to get diesel-like temperatures without experiencing misfire issues. Up to this time, OEMs have evidently found that there is not enough volume potential in a heavy-duty gasoline engine intended specifically for Class 4 – 7 applications to justify the development of one. Existing GM, Ford, and Chrysler heavy-duty gasoline engines were developed for (and with the exception of Ford) are only applied in Classes 2b and 3. Ford has expanded the application range of their

6.8 liter V-10 up into Class 7. Using information from the separate cost report that is included with this project, it is clear that the cost increment for an upgraded gasoline engine with EGR and a 3-way catalyst is far lower than that of a diesel engine with SCR and DPF. SwRI believes that the large price difference between gasoline engines with simple 3-way catalyst aftertreatment, compared to diesel engines with expensive HPCR fuel systems and SCR + DPF aftertreatment, may in the future lead to more gasoline engines being developed for and used in medium-duty vehicles (Classes 4 – 7). This is particularly likely if the fuel consumption and durability issues of heavy-duty gasoline engines can be improved.

Two gasoline engine GT-Power models were developed for this project. One model is a 6.2 liter V-8 engine with port injection. This naturally aspirated engine is now used in Class 2b and 3 applications. This engine could in the future be developed for heavier duty applications. The other GT model is of a 3.5 liter V-6 with turbocharging and direct injection. This engine is now applied to Class 2a trucks, but future versions could be developed for heavier duty applications. We did not develop any other versions of these two models to represent different displacements.

The Kenworth T700 Class 8 tractor trailer truck, the Kenworth T270 Class 6 box delivery truck, and the Ford F-650 Class 5 tow truck were selected for the program because extensive vehicle test data was available from an EPA program. This data was used to calibrate the vehicle simulation models. These trucks are also good representatives of medium- and heavy-duty trucks. The T270 and F-650 were modeled using the Cummins ISB engine that they come standard with. The T700 offers both PACCAR and Cummins engines, but this vehicle was simulated with the Detroit Diesel DD15. This engine could be used in the T700, but for business reasons it is not. The DD15 was used for this study because of the extensive engine benchmarking data that is available.

While engine technologies have been simulated in substantial detail, this study takes a different approach to vehicle technologies. In this study, the fuel consumption sensitivity of the vehicle to various forms of power demand reduction is explored, without attempting to simulate specific features. Therefore, reductions in Cd and Crr are assumed, in line with values that the literature suggests are feasible. In other cases, available but proprietary experimental data was employed, such as for transmission and axle mechanical efficiency.

Note that all results presented in this report are in terms of percent change in fuel consumption, not fuel economy. Fuel consumption units align well with the units used in EPA and NHTSA GHG and fuel consumption regulations.

Table 3.1 below summarizes how the selected vehicles and engines fit into the US vehicle classification system, and Table 3.2 summarizes the fundamental characteristics of the engine in their baseline form.

TABLE 3.1 VEHICLE AND ENGINE CLASSIFICATION

Class	Vehicle	Diesel	Gasoline	Base Transmission
2b	Ram Pickup	Cummins 6.7 Liter 385 HP (base), 4.5 Liter 256 HP	3.5 L V-6, 6.2 L V-8	6-Speed Automatic
3				
4				
5	F-650 Tow Truck	Cummins 6.7 Liter 300 HP (base), 4.5 Liter 256 HP	3.5 L V-6, 6.2 L V-8	5-Speed Automatic
6	T270 Box Truck			
7				
8	T700 Tractor-Trailer	Detroit 14.8 L DD15 (base), 12.3 L Derivative	None	10-Speed AMT

TABLE 3.2 ENGINE CHARACTERISTICS

Engine	Displacement Liters	Rated HP @ RPM	Torque Peak lb-ft @ RPM	Best BSFC g/kW-hr	Other
ISB Pickup	6.7	385 @ 3000	850 @ 1600	198.6	Part load EGR
ISB MD	6.7	300 @ 2500	750 @ 1300	207.8	Full time EGR
V-6	3.5	370 @ 5500	420 @ 3500	238.0	Turbo, DI
V-8	6.2	316 @ 5500	400 @ 4200	236.5	NA, PFI
DD15	14.6	485 @ 1800	1650 @ 1240	185.7	Turbocompound

3.1 Technology Lists

A wide range of both engine and vehicle technologies were explored in this project. These technologies are listed in tabular form below. Additional details are provided in Appendix A (gasoline engine technologies), Appendix B (diesel engine technologies), Appendix C (vehicle technologies), and Appendix D (waste heat recovery systems).

3.1.1 Engine Technologies

The tables below list technologies that were applied to the engines in the program. There are limited combustion related technologies in this list, since GT-POWER is not capable of modeling these technologies with any degree of confidence, unless extensive experimental data is available to calibrate the model. Examples of combustion technologies left out of the study include low temperature diesel combustion and dual fuel engines. In the literature, combustion technologies have generally been shown to offer benefits in the 1 to 2% range (see Section 2).

TABLE 3.3 ENGINE TECHNOLOGIES EVALUATED ON THE DD15

Technology	Hardware Content	Comments
1. Baseline DD15	Production 2011 DD15	Complies with 2014 GHG requirement, but with zero margin
2. Optimized Mechanical Turbocompound	Downsized power turbine	Attempt to improve BSFC at cruise, at the expense of high RPM
3. Optimized Electrical Turbocompound	Delete power turbine gear train, add electrical generator and electric motor	Decouples power turbine speed from crankshaft speed. Power fed back to crank via electric motor
4. No EGR	Remove EGR cooler, valve, and plumbing. Turbocharger resized to match.	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be very challenging
5. Turbocompound Removed	Remove power turbine, turbine gear train, and plumbing. Turbocharger resized to match.	Still a single stage, fixed geometry turbo. Unable to flow adequate EGR below 1400 RPM, so would require very high SCR efficiency
6. EGR and Turbocompound Removed	Delete EGR and turbocompound hardware. Turbocharger resized to match	Still a single stage, fixed geometry turbo. Would require a very high conversion efficiency SCR to meet NOx requirement
7. Asymmetric Turbo	Delete turbocompound, add fixed geometry turbo with asymmetric volute, drive EGR from only cylinders 1-3	Represents 2014 DD15. Only half the engine suffers from negative Δp required to flow EGR. This technology is covered by a Daimler patent, so other OEMs would need to license it or design around it.
8. Reduced Exhaust Backpressure	Higher flow capacity aftertreatment, engine unchanged	Determine BSFC sensitivity to exhaust restriction
9. Reduced Inlet Restriction	Higher flow capacity intake system, engine unchanged	Determine BSFC sensitivity to intake restriction
10. Reduced CAC Restriction	Higher flow capacity charge air cooler, engine unchanged	Determine BSFC sensitivity to charge air cooler restriction
11. Reduced Engine Friction	Variable speed water pump, variable displacement oil pump, on/off piston cooling, reduced piston/ring/liner friction, low viscosity lube	Assume a FMEP reduction of 10% at high speed and load, increasing to 35% at low speed, light load, where cooling needs are reduced
12. High Efficiency Turbo	Upgrade fixed geometry turbo efficiency by 10% (half compressor, half turbine).	Determine BSFC sensitivity to turbo efficiency. Note that additional technology would be required to maintain EGR flow if desired, such as turbocompound or an intake throttle
13. No EGR, No Turbocompound, High Efficiency Turbo	Delete EGR and turbocompound systems, upgrade turbo efficiency by 10% (half compressor, half turbine)	Determine effect of turbo efficiency on a non-EGR engine. Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue.
14. Downspeed A	No hardware change	Increase low speed torque, reduce rated speed, maintain PCP limit and maximum engine power. Operate engine at lower speed during cruise
15. Downspeed B	No hardware change	A more radical version of Downspeed A. Both versions of downspeeding involve changes to vehicle gearing, but are classified as an engine technology for this report
16. Downsize, Constant Torque	higher BMEP (See Appendix B for details)	Vehicle performance not affected. Engine loads increased.
17. Downsize, Constant BMEP	same BMEP as baseline (See Appendix B for details)	Power and torque reduced 16.7%
18. Variable Valve Train	Add VVT hardware	Variable valve lift and duration
19. Water-Based Bottoming Cycle	EGR and exhaust heat exchangers, expander, condenser, pump	See Appendix B for details
20. R-245 Based Bottoming Cycle	EGR and exhaust heat exchangers, expander, condenser, pump	See Appendix B for details

TABLE 3.4 ENGINE TECHNOLOGIES EVALUATED ON THE ISB 6.7 MEDIUM-DUTY ENGINE

Technology	Hardware Content	Comments
21. Baseline ISB	Production 2012 ISB	Most popular MD truck engine
22. Reduced Exhaust Restriction	Higher flow capacity aftertreatment, engine unchanged	Determine BSFC sensitivity to exhaust restriction
23. Reduced Engine Friction	Variable speed water pump, variable displacement oil pump, on/off piston cooling, reduced piston/ring/liner friction, low viscosity lube	Assume a FMEP reduction of 10% at high speed and load, increasing to 35% at low speed, light load, where cooling needs are reduced
24. EGR Removed	Remove EGR cooler, valve, and plumbing. Turbocharger resized to match.	Would require a very high conversion efficiency SCR to meet NOx requirement. OBD could be a major issue
25. High Efficiency Turbo	Upgrade turbo efficiency by 10% (half compressor, half turbine)	Determine BSFC sensitivity to turbo efficiency.
26. 8-Cylinder Version	Log-style exhaust manifold, rescaled turbo size, unchanged combustion parameters, EGR rate, and AFR.	Lower peak torque and rated speeds to reflect typical 9 liter engine ratings
27. Variable Valve Train	Add VVT hardware	Variable valve lift and duration. This technology was dropped due to disappointing results. The technology is described in Section 1.2 of Appendix A

TABLE 3.5 ENGINE TECHNOLOGIES EVALUATED ON THE ISB 6.7 ENGINE FOR CLASS 2B/3 PICKUPS

Technology	Hardware Content	Comments
28. Baseline ISB	Production 2012 ISB for Ram	Higher power and torque than MD version, no EGR at high loads, chassis certified
29. Reduced Exhaust Restriction	Higher flow capacity aftertreatment, engine unchanged	Determine BSFC sensitivity to exhaust restriction
30. High Efficiency Turbo	Upgrade turbo efficiency by 10% (half compressor, half turbine)	Determine BSFC sensitivity to turbo efficiency.
31. Reduced Engine Friction	Variable speed water pump, variable displacement oil pump, on/off piston cooling, reduced piston/ring/liner friction, low viscosity lube	Assume a FMEP reduction of 10% at high speed and load, increasing to 35% at low speed, light load, where cooling needs are reduced
32. 4-Cylinder Version	Log-style exhaust manifold, resized single-entry turbo, unchanged combustion parameters, EGR rate, and AFR.	Constant BMEP, so power and torque are reduced by 1/3 from baseline.

TABLE 3.6 ENGINE TECHNOLOGIES EVALUATED ON THE 3.5 LITER V-6 TURBO GDI

Technology	Hardware Content	Comments
33. Baseline 3.5 V-6	2012 Ford EcoBoost 3.5 used in F-150 (Class 2a)	Not used in heavier applications yet, but the potential is there; used as a representative of a downsized, boosted engine for heavier duty applications
34. Variable Valve Train with Cam Phaser	Add VVT and cam phaser hardware	Variable valve lift and duration, plus valve event phasing. This technology is much more promising on gasoline engines
35. Cylinder Deactivation	Cylinder deactivation hardware for OHC engine	Operate engine on 3, 4, or 6 cylinders as required. Gives light load benefit
36. Lean Burn GDI	SCR or other NOx aftertreatment	Requires NOx aftertreatment. Exhaust temperature is a problem
37. Stoich EGR	Low pressure loop EGR system, EGR valve and cooler, high energy ignition	High energy ignition needed to ignite dilute air/fuel mixture
38. EGR + Downspeed	Requires higher cylinder pressure capability	Increase low speed torque, reduce rated speed, increase cylinder pressure. Operate engine at lower speed during cruise. Higher BMEP to retain vehicle performance and rated power
39. Reduced Engine Friction	Variable speed water pump, variable displacement oil pump, on/off piston cooling, reduced piston/ring/liner friction, low viscosity lube	Assume a FMEP reduction of 10% across the range, given the higher level of past friction reduction work on gasoline engines compared to diesel
40. High Efficiency Turbo	Upgrade turbo efficiency by 10% (half compressor, half turbine)	Determine BSFC sensitivity to turbo efficiency.

TABLE 3.7 ENGINE TECHNOLOGIES EVALUATED ON 6.2 LITER PORT-INJECTED V-8

Technology	Hardware Content	Comments
41. Baseline 6.2 V-8	2012 6.2 V-8 used in Class 2b / 3 pickup trucks	Not used in heavier applications yet, but the potential is there
42. Convert to GDI	GDI fuel system	No change to power and torque
43. Lean Burn GDI	SCR or other NOx aftertreatment	Requires NOx aftertreatment. Exhaust temperature is a problem. Rated power maintained by going rich at full load
44. Variable Valve Train with Cam Phaser	Add VVT and cam phaser hardware	Variable valve lift and duration, plus valve event phasing. Value of cam phasers also evaluated
45. Cylinder Deactivation	Cylinder deactivation hardware for OHC engine	Operate engine on 4 or 8 cylinders as required. Gives light load benefit
46. Stoich GDI EGR	Low pressure loop EGR system, EGR valve and cooler, high energy ignition	High energy ignition needed to ignite dilute air/fuel mixture
47. Reduced Engine Friction	Variable speed water pump, variable displacement oil pump, on/off piston cooling, reduced piston/ring/liner friction, low viscosity lube	Assume a FMEP reduction of 10% across the range, given the higher level of past friction reduction work on gasoline engines compared to diesel

3.1.2 Vehicle Technologies

The tables below list technologies that were applied to the vehicles in the program.

TABLE 3.8 VEHICLE TECHNOLOGIES EVALUATED ON RAM PICKUP (CLASS 2B / 3)

Technology	Hardware Content	Comments
A. Baseline Ram	ISB diesel, 6-speed automatic transmission	Coastdown results (Cd and Crr values) from the 2007 Ram 2500, powertrain data from 2011
B. 6.2 V-8 Port Injected	Replace ISB diesel with baseline gasoline V-8	
C. 3.5 V-6 Turbo GDI	Replace ISB diesel with baseline gasoline V-6	
D. Reduced A/C Power Demand	Combination of increased cab insulation, reduced reheat, more efficient compressor	Assumed a 40% power demand reduction from a baseline A/C power demand of 1.5 kW
E. Improved Cd	Radiator shutters, belly pan, cab and bed tweaks	Assumed 25% Cd reduction
F. Improved Crr	Low rolling resistance tires	Assumed 30% Crr reduction
G. Transmission Upgrade	Replace baseline 6-speed automatic with 8-speed	Modified shift schedule and gearing with the 8-speed to improve fuel economy and at least maintain vehicle performance
H. Weight Reduction	Material substitution – 500 pounds	Weight difference between engines also included
I. Chassis and Driveline Friction	Synthetic lube, improved axle efficiency, improved bearings	Assume 30% chassis friction reduction
J. Hybrid Systems	TBD	To be in Final Report #2

TABLE 3.9 VEHICLE TECHNOLOGIES EVALUATED ON KENWORTH T270 BOX TRUCK (CLASS 6)

Technology	Hardware Content	Comments
K. Baseline T270	ISB diesel engine, Allison 5-speed automatic	13' 2" X 102" delivery box height X width. Coastdown data available from EPA project.
L. 6.2 V-8 Port Injected	Replace ISB diesel with baseline gasoline V-8	
M. 3.5 V-6 Turbo GDI	Replace ISB diesel with baseline gasoline V-6	
N. Reduced A/C Power Demand	Combination of increased cab insulation, reduced reheat, more efficient compressor	Assumed a 40% power demand reduction from a baseline A/C power demand of 1.5 kW
O. Improved Cd	Roof fairing, cab-to-box fairing, side skirts	Assumed 15% Cd reduction
P. Improved Crr	Low rolling resistance tires	Assumed 30% Crr reduction
Q. Automatic Transmission Upgrade	Replace baseline 5-speed automatic with 8-speed	Modified shift schedule and gearing with the 8-speed to improve fuel economy and at least maintain vehicle performance
R. AMT Alternatives	6-speed and 10-speed AMT	Compare to automatics
S. Weight Reduction	Material substitution – 1000 pounds	Weight difference between engines also included
T. Chassis and Driveline Friction	Synthetic lube, improved axle efficiency, improved bearings	Assume 30% chassis friction reduction
U. Hybrid Systems	TBD	To be in Final Report #2

TABLE 3.10 VEHICLE TECHNOLOGIES EVALUATED ON FORD F-650 TOW TRUCK (CLASS 6)

Technology	Hardware Content	Comments
V. Baseline F-650	ISB diesel engine, Allison 5-speed automatic	Tow truck equipment mounted on chassis. Coastdown data available from EPA project.
W. 6.2 V-8 Port Injected	Replace ISB diesel with baseline gasoline V-8	
X. 3.5 V-6 Turbo GDI	Replace ISB diesel with baseline gasoline V-6	
Y. Reduced A/C Power Demand	Combination of increased cab insulation, reduced reheat, more efficient compressor	Assumed a 40% power demand reduction from a baseline A/C power demand of 1.5 kW
Z. Improved Cd	Front air dam, cab tweaks, side skirts	Assumed a 10% Cd reduction
AA. Improved Crr	Low rolling resistance tires	Assumed a 30% Crr reduction
BB. Automatic Transmission Upgrade	Replace baseline 5-speed automatic with 8-speed	Modified shift schedule and gearing with the 8-speed to improve fuel economy and at least maintain vehicle performance
CC. AMT Alternatives	6-speed and 10-speed AMT	Compare to automatics
DD. Weight Reduction	Material substitution – 1000 pounds	Weight difference between engines also included
EE. Chassis and Driveline Friction	Synthetic lube, improved axle efficiency, improved bearings	Assume 30% chassis friction reduction
FF. Hybrid Systems	TBD	To be in Final Report #2

TABLE 3.11 EVALUATION OF TRACTOR AND TRAILER TECHNOLOGIES ON KENWORTH T-700 TRACTOR (CLASS 8)

Technology	Hardware Content	Comments
GG. Baseline T-700	DD15 diesel engine, 10-Speed Eaton AMT, 53' box van trailer	SmartWay tractor, standard (NOT SmartWay) trailer. Coastdown data available from EPA project.
HH. Reduced A/C Power Demand	Combination of increased cab insulation, reduced reheat, more efficient compressor	Assumed a 40% power demand reduction from a baseline A/C power demand of 1.5 kW
II. Improved Cd	Trailer: full skirt, boat tail, gap reducer. Tractor: cameras replace mirrors, radiator shutters, gap reducing fairings, skirt over drive axles, under - chassis air flow mgmt. devices	Assumed a maximum of 25% Cd reduction, and also calculated benefits for 5%, 10%, 15%, and 20% Cd reduction
JJ. Improved Crr	Low rolling resistance tires	Assumed a 30% Crr reduction
KK. Weight Reduction	Material substitution and redesign of cab and chassis components – 6.5% and 13% weight reductions	1000 and 2000 kg (2200 and 4400 pound) reductions
LL. Chassis and Driveline Friction	Synthetic lube, improved axle efficiency, improved bearings	Assume 20% chassis friction reduction in the tractor
MM. 6X2 Axles	Replace 6X4 with 6X2	Remove friction of one drive axle. Single drive axle is more efficient than front axle of a tandem
NN. Road Speed Governor	Use existing feature	Evaluate unlimited vs. 65, 60, and 55 MPH limits
OO. 18-Speed AMT	Replace 10-speed with 18-speed	Smaller splits allow the engine to stay in higher efficiency zones
PP. Manual Transmission	Replace AMT with manual	Shift points 200 RPM higher than AMT

3.2 Modeling Methodology

The engines and engine technologies were modeled in GT-Power, which is a commercially available simulation tool. Each baseline model was calibrated using experimental engine data. In many cases, detailed combustion heat release data was available from engine testing. This allowed heat release to be input directly into the model, rather than estimated by GT. We also used actual turbocharger efficiency maps as an input, although these maps were not necessarily from the engine being simulated. The turbo maps were scaled up or down to achieve the required air flow for each specific engine technology we simulated.

One dimensional CFD tools such as GT-Power have certain advantages and limitations. Some advantages relative to 3-D CFD tools include:

- Rapid solution time
- Accurate calculation of engine air flows, pressures, and temperatures (provided the input geometry data is correct)
- Very useful for predicting the effects of basic parameters such as compression ratio, combustion timing, air/fuel ratio, intake and exhaust restriction, etc.
- Very useful for determining required turbocharger match
- Fairly accurate representation of overall fuel consumption and CO_2 emissions (typically within +/- 3%)
- More accurate representation of small changes in fuel consumption and CO_2 as a result of a technology change (differences of less than 1% can often be reliably predicted)

Areas of weakness in tools like GT-Power include:

- Unreliable predictions of NOx, PM, and other criteria emissions
- Predictions of combustion parameters such as rate of heat release are simplified unless experimental data is available to use as an input. Because of that, the prediction on combustion related technologies, such as LTC and RCCI would not be as reliable as prediction of air handling system technologies.
- Predictions of turbocharger performance are based on the maps that are provided to the program, which sometimes do not reflect real-life performance on the engine. Can be improved if measured engine data is available to baseline and tweak the turbo maps to match actual, on-engine turbo performance.

One issue with simulating turbocharger performance is the fact that turbo efficiency maps are measured on a gas stand. The gas stand has steady flow, unlike the pulsating flow of an actual engine. As a result, the gas stand will miss performance that is a function of fluctuating flow, such as the benefit of a dual entry turbine housing, which utilizes the pulsation energy from blow-down pluses in the exhaust manifold. If engine test data is available, the turbo performance maps determined on a gas stand can be modified to reflect actual on-engine performance.

To overcome the weaknesses of GT-Power, SwRI used measured combustion heat release data whenever it was available. All of the engine models used measured heat release for the baseline technology, and in many cases, experimental data was available for specific technologies that had an effect on combustion. Except in specific cases that are noted in the discussion, EGR rates and air/fuel ratios were controlled to match the baseline engine performance. Technologies that would affect heat release rates and combustion duration will have effects on efficiency that are not captured in the GT-POWER models used in this project. Technologies where assumptions had to be made regarding combustion are noted in the results section. SwRI also used actual turbocharger performance maps as a basis, and scaled them to match given engines and technologies. This approach provides turbocharger performance that matches at given points and has the right characteristics across the engine speed/load range. Having data on a full family of turbochargers that would be applied to the engine being simulated would be even better. Unfortunately, full turbo map data was not available for all of the engine permutations in our study.

For each engine and engine technology, the GT-Power model was run over a range of speed and load conditions. The resulting fuel consumption and CO_2 data were used to create a fuel consumption map. The map provides projected fuel consumption over a range of 20 speeds and 20 loads, for a total of 400 data points. Not all of these data points were actually simulated – many were generated by interpolation between simulated speed/load points. Appendix A and B provide details on the number of speed/load points that were simulated for each engine. The 20 X 20 point fuel maps were then provided to the vehicle simulation tool to represent the engine performance. In addition to the fuel maps, the full load torque curve and motoring torque curve (the torque required to spin the engine with zero fuel) were provided to the vehicle simulation tool.

Note that all engine simulations are done for steady state operating conditions. During transient operating conditions such as a shift event or accelerator pedal position change, the engine may not have the same torque capability and efficiency as it does at steady state. On highly transient drive cycles, this can lead to an over-estimation of vehicle performance and efficiency. Modeling of complete engine and vehicle performance during transients is possible, but very time consuming. For this large study that evaluates many technologies, transient simulation was judged to be too time consuming to perform.

Appendix A includes details of each gasoline engine model, including sources of input data and comparisons to experimental results. The assumptions made for each technology are also described. Appendix A also includes the fuel map results for each gasoline engine and technology. Appendix B includes the same information for the two diesel engines.

Vehicles and vehicle technologies were modeled using the SwRI Vehicle Simulator tool. This MATLAB-based tool is similar to the NREL tool called Advisor. The Vehicle Simulator tool is a deterministic model (has no randomness) and has the ability to handle a wide range of vehicle technologies including automatic transmissions, automated manual transmissions, hybrid systems, etc. One advantage of the SwRI tool is that features can easily be ported to the GEM tool. Any desired drive cycle can be put into the Vehicle Simulator tool. The following drive cycles were used for this program:

TABLE 3.12 VEHICLES AND DRIVE CYCLES USED IN STUDY

Vehicle	Drive Cycles
Ram Pickup	FTP City, FTP Highway, US06, SC03, WHVC, 65 MPH
T270 Box Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
F-650 Tow Truck	GEM Cycles, CILCC, Parcel Delivery Cycle, WHVC
T-700 Tractor	GEM Cycles, WHVC, NESCCAF Long Haul Cycle

The cycles listed above are described in detail in Appendix C. The current version of GEM includes 3 cycles. One is a low speed urban cycle developed by CARB. The second is a constant 55 MPH with no grade or wind. The final cycle is a 65 MPH constant speed with no grade or wind. For the 55 and 65 MPH cycles, only data from the steady-state portion of the cycle is reported. The US06 and SC03 cycles are carried over from light-duty applications. Since heavy-duty pickup trucks are often used as a car, it is appropriate to evaluate their performance on car-like drive cycles. The acronym CILCC stands for Combined International Local and Commuter Cycle. The parcel delivery cycle was derived from the operations of a Class 6 parcel delivery truck in the US market. The CILCC and Parcel Delivery cycles were used to represent the local operations that are typical for many vocational trucks.

WHVC stands for World Harmonized Vehicle Cycle. This cycle is intended for medium- and heavy-duty vehicles, and includes a low speed urban segment, a moderate speed suburban segment, and a highway cruise segment. The highway segment of the WHVC does not include grade or wind, and the speeds on this segment reflect the European practice of installing road speed governors on trucks to limit maximum vehicle speed to 90 km/h (56 MPH). The WHVC is the only cycle other than the GEM cycles that were applied across the complete range of Class 2b through Class 8 vehicles. The NESCCAF long haul cycle includes brief urban/suburban segments and 4 extended highway cruise segments at 65 to 70 MPH. One of highway cruise segments includes a cyclic grade of +/- 1%, and another highway cruise segment includes a cyclic grade of +/- 3%. Like all the other cycles, the NESCCAF cycle does not include the effect of any wind.

The reason for exploring several duty cycles is to develop an understanding of how different engine and vehicle technologies perform across a range of drive cycles. Certain technologies may be insensitive to payload or drive cycle, while others can be extremely sensitive. One of the questions to be explored by this study is whether the existing GEM cycles do an adequate job of covering the range of drive cycles experienced in the field.

Appendix C describes the input data required by the SwRI Vehicle Simulator tool. In most cases, SwRI used measured data from test vehicles and components, or information provided by OEMs and component suppliers as inputs. In certain cases, such as axle and transmission efficiency, SwRI used test data from other SwRI projects as inputs to the simulation. This existing data is proprietary to SwRI and its specific clients, and was not created or derived from federally funded work. In these limited cases, SwRI cannot provide the actual input data used in the simulation runs.

One of the many inputs required by the SwRI Vehicle Simulator tool is the transmission shift schedule. For automatic and automated manual transmissions, the shift schedule can be relatively straightforward. It can be measured directly in vehicle or powertrain testing, or it can be provided by the transmission manufacturer. Determining shift schedules for manual transmissions is more difficult. Different drivers may have dramatically different shifting habits, which will have a substantial effect on fuel consumption. Extensive recording of driver performance in the field would be required to arrive at either an "average driver" shift schedule, or a range of shift schedules that covers most of the driver population. Since this data was not available, we have simulated manual transmissions in this report by adding 200 RPM to the upshift points of the automated manual transmission. This offset is an attempt to reflect typical driver behavior. In order to provide consistency when evaluating engine and vehicle technologies, the AMT transmission with programmed shift schedules was used as the baseline for all runs.

One factor that is neglected in the simulation is the weight increases that result from adding efficiency technologies to the vehicle. Some technologies, such as low rolling resistance tires, can be weight neutral or even a weight reduction. Other technologies, such as aerodynamic features and waste heat recovery systems, definitely add weight. Unfortunately, good weight estimates for many technologies are not available in the literature, so the simulations performed in this project do not adjust weight for most technologies. If a reader would like to take into account the impact of a known or assumed weight increase, the vehicle fuel consumption sensitivity to changes in weight is provided for all vehicles.

The situation is simple for any vehicle not operating at the legal weight limit. For example, if vehicle fuel consumption increases 0.7% for every 1,000 pound weight increase, there would be a fuel penalty of 0.35% for a 500 pound weight increase. However, if the vehicle is operating at the weight limit, then payload must be reduced to stay within the weight limit. Consider the example of a tractor-trailer with an empty weight of 34,000 pounds, running at the legal limit of 80,000. In this case, an increase in empty weight of 500 pounds has no effect on vehicle fuel consumption, because the loaded vehicle weight is unchanged. However, the empty weight increase will raise load-specific fuel consumption by about 1.1%, because payload is reduced by about 1.1%. This example shows how the impact of a weight increase is greater if the vehicle is operating at maximum weight, when payload must be reduced.

Another factor that is not considered in the simulation is the fuel required to maintain the performance of the emissions aftertreatment system. This includes fuel used to achieve rapid light-off of the aftertreatment during a cold start, fuel used for thermal management to keep the aftertreatment at the desired temperature during light load operation, and fuel used to regenerate the aftertreatment to prevent plugging or excessive sulfur loading. Getting an accurate prediction of the fuel used for these purposes requires an extensive understanding of the complex control strategies employed. These strategies vary greatly from one manufacturer to another, and reverse engineering of these strategies is a difficult challenge. As a result, this study did not explore fuel consumption related to aftertreatment operation.

3.3 Results

This section will cover the results of the engines and vehicle types listed in Sections 3.1.1 and 3.1.2. Results presented in this report are in terms of percent reduction in fuel consumption (also called percent fuel savings). These results translate directly into percent reduction in grams of CO_2 or gallons of fuel per hp-hr, as well as grams of CO_2 or gallons per 1000 ton-miles, which are the units used in the Phase 1 regulations.

3.3.1 Class 8 Tractor-Trailer Truck Engine Technology Results

Class 8 tractors are typically powered by 11 to 16 liter engines. For standard 80,000 pound long haul applications, 15 liter engines such as the Cummins ISX and Detroit DD15 tend to predominate in terms of sales volume, but there are also 13 liter engines used in this market that are supplied by Volvo, Navistar, Detroit Diesel and PACCAR. The Kenworth T-700 vehicle simulated for this project was chosen because it was used in an EPA program looking at Phase 2 GHG regulation test methodologies. As a result, a substantial amount of test data was available to calibrate the simulation model. This data is summarized in Appendix E. The T-700 is a SmartWay certified tractor, with extensive aerodynamic treatment. The trailer used for the simulation, however, was a basic 53 foot box van trailer with no aerodynamic treatment and with standard (not low rolling resistance) tires. This combination reflects the type of vehicle that will comply with the 2018 GHG and fuel consumption requirements.

The Kenworth T-700 is sold with many ratings of two basic engines: the PACCAR MX-13 (a 12.9 liter engine) and the Cummins ISX (a 15 liter engine). The Detroit DD15 engine used in this study is not offered in the T-700, but it has performance comparable to the ISX, and the DD15 is certainly an engine that *could* be applied in the T-700. The DD15 was chosen because of data available from a SwRI benchmarking program that was performed on a 2011 DD15. The Kenworth T-700 tractor and standard 53 foot box van trailer used to acquire the experimental coast-down data that was used to calibrate the simulation model are shown in Figure 3.1 below.

FIGURE 3.1 KENWORTH T-700 TRACTOR AND STANDARD 53 FOOT BOX VAN TRAILER

3.3.1.1 Results for Baseline Kenworth T-700 / DD15 Tractor-Trailer Vehicle

The tractor-trailer combination was run at the following payloads and combined vehicle weights: 0% payload and a vehicle weight of 33,960 pounds, 50% payload (23,020 pounds of payload) and a vehicle weight of 56,980 pounds, and 100% payload (46,040 pounds of payload) and a vehicle weight of 80,000 pounds. Figure 3.2 shows the *fuel economy* performance of the baseline vehicle, across all 5 drive cycles and 3 payloads. Figure 3.3 shows the same results, but in terms of *fuel consumption*. All of the remaining results in Section 5.3.1 will be given in terms of percent difference in *fuel consumption* compared to the baseline performance. The same data is presented in tabular form in Tables 3.11 and 3.12 below.

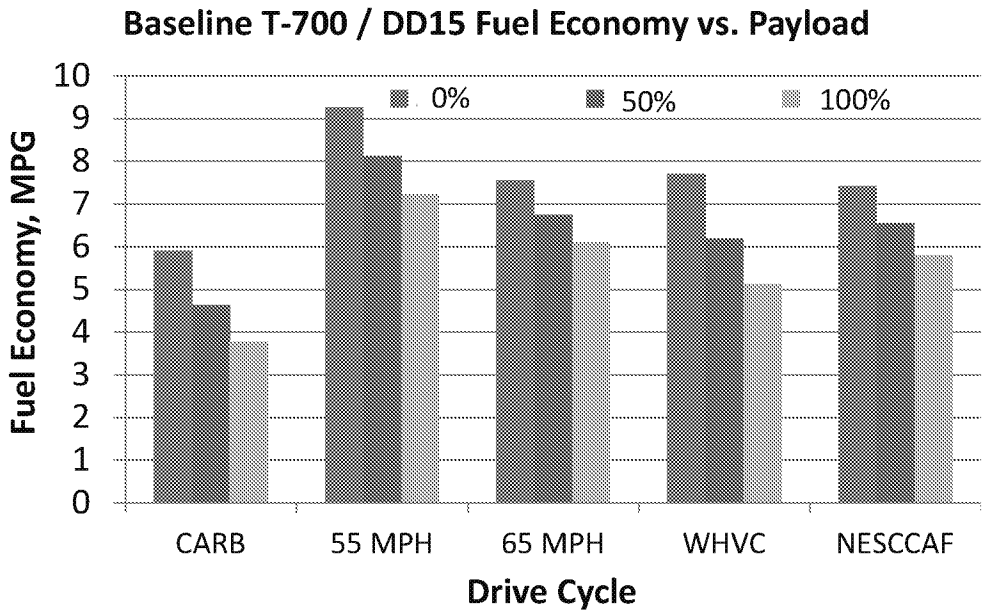


FIGURE 3.2 BASELINE T-700 / DD15 FUEL ECONOMY IN MPG AS A FUNCTION OF PAYLOAD

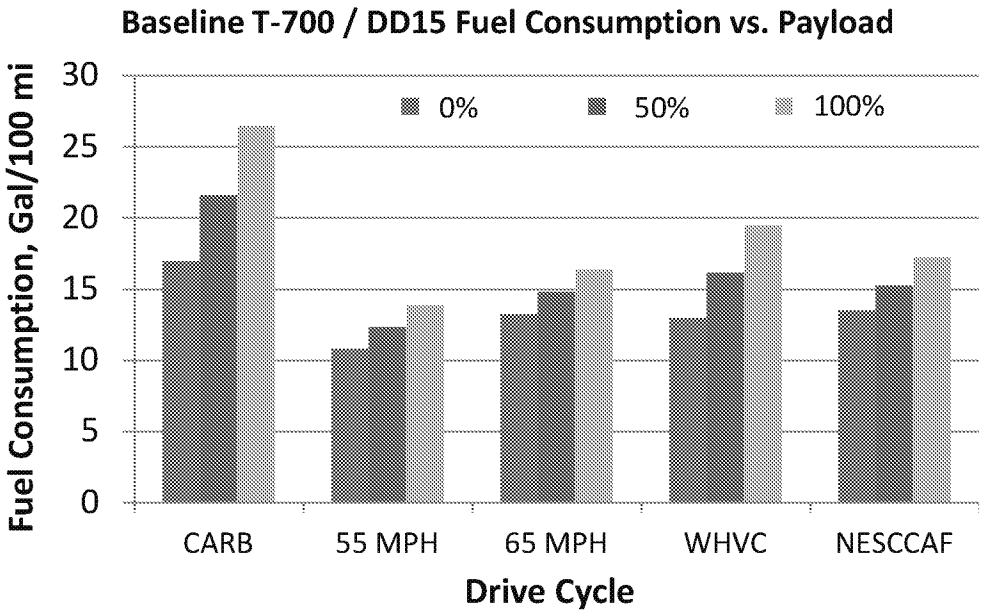


FIGURE 3.3 BASELINE T-700 / DD15 FUEL CONSUMPTION IN GALLONS PER 100 MILES AS A FUNCTION OF PAYLOAD

TABLE 3.13 FUEL ECONOMY OF THE BASELINE T-700 / DD15 VEHICLE IN MPG

	MPG @Percent Payload		
Drive Cycle	0%	50%	100%
CARB	5.90	4.63	3.78
55 MPH	9.26	8.12	7.22
65 MPH	7.55	6.75	6.11
WHVC	7.71	6.2	5.13
NESCCAF	7.42	6.56	5.80

TABLE 3.14 FUEL CONSUMPTION OF THE BASELINE T-700 / DD15 VEHICLE IN GALLONS/100 MILE

	Gallons/100 mi. @Percent Payload		
Drive Cycle	0%	50%	100%
CARB	16.9	21.6	26.5
55 MPH	10.8	12.3	13.9
65 MPH	13.2	14.8	16.4
WHVC	13.0	16.1	19.5
NESCCAF	13.5	15.2	17.2

3.3.1.2 Summary of DD15 engine technology results in T-700 truck

The engine technologies listed in Tables 3.13 and 3.14 above were all evaluated using the baseline tractor-trailer configuration. Appendix B describes the details of the DD15 model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technologies.

Table 3.15 below summarizes the results of engine technology simulations. Results are provided for each technology on 5 drive cycles. Each drive cycle is run at 3 payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 15 data points for each of the 17 technologies that were evaluated. The results shown are in terms of percent reduction in fuel consumption compared to the baseline production 2011 DD15 engine GT model.

TABLE 3.15 FUEL SAVINGS RESULTS OF DD15 ENGINE, USING THE BASELINE T700 TRACTOR-TRAILER

Technology	Fuel Consumption Reduction (Percent) On Drive Cycle and at Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
2. Opt. TCPD	0.7	0.6	0.4	0.7	0.7	0.8	0.6	0.6	0.6	0.7	0.6	0.5	0.4	0.4	0.3
3. Elec. TCPD	0.9	0.9	0.8	0.8	0.9	1.0	0.8	0.9	1.0	0.9	0.9	0.9	0.8	0.9	0.8
4. No EGR	0.1	0.3	0.5	0.6	0.7	0.7	0.5	0.6	0.7	0.2	0.4	0.5	0.5	0.6	0.7
5. No TCPD	1.5	1.2	0.9	0.9	0.7	0.7	1.3	1.2	1.1	1.3	1.0	0.8	1.3	1.0	1.0
6. No EGR or TCPD	1.7	1.6	1.5	1.6	1.6	1.6	2.0	2.0	2.0	1.6	1.5	1.4	1.9	1.7	1.7
7. Asym. Turbo	1.6	1.3	1.0	1.0	0.8	0.8	1.4	1.3	1.2	1.4	1.1	0.9	1.3	1.1	0.9
8. Low Back Pres.	0.3	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.5	0.3	0.4	0.4	0.4	0.5	0.5
9. Low Intake Rest.	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
10. 0 CAC Rest.	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
11. Reduced FMEP	6.1	4.6	3.7	3.8	3.1	2.7	2.4	2.1	1.9	5.3	3.9	3.1	2.8	2.3	2.0
12. + 5% Turbo Eff	2.4	2.3	2.2	2.3	2.4	2.5	2.8	2.8	2.9	2.3	2.3	2.2	2.6	2.5	2.5
13. No EGR, no TCPD, +5% T	2.4	2.5	2.5	2.5	2.5	2.7	3.0	3.1	3.2	2.4	2.5	2.5	2.8	2.8	2.8
14. Downspeed A	5.0	3.9	3.0	3.2	2.7	2.3	2.3	2.0	1.5	4.4	3.4	2.7	3.1	2.4	2.1
15. Downspeed B	5.7	4.2	3.3	0.1	0.8	1.1	4.5	4.0	3.6	4.0	3.1	2.5	5.0	3.8	3.4
16. Downsized Torque	5.0	3.7	2.9	2.3	1.8	1.6	2.3	2.0	1.8	4.1	2.9	2.3	2.5	2.0	1.7
17. Downsized BMEP	5.6	3.9	2.5	2.1	1.5	0.8	1.7	1.6	0.3	4.2	2.7	1.7	2.5	1.9	2.0
18. VVA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19. Water BC	N/A	N/A	N/A	3.7	4.1	4.4	4.3	4.6	4.8	N/A	N/A	N/A	4.2	4.7	5.0
20. R245 BC	N/A	N/A	N/A	2.6	2.8	2.9	2.5	2.7	2.8	N/A	N/A	N/A	2.4	2.6	2.6

One technology listed in Table 3.3 does not have results shown in Table 3.15. The benefits from a study of variable valve lift and duration at a few engine operating points were disappointing, with fuel savings of under 1%. This result may come as a surprise to those with spark ignited engine experience, where VVA is much more effective, but this result is typical for diesel engines [NESCCAF, 2009]. Given the substantial effort involved in developing a new fuel map with VVA (the valve events must be optimized separately at every operating condition), the decision was made to not progress this technology to a full engine map and vehicle simulation evaluation. See Appendix B for more details.

The results shown in Table 3.15 can be presented in graphical form. To simplify the graph, only results for the 50% payload are shown in Figure 3.4 below. The maximum Y-Axis value of 16% is used to maintain consistency with later plots of vehicle technology results.

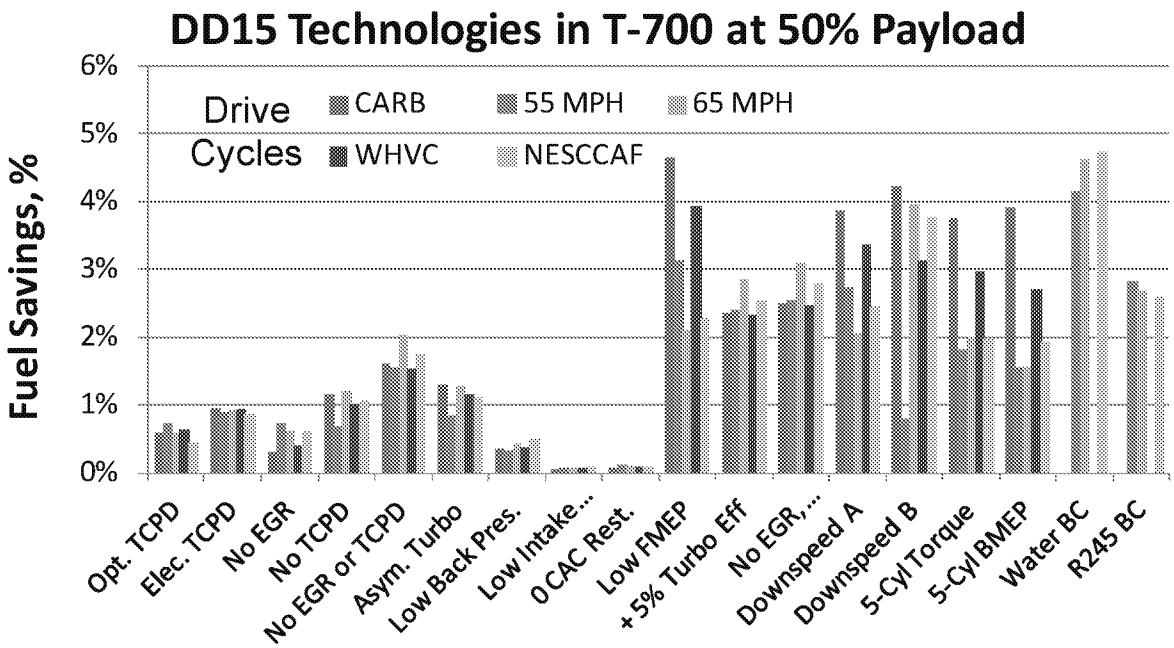


FIGURE 3.4 FUEL SAVINGS RESULTS OF DD15 ENGINE, USING BASELINE T-700 TRACTOR-TRAILER

In the following subsections, each engine technology is given its full name in the section heading, along with the abbreviated name used in Table 3.15 and Figure 3.4. The abbreviations are provided in parentheses.

3.3.1.3 Technology #2, Optimized Turbocompound (Opt. TCPD)

The Optimized Turbocompound technology represents an effort to modify the base engine by going to a power turbine that is downsized, in an effort to extract more exhaust energy at cruise conditions. The penalty for this is higher backpressure (and thus pumping loss) on the engine at high speed and load. In the simulated drive cycles, the engine rarely operates near rated speed, so this penalty is insignificant. Nevertheless, as the results in Table 3.15 and Figure

3.4 show, the benefit from downsizing the turbocompound is small (under 1%), regardless of the drive cycle.

3.3.1.4 Technology #3, Electric Turbocompound (Elec. TCPD)

An electric turbocompound uses the output of the power turbine to drive a generator. The electricity is then used to drive an electric motor which is connected to the crankshaft. This allows the power turbine speed to be independent of engine speed, which helps achieve better efficiency across a wider portion of the engine operating range. However, as the results presented above show, the fuel consumption and GHG benefit is limited to 0.8% to 1% on all of the drive cycles.

3.3.1.5 Technology #4, No EGR

Driving EGR flow in an engine requires pumping work. The exhaust manifold pressure must be maintained higher than the intake manifold pressure in order for EGR to flow. Removing EGR has two benefits: pumping work can be reduced, and combustion heat release rates will increase. In the case of the DD15 engine, however, removing EGR does not eliminate much pumping work, because the power turbine keeps exhaust manifold pressure high. As a result, removing EGR has only a marginal benefit on this engine – less than 1%. Note that this no-EGR technology involves very high engine-out NOx, which in turn requires a very high SCR conversion efficiency and high urea consumption, which could present significant challenges in OBD.

3.3.1.6 Technology #5, Turbocompound Removed (No TCPD)

For 2013, Detroit removed the turbocompound system from one version of the DD15. SwRI simulated this approach in two steps. In the first step, we removed the turbocompound system, but retained a standard dual entry fixed geometry turbocharger and the EGR system. This technology is labeled "No TCPD" in the table and figure above. The turbo was rematched to accommodate the removal of the turbocompound power turbine. This configuration is not able to flow EGR at lower engine speeds. One option is to add an intake throttle to drive EGR flow. This approach would increase fuel consumption at lower engine speeds, due to pumping losses. The other alternative is a higher conversion efficiency SCR and higher urea consumption, which is the option modeled here. It is something of a surprise that removing the turbocompound system provides a slight fuel consumption benefit of 0.7% to 1.5% on all drive cycles and at all payloads. Note, however, that none of the evaluated drive cycles and payloads require the engine to operate at full load for a significant period of time. In the past, several researchers have found benefits from adding turbocompound (See Section 2), but a recent paper from Daimler describing the new version of the DD15 [MTZ 2013] provides experimental data similar to SwRI's simulation results.

3.3.1.7 Technology #6, EGR and Turbocompound Removed (No EGR or TCPD)

Once the turbocompound system is removed, the engine can benefit from not requiring backpressure to drive EGR flow. This technology simulation determined that the benefit, assuming no changes in turbocharger efficiency, approaches 2%. Note again that this no-EGR technology involves very high engine-out NOx, which in turn requires a very high SCR conversion efficiency and high urea consumption.

3.3.1.8 Technology #7, Asymmetric Turbo (Asym. Turbo)

This technology is a simulation of the 2013 model DD15 recently introduced by Detroit. In this version, there is no turbocompound. The conventional dual entry turbocharger is replaced by an asymmetric dual entry, fixed geometry turbocharger. One turbine volute is substantially smaller than the other. The small volute imposes a backpressure on the front 3 cylinders, enabling EGR flow from these three cylinders. The back 3 cylinders are able to run with a positive intake to exhaust pressure ratio, also known as a positive Δp. There is a wastegate on the larger turbine volute, which can be modulated to retain the desired back pressure on the front 3 cylinders, so that they achieve the required EGR flow. This technology provided results 0.8% to 1.6% better than the baseline across the range of drive cycles and payloads. Note that none of the simulated drive cycles and payloads require full engine power for a significant period of time. It should be noted that this technology approach is currently unique to Detroit (Daimler) engines in the heavy-duty industry. All other manufacturers use a variable geometry turbocharger to regulate the manifold pressure ratio and thus EGR flow.

3.3.1.9 Technology #8, Reduced Exhaust Backpressure (Low Back Pres.)

Engine efficiency can be improved by reducing restrictions on air flow. Modern aftertreatment systems impose higher back pressure on the engine than the muffler-only systems used before 2007. For this technology simulation, exhaust back pressure was reduced by about 60%. This amount of back pressure reduction would be very difficult to achieve in production feasible hardware, but even with the very optimistic reduction in back pressure, the effect was 0.5% or less for all drive cycles and payloads.

3.3.1.10 Technology #9, Reduced Inlet Restriction (Low Intake Rest.)

This simulation evaluated the effect of lower restriction through the intake air system, air filter, and plumbing connecting to the turbocharger compressor inlet. A 50 – 60% reduction in restriction was modeled. Very small benefits (under 0.1%) were found for all drive cycles and payloads.

3.3.1.11 Technology #10, Reduced Charge Air Cooler Restriction (0 CAC Rest.)

The charge air cooler system includes the plumbing from the turbocharger compressor outlet to the charge air cooler, and then back to the intake manifold. A 50 – 60% reduction in restriction was modeled, and extremely small benefits (around 0.1%) were found for all drive cycles and payloads.

3.3.1.12 Technology #11, Reduced Engine Friction (Low FMEP)

Assuming a reduction in FMEP ranging from 10% at high speed and load, to 35% at low speed and light load (see Appendix B, page 33 for details), significant benefits were found. The benefits are duty cycle and payload dependent. Low speed, low average power demand cycles such as the CARB cycle show the biggest benefit, exceeding 6% at zero payload. High average power demand cycles such as 65 MPH cruise and the NESCCAF cycle show a 2% to 2.5% benefit, less than half the benefit found on the CARB cycle. For all drive cycles, the largest benefit occurs with zero payload, and the smallest benefit at 100% payload. This result is to be expected, since at light load the FMEP makes up a greater portion of overall engine output.

3.3.1.13 Technology #12, High Efficiency Turbo (+5% Turbo Eff.)

SwRI applied an assumption of a 5% increase in both compressor and turbine efficiency, under all operating conditions, resulting in an overall turbocharger efficiency increase of 10%, not 10 points (for example, from 50% to 55% overall efficiency). This technology provides a fuel savings of 2.2 – 2.9% across all drive cycles and payload levels. Turbocharger efficiency can be improved with different bearing technology, tighter wheel to housing clearances, and other features. SwRI is aware of some experimental turbochargers that around 10% more efficient than current products, but none for which published results are available. The benefit of increased turbo efficiency is linear. As a result, if a 2% overall improvement is obtained, the fuel savings will be about 20% of the values provided in this report. More discussion can be found in Appendix B.

3.3.1.14 Technology #13, No EGR, No Turbocompound, High Efficiency Turbo (No EGR, TCPD, +5%T)

This simulation represents a combination of three technologies. The EGR system and turbocompound systems are removed, and a high efficiency turbocharger replaces the original turbocharger. The turbo efficiency increase is the same as in Technology #12, but in this case the turbo is rematched to work without a turbocompound system. The benefit of this technology is 2.4 to 3.2% fuel savings. The performance of the technology is slightly higher on the high power demand cycles, such as the 65 MPH cruise. Note that this no-EGR technology involves very high engine-out NOx, which in turn requires a very high SCR conversion efficiency and high urea consumption. Achieving very high conversion efficiency across the entire operating range is a significant technical challenge. Providing OBD functionality that can detect any problems such a system with sufficient resolution is an even larger challenge.

3.3.1.15 Technology #14, Downspeed A

The engine torque curve was modified to generate higher torque at low speed, and the maximum engine speed was reduced. Details of the engine BSFC map are provided in Appendix B. The current cylinder pressure limit of just over 200 bar was retained. The vehicle's axle ratio was modified from 3.36 to 2.97 to reduce cruise RPM from 1368 RPM to 1209 RPM at 65 MPH, while retaining approximately the same power margin at the 65 MPH cruise point. Details of the changes are shown in Appendix C. The downspeeding strategy had the largest benefits on the low speed drive cycles and at zero payload, where benefits over 4% can be found. The value at high speed and load is closer to 2%.

3.3.1.16 Technology #15, Downspeed B

Downspeed strategy B is more radical than Downspeed A. The peak torque RPM was pushed down to 1000 RPM, and torque was increased again. The rated engine speed was reduced to 1600 RPM. Details of the engine BSFC map are provided in Appendix B. The vehicle's axle ratio was modified from the baseline of 3.36 to 2.58 to reduce cruise RPM to 1051 RPM at 65 MPH, while retaining approximately the same power margin at the 65 MPH cruise point. Downspeed B provided larger fuel saving benefits under all drive cycles except for the 55 MPH cruise and the WHVC. At 55 MPH, the vehicle needed to run a gear down compared to Downspeed A, which resulted in a smaller fuel savings than was achieved by Downspeed A. The WHVC high speed cruise portion is also at low road speed (about 50 MPH), so Downspeed B runs that a gear down. The savings at 55 MPH were still in the 1 to 2% range.

3.3.1.17 Technology #16, Downsize at Constant Torque

The DD15 model was downsized to 12.5 liter. The goal is to reduce displacement, and thus engine friction. At light loads, the smaller size engine operates at higher BMEP than the 15 liter engine, which provides an efficiency benefit. For this configuration, the smaller engine retains the same power and torque as the original, which means that full load BMEP levels are increased. Vehicle performance in this case is unchanged. There is often a fuel consumption penalty at high BMEP, because timing must be retarded to limit cylinder pressure. The extent of the timing retard, and the BMEP level at which a retard is required, are functions of the cylinder pressure limit of a given engine. As expected, this technology provides the largest benefits (up to 5%) in the low speed CARB drive cycle at zero payload. At high speeds and loads, the benefit drops under 2%.

3.3.1.18 Technology #17, Downsize at Constant BMEP

This technology is similar to #16, except that the torque curve is reduced to keep maximum BMEP equal to that of the original 15-liter 6-cylinder engine. As a result, vehicle performance will suffer due to a 17% reduction in power and torque. On the 5 drive cycles and 3 payloads evaluated, this configuration provided fuel savings similar to or slightly lower than those of Technology #16.

As a simple metric for the penalty of a lower power rating, consider the minimum speed reached on the 3% grade segment of the NESCCAF cycle. For a vehicle at 100% payload, the minimum speeds on a 3% grade are:

Baseline DD15	46.3 MPH
Downsized DD15	36.9 MPH

The vehicle was able to follow the remaining drive cycles without an issue, despite the reduction in available power and torque. In real-world driving, there would be penalties on acceleration times and speeds on a grade. For the NESCCAF cycle, the cycle time is lengthened for the lower power engine, so that the vehicle covers the same distance, but at a slightly lower average speed.

3.3.1.19 Technology #18, Variable Valve Actuation (VVT)

VVT was explored in the GT-POWER model of the engine, but the fuel consumption benefits were very small (well under 1%). Given the high cost of the system and the intensive analysis to optimize VVT over the whole operating range, VVT was dropped from the project. It should be noted, however, that VVT can be of value in providing thermal management (increased heat) for the aftertreatment system. There are several alternatives for thermal management, including an intake throttle, retarded ignition timing, and changes in exhaust valve opening timing (from a VVT system). The VVT approach may be the lowest fuel consumption approach to thermal management, but exploring this approach was outside of the project scope.

3.3.1.20 Technology #19, Water-Based Bottoming Cycle (Water BC)

A bottoming cycle is a Rankine cycle heat engine that in this case extracts energy from the EGR stream and the post-aftertreatment exhaust stream. Water is boiled with EGR and exhaust heat. The water drives an expander (turbine or piston expander) to extract power. A condenser located at the front of the truck condenses the post-expansion steam back into water. A pump then drives the water under pressure back to the boiler. Details of the bottoming cycle, including assumptions about heat exchangers, temperatures, and pressures, are in Appendix D. Because bottoming cycles have very poor transient response, and the simulation model does not have transient capability, the simulation results are only reported for cycles with extensive steady state components. On these cycles (55 MPH, 65 MPH, and NESCCAF), the water based bottoming cycle provides a benefit of 4.1 to 4.7%.

Note that a bottoming cycle system adds significant hardware, and thus weight, to the truck. This analysis does not include the effect of increased weight. On the test cycles run, this effect will be very small. However, for operators who run at the maximum legal weight, the addition of a bottoming cycle will reduce their payload, and thus the freight efficiency, compared to the performance shown here. Another important note is that while all other engine technologies are compared to the baseline DD15 engine, the bottoming cycle results are based on the asymmetric turbo technology (5.3.1.8). This is because the turbocompound system is a method of extracting energy from the exhaust, as is a bottoming cycle. The performance of the bottoming cycle is compromised if there is another energy extraction feature in front of it.

3.3.1.21 Technology #20, R245 Refrigerant-Based Bottoming Cycle (R245BC)

R245 is an alternative material that avoids the freezing issue of a water-based system. R245 has a high GHG factor, so there are other materials with similar thermodynamic properties that are under development. From a thermodynamic perspective, however, a model using R245 should represent the performance of these alternative materials. The main thermodynamic difference between water and R245 is that the refrigerant has a low temperature limit. To stay under that limit, a much higher mass flow is used in the bottoming cycle system. Because bottoming cycles have very poor transient response, and the simulation model does not have transient capability, the simulation results are only reported for cycles with extensive steady state components. The efficiency of the cycle is lower with R245, because of the lower operating temperature. See Appendix D for details. On the drive cycles of interest (55 MPH, 65 MPH, and NESCCAF), the R245 bottoming cycle provides fuel savings of 2.6% to 2.8%. These results are lower than results reported in the SuperTruck program. At least one of those bottoming cycles includes a recuperator, which should increase the performance of the cycle. This feature will be evaluated in the second project report.

3.3.2 T-700 Class 8 Tractor-Trailer Truck Vehicle Technology Results

The vehicle technologies listed in Table 3.9 were all evaluated using the baseline version of the DD15 engine. Appendix G describes the details of each vehicle technology, including parameters and assumptions. Performance of the baseline vehicle is described above in Figures 3.1 and 3.2, as well as Tables 3.11 and 3.12.

Table 3.14 below summarizes the simulation results for all of the vehicle technologies. Results are provided for each technology on 5 drive cycles. Each drive cycle is run at 3 payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 15 data points for each of the 10 technologies that were evaluated. The results shown are in terms of percent reduction in fuel consumption compared to the baseline production T-700 tractor-trailer vehicle model.

Note that the road speed governor, Technology NN, was only simulated on the NESCCAF cycle. The remaining drive cycles have N/A shown for the road speed governor simulation.

TABLE 3.16 FUEL SAVINGS RESULTS OF T-700 VEHICLE TECHNOLOGIES, USING THE BASELINE DD15 ENGINE

Technology	Fuel Consumption Reduction (Percent) On Drive Cycle and Percent of Maximum Payload														
	CARB			55 MPH			65 MPH			WHVC			NESCCAF		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
HH. A/C -40%	1.0	0.8	0.7	1	0.5	0.4	0.4	0.4	0.3	0.9	0.7	0.5	0.4	0.4	0.3
II. Cd - 25%	2.0	1.6	1.3	14	12	11	16	15	13	5.7	4.5	3.7	14	12	10
JJ. Crr - 30%	3.0	4.0	4.6	6	9.1	11	5.2	7.8	10	4.4	5.7	6.5	4.8	6.9	8.4
KK. Weight – 2200 lb	2.5	2.1	1.8	1.3	1.2	1.1	1.1	1.0	0.9	2.2	1.9	1.7	1.2	1.2	1.1
KK. Weight – 4400 lb	5.0	4.2	3.6	3	2.4	2.1	2.2	2.0	1.8	4.3	3.9	3.3	2.3	2.4	2.1
LL. Chassis Fr - 20%	0.5	0.6	0.6	0.9	0.9	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.8	0.8	0.8
MM. 6X2 Axles	1.3	1.4	1.4	1.7	1.7	1.6	1.7	1.6	1.6	1.5	1.5	1.5	1.6	1.6	1.5
NN. Vmax = 65	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.2	1.6	1.4
NN. Vmax = 60	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10	8.0	6.8
NN. Vmax = 55	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	18	14	12
OO. 18-spd AMT	0.5	0.4	0.2	0.5	0.7	0.8	0.7	0.8	0.8	-0.8	-0.7	-0.7	0.6	0.6	0.8
PP. 10-spd Manual	-8.3	-6.3	-5.2	-16	-13	-11	0.0	0.0	0.0	-9.3	-6.9	-5.4	-0.8	-1.1	-0.8

The results shown in Table 3.16 can be presented in graphical form. To simplify the graph, only results for the 50% payload are shown in Figure 3.5 and 3.6 below. The maximum Y-Axis value of 16% is consistent with the engine results in Figure 3.4. Again, note that the road speed governor was only simulated on the NESCCAF cycle, so the alternative road speed governor settings have only a single bar of data. A review of Figure 3.5 shows that certain vehicle technologies have a much larger effect than the engine technologies shown in Figure 3.4. It is also apparent that the fuel savings offered by most vehicle technologies is very duty cycle and payload dependent. Figure 3.6 expands the Y-axis to cover negative values. The 18-speed AMT has a slight penalty compared to the 10-speed AMT on the WHVC. This is because the 10-speed AMT runs the high speed portion of the WHVC in top gear, at approximately 1133 RPM, while the 18-speed AMT runs this portion of the cycle in 17th gear, at approximately 1335 RPM. The 10-speed manual transmission has a penalty on all cycles except the 65 MPH cruise. The largest penalty is at 55 MPH, where the manual transmission runs a gear down. Recall that there is no physical difference in gearing between the 10-speed manual and AMT transmissions. The manual has upshift speeds set 200 RPM higher than the AMT, to simulate "typical" driver behavior.

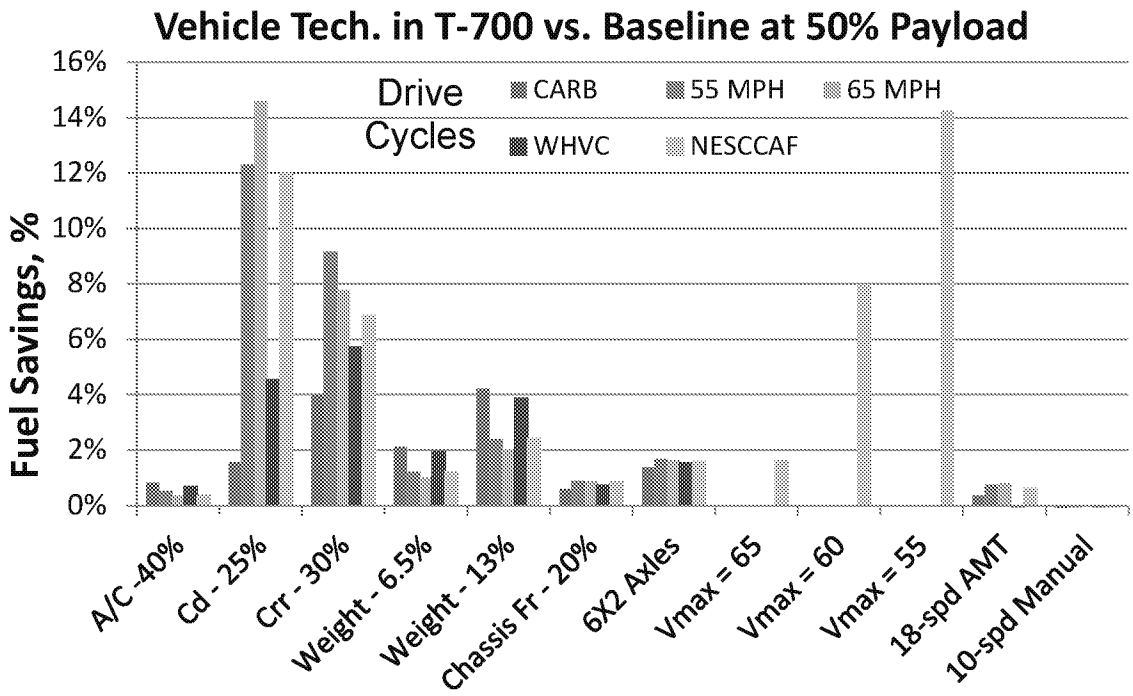


FIGURE 3.5 FUEL SAVINGS RESULTS OF VEHICLE TECHNOLOGIES IN THE T-700 TRACTOR-TRAILER, USING THE BASELINE DD15 ENGINE

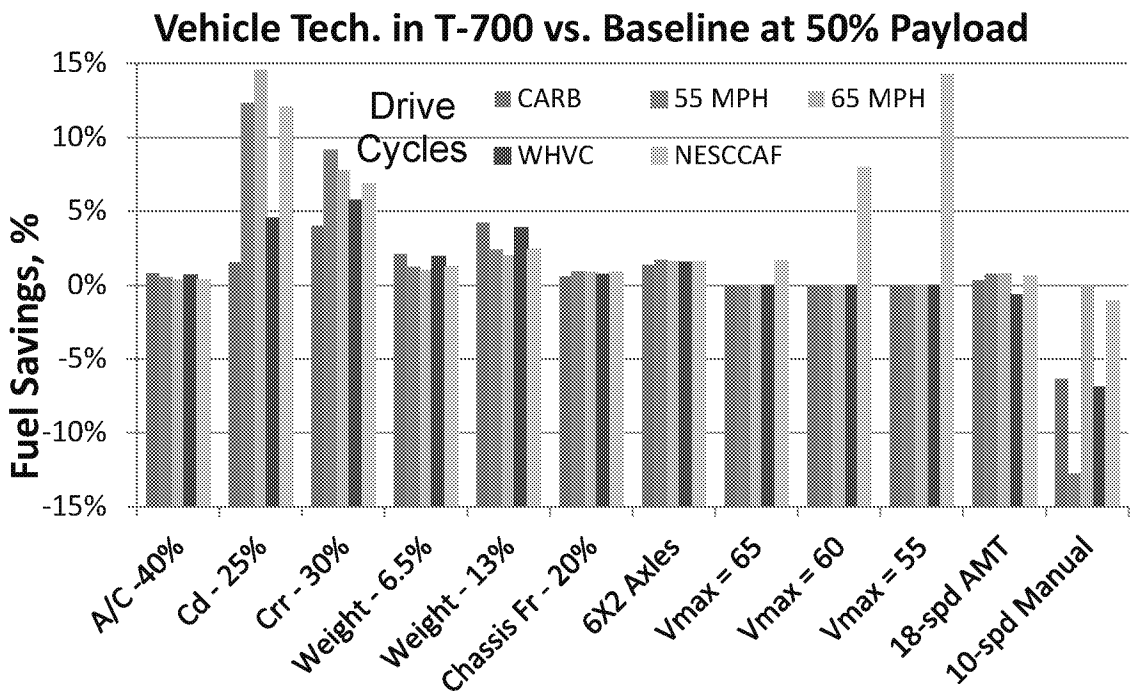


FIGURE 3.6 SAME RESULTS AS FIGURE 3.5, BUT SHOWING NEGATIVE FUEL SAVINGS VALUES FOR THE 18-SPD AMT AND THE 10-SPD MANUAL TRANSMISSIONS ON CERTAIN CYCLES

In the following subsections, each vehicle technology is given its full name in the section heading, along with the abbreviated names used in Table 3.16 and Figure 3.5. The abbreviations are provided in parentheses.

3.3.2.1 Technology HH, Reduced A/C Power Demand (A/C -40%)

For all duty cycles evaluated in this project, the air conditioner is operating. Average A/C power demand is assumed to be 1.5 Kw, and was applied as a steady load. The reduced A/C power demand technology set is assumed to reduce power demand by 40% to 900 watts. This provides a 0.3% to 1% benefit, with the largest benefit occurring on the CARB cycle at zero payload, where the average engine operating loads are the lowest. The smallest benefit is observed on the 65 MPH cruise cycle, where vehicle power demand is high. Note that in actual service, the air conditioner is not used all the time, so the real-world benefits will be less than those shown in Table 3.16. On the other hand, this technology can represent any feature that reduces auxiliary load by 600 Watts.

3.3.2.2 Technology II, Improved Cd (Cd – 25%)

This technology involves a substantial reduction in aerodynamic drag for the tractor-trailer combination. Both tractor and trailer features will be required to achieve a 25% reduction in Cd. Detailed assumptions about the features required to achieve a given level of Cd improvement are provided in Appendix C. No specific set of features is simulated here. A reduction in Cd based on the literature review was assumed, and the manufacturer is free to put together a set of features that can meet the target. The results from a Cd reduction vary widely, from a 1.3% benefit on the CARB cycle at 100% payload up to an impressive 16% at 65 MPH with zero payload. The results are also strongly dependent on payload. Light payloads reduce the power demand from tire rolling resistance and the requirement to accelerate the vehicle inertia, and this makes aerodynamic drag a larger portion of the total power demand. Aerodynamic features will provide a significant benefit on any vehicle that runs a significant portion of its mileage at high road speeds.

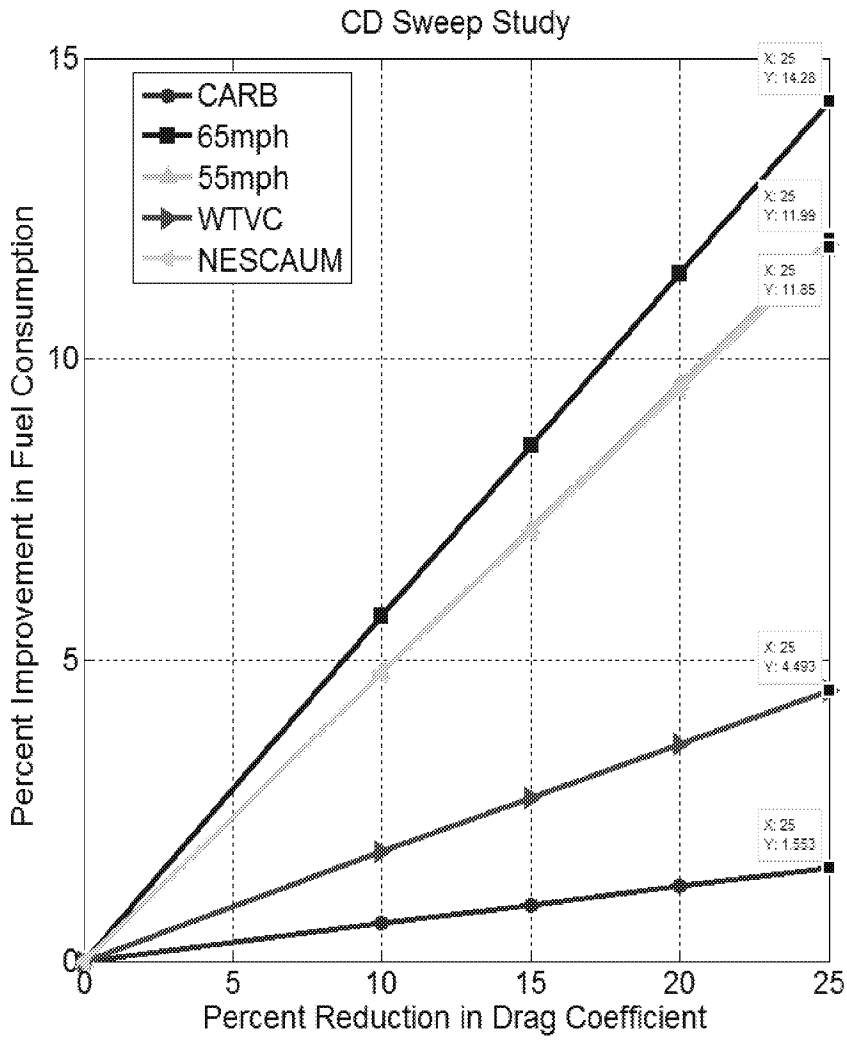


FIGURE 3.7 FUEL SAVINGS OVER A RANGE OF CD REDUCTIONS AT 50% PAYLOAD

Because of the large benefits obtained with Cd reductions, they were evaluated over a range of Cd values. These results are shown in Figure 3.7 below. A linear relationship between Cd reduction and fuel savings is shown. The first increment of Cd improvement, 10%, is based on the application of a full length trailer skirt. The 15% improvement increment assumes both a trailer skirt and boat tail. The 20% improvement increment assumes a full length trailer skirt that extends over the trailer bogey. This feature would require regulatory changes or design changes to stay within the width limit. The 20% improvement package also includes a gap reduction feature. The 25% package includes extending the tractor side skirts over the drive axles, and a feature to completely close the trailer gap. It is worth noting that most of the aerodynamic improvement features are added to the trailer, not the tractor. See Section 2 for a discussion of the potential for tractor aerodynamics separate from the trailer.

3.3.2.3 Technology JJ, Improved Crr (Crr – 30%)

This technology assumes an improvement in tire rolling resistance by 30%, based on the literature review. The specific features that would be required to achieve this improvement were not simulated. Tire rolling resistance is most important at moderate speeds in steady state operation, such as the 55 MPH cruise cycle. At higher speeds, aerodynamic drag grows, which

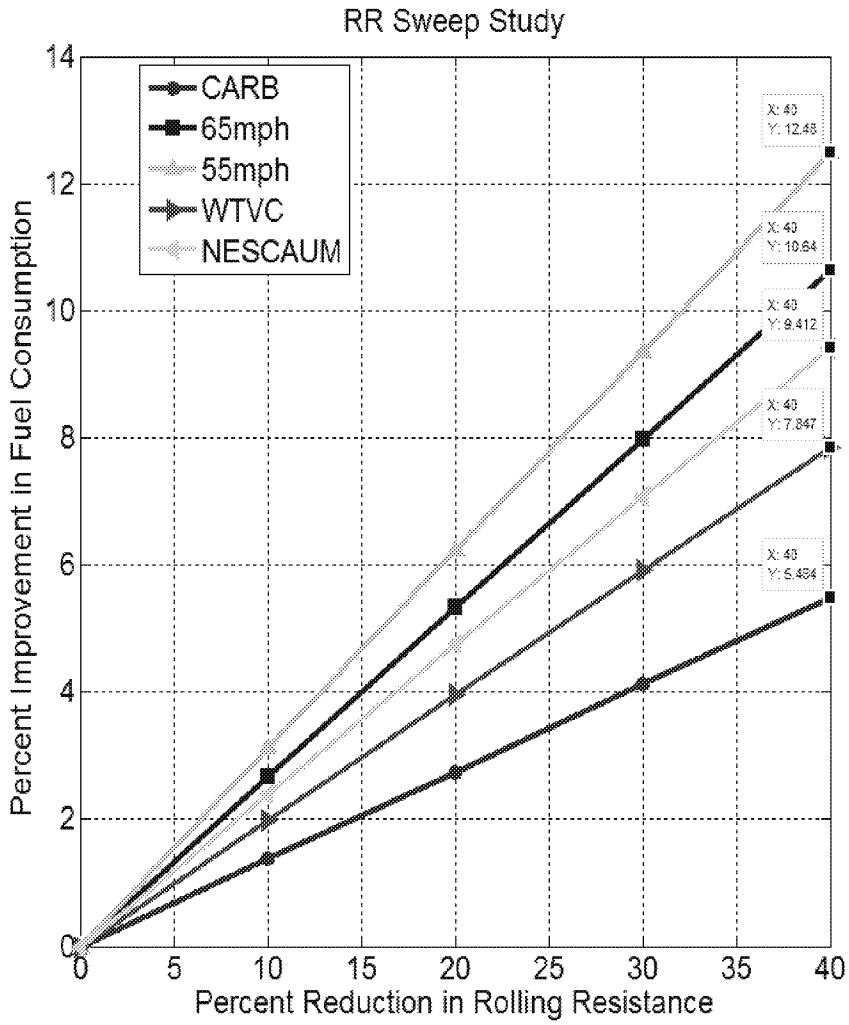


FIGURE 3.8 FUEL SAVINGS OVER A RANGE OF CRR REDUCTIONS AT 50% PAYLOAD

reduces the rolling resistance share of total vehicle power demand. In highly transient cycles such as CARB, the power required to accelerate the vehicle inertia overshadows the rolling resistance power demand. The benefit of lower Crr is very payload dependent. At 100% payload, rolling resistance plays a larger share in overall vehicle power demand than at 0% payload.

Because of the large benefits obtained with Crr reductions, they were evaluated over a range of Crr values from a 10% improvement to a 40% improvement, which is larger than the project target of 30%. These results are shown in Figure 3.8 above. A linear relationship between Crr reduction and fuel savings is shown. At 100% payload, the trailer tires carry 42.5% of the vehicle weight, so trailer tires make a substantial contribution to overall vehicle rolling resistance. With the Crr values assigned to the steer, drive, and trailer axles, 36.2% of the total vehicle rolling resistance can be attributed to the trailer tires at full payload. At zero payload, the trailer tires carry about 22% of the total vehicle weight, and account for about 17% of rolling resistance.

Some background on the math in the previous paragraph: at 100% payload, the truck weighs 80,000 pounds. Each tandem axle set (tractor tandem and trailer tandem) is allowed to carry 34,000 pounds, for a total of 68,000 pounds on the tandems. This leaves 12,000 pounds on the steer axle. The trailer tires thus carry 34,000 out of 80,000 pounds, or 42.5% of the total vehicle weight. At zero payload, the vehicle weighs 34,000 pounds total, including an empty trailer that weighs 15,000 pounds. The trailer tandem carries half the trailer weight, or 7,500 pounds. This means that the trailer tires carry 7,500 pounds out of the total of 34,000, or 22%. The rolling resistance coefficient of trailer tires is normally less than that of the tractor tires, especially the traction tires used on the drive axles, so the trailer accounts for a slightly lower percentage of total vehicle rolling resistance than the portion of vehicle weight carried by the trailer tires.

3.3.2.4 Technology KK, Weight Reduction (Weight – 2,200 lb. and Weight – 4,400 lb.)

The baseline T-700 tractor-trailer vehicle has an empty weight of 34,000 pounds. This technology simulation looked at the effect of a 2,200 and 4,400 pound weight reduction (6.5% and 13% of the empty vehicle weight). The payload weight was left unchanged, so the weight of the loaded vehicle decreased by the same amount as the empty weight. The fuel savings found were linearly proportional to the weight reduction. A 6.5% weight reduction was worth 0.9% to 2.5%, while the 13% weight reduction provided benefits from 1.8% to 5%. The benefits of weight reduction are greatest in transient operation, where lower weight translates into reduced power demand for acceleration. At steady speed, the weight reduction only affects rolling resistance. Therefore, the largest benefits are seen on the CARB cycle, and the smallest benefit is on the 65 MPH cycle. The benefit of weight reduction is linear, so an 1100 pound weight reduction will have half of the fuel savings of the 2200 pound weight reduction.

Operators who run below the maximum legal weight will see benefits from weight reduction as described in the paragraph above. Operators who run at the maximum legal load will increase payload to take advantage of a weight reduction. This means that their vehicle fuel consumption will be unchanged, but their load specific fuel consumption (gallons per 1000 ton-miles) will improve significantly. In practice, OEMs will struggle to maintain constant weight as new aerodynamic and safety features are added to trucks. Penalties for weight increases will essentially match the benefits for a weight reduction of the same size. More discussion of weight reduction technologies can be found in Appendix C.

3.3.2.5 Technology LL, Chassis and Driveline Friction Reduction (Chassis Fr -20%)

This simulation evaluates the potential for features such as improved axle efficiency, improved wheel bearings, and synthetic lubricants used in the driveline. The benefits range from 0.5% to 0.9%, with the high speed cycles showing the largest benefits.

3.3.2.6 Technology MM, 6X2 Axles

6X2 drive configurations are popular in Europe, but are just coming onto the market in North America. With the conventional 6X4 arrangement, the front axle in a tandem is less efficient than the rear axle of the tandem. This is because the front axle needs to split torque and pass along a portion of the torque to the rear axle in the tandem. There are more gear sets and oil seals in the front axle of a tandem. With the 6X2 setup, the single drive axle is basically a beefed-up version of the rear axle in a tandem pair. One significant penalty of the 6X2 setup is limited traction. Only a small portion of the total vehicle weight rests upon the drive axle. This makes 6X2 arrangements unsuitable for vehicles that need to go off road, or that frequently operate in low friction conditions. Benefits for the 6X2 configuration range from 1.3 to 1.7%. The larger benefits are on high speed cycles.

3.3.2.7 Technology NN, Road Speed Governor (Vmax = 65, Vmax = 60, Vmax = 55)

Road speed governors only have an effect on a duty cycle where the maximum vehicle speed is higher than the road speed governor setting. As a result, the road speed governor was evaluated on the NESCCAF cycle, which has cruise speeds ranging from 65 to 70 MPH. The drive cycle automatically compensated for the lower speeds by lengthening the cycle time, so that the same distance is covered regardless of cruise speed. On this cycle, a 65 MPH governor setting has only a modest benefit (1.4% to 2.2%), because the speed reduction is small. At 60 MPH, the benefits grow to a range of 6.8% to 10%, and at 55 MPH, the fuel savings range from 12% to 18%. The larger benefits are at zero payload, while the smallest benefits are at 100% payload. These fuel savings must be offset against the costs of longer trip times. If trip time does not increase, that means that speed is being limited by some factor other than the governor setting (traffic and road conditions, posted speed limits, vehicle capability, etc.). Longer trip time drives higher labor cost, and a larger number of vehicles will be required to deliver the same freight volume (ton-miles). Additional vehicles add both cost and congestion, offsetting at least some of the fuel savings from a lower governor setting.

3.3.2.8 Technology OO, 18-Speed AMT

The baseline 10-speed AMT is replaced by an 18-speed AMT to evaluate the potential benefit of closer gear splits. The narrow splits offer the potential to keep the engine closer to its best BSFC operating point. One downside of a higher gear count is more shift events. Every shift event with a manual or AMT causes a power interruption. Power interruptions reduce vehicle performance and annoy the driver. Power interruptions also have the effect of making the engine operate briefly in a less efficient transient condition. Unfortunately, since the

modeling analysis is based on steady state engine fuel maps, the effect of adding additional transients cannot be evaluated.

The 18-speed AMT provided slight benefits (<1%) on all the drive cycles except the WHVC, where it caused a slight penalty (<1%). An examination of the engine fuel map shows that there is very little benefit to the slightly narrower operating range that an 18-speed AMT provides. In field service, the frequent shifting of the 18-speed would more than offset the slight advantage on fuel efficiency in transient operating conditions. In practice, as one of many examples, the 18-speed is used in heavy haul applications, where keeping the engine at maximum power is important.

3.3.2.9 Technology PP, 10-Speed Manual

Ten speed manual transmissions dominate the long haul market today, but the market share of AMT transmissions is growing. For this study, the manual and AMT have identical gear ratios. The only difference is the addition of hardware to enable computer-controlled shifting in the AMT. AMT transmissions have the advantage of taking away shift point decisions from the driver. The very best driver using a manual transmission may be able to beat the fuel efficiency of an AMT by a small margin, but the average driver cannot match AMT performance. The worst drivers use significantly more fuel with a manual than with an AMT. In this study, the "average" driver's shift strategy was modeled by simply pushing the upshift points higher by 200 RPM compared to the AMT shift schedule. Full throttle upshifts occur at 1400 – 1500 RPM for the AMT, and 1600 – 1700 RPM for the "manual". It should be noted that the AMT shift schedule used for this study (based on the Eaton Ultrashift production shift schedule) has the effect of limiting vehicle performance, since engine power drops significantly after each upshift at 1400 to 1500 RPM. A driver interested in good performance (as opposed to good fuel economy) would use higher engine speeds to maintain power after upshifts.

At 65 MPH cruise, there is no difference between the 10-speed manual and AMT, because in both cases, the truck is running in top gear. At 55 MPH, the manual is running a gear down. The higher engine speed hurts the fuel efficiency of the manual running in 9th gear, but pushing engine BMEP down to a lower level (higher speed = lower torque) hurts efficiency even more. The efficiency penalty at 55 MPH for the manual is worst at 0% payload (16%). On the CARB and WHVC cycles, efficiency penalties of 5% to 9% are seen with the manual. On the NESCCAF cycle, the penalty is around 1%, because most of this cycle is run at higher road speed, with the transmission in top gear regardless of whether it is a manual or an AMT.

Another way of looking at the 10-speed manual results is as the inverse of the effectiveness of an AMT. To enhance the accuracy and repeatability of the vehicle simulations, the baseline vehicle was modeled with an AMT with programmed shift patterns rather than an operator-dependent manual transmission. Therefore, the inverse results for the CARB and WHVC cycles for 10-speed AMT indicate an efficiency increase of 5% to 9% over a 10-speed manual.

3.3.3 Kenworth T270 Class 6 Delivery Truck Engine Technology Results

Class 6 trucks are typically powered by 5 – 8 liter diesel engines. Ford, however, offers a 6.8 liter V-10 gasoline engine for Classes 4 – 7. Given the cost advantage of gasoline engines in medium-duty vehicles, SwRI expects that gasoline will become more popular in MD provided their efficiency and durability disadvantages can be mitigated.

Three engines are included in the evaluation of Class 2b – 6 vehicles for this study: the Cummins ISB 6.7 liter diesel, a 6.2 liter V-8 gasoline engine that is currently offered in Class 2b and 3 vehicles, and which may in time replace the older V-10 in heavier vehicles, and a Ford 3.5 liter turbocharged V-6 which is currently offered in Class 2a vehicles. The ISB diesel is considered the baseline engine for these vehicles. The Cummins ISB, branded under the PACCAR PX-7 name, is the standard engine sold in the T270 truck. Data for modeling the Kenworth T270 truck came from the example shown in the photographs below. A listing of vehicle parameters is provided in Appendix C.

FIGURE 3.9 KENWORTH T270 CLASS 6 BOX DELIVERY TRUCK

3.3.3.1 Baseline engine and vehicle results for T270 truck

The T270 truck was evaluated at the following payloads and vehicle weights: 0% payload and a vehicle weight of 17,141 pounds, 50% payload (4430 pounds of cargo) and a vehicle weight of 21,570 pounds, and 100% payload (8860 pounds of cargo) and a vehicle weight of 26,001 pounds. Figure 3.10 below shows the *fuel economy* performance of the T270 truck with the three engines in their baseline form, all evaluated at 50% payload. Figure 3.11 shows the *fuel consumption* results for the same engines and payload. The same data is provided in tabular form in Tables 3.17 and 3.18 below the figures.

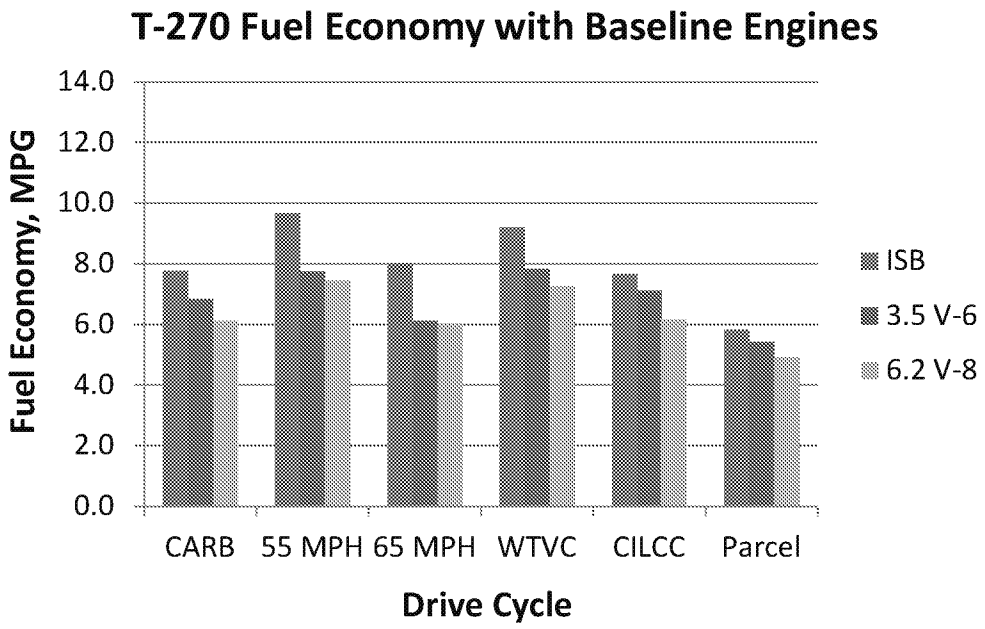


FIGURE 3.10 FUEL *ECONOMY* OF THE KENWORTH T270 BOX DELIVERY TRUCK AT 50% PAYLOAD, COMPARING THREE ENGINES

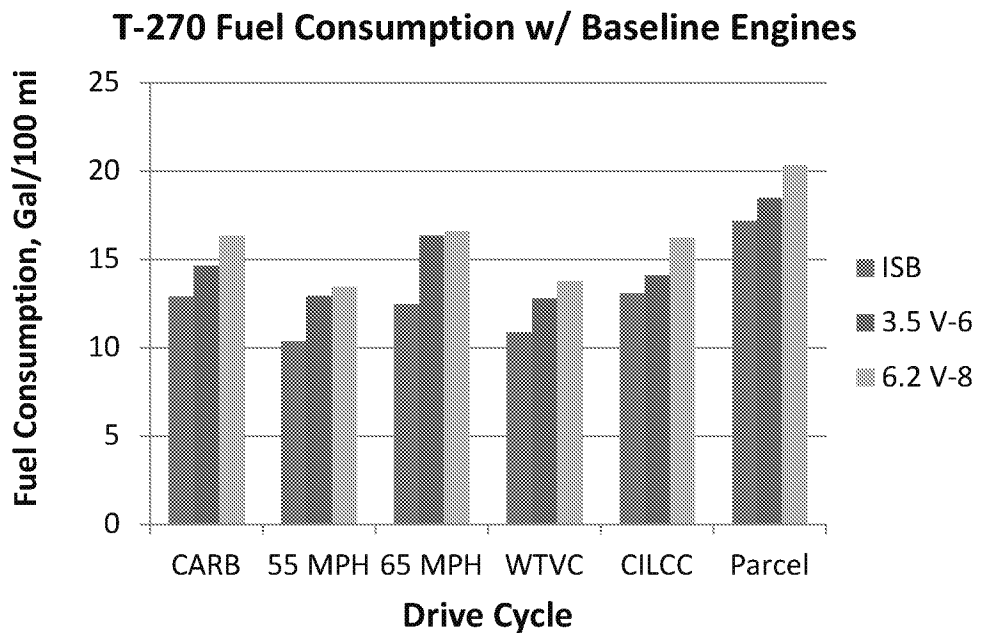


FIGURE 3.11 FUEL *CONSUMPTION* OF THE KENWORTH T270 BOX DELIVERY TRUCK AT 50% PAYLOAD, COMPARING THREE ENGINES

TABLE 3.17 FUEL *ECONOMY* OF THE KENWORTH T270 BOX DELIVERY TRUCK AT 50% PAYLOAD, COMPARING THREE ENGINES

Drive Cycle	ISB	3.5 V-6	6.2 V-8
CARB	7.7	6.8	6.1
55 MPH	9.7	7.7	7.4
65 MPH	8.0	6.1	6.0
WTVC	9.2	7.8	7.3
CILCC	7.6	7.1	6.2
Parcel	5.8	5.4	4.9

TABLE 3.18 FUEL *CONSUMPTION* OF THE KENWORTH T270 BOX DELIVERY TRUCK AT 50% PAYLOAD, COMPARING THREE ENGINES

Drive Cycle	ISB	3.5 V-6	6.2 V-8
CARB	12.9	14.6	16.3
55 MPH	10.3	12.9	13.4
65 MPH	12.5	16.3	16.6
WTVC	10.9	12.8	13.8
CILCC	13.2	14.1	16.2
Parcel	17.1	18.5	20.3

An alternative way of comparing the three engine options in the T270 is provided in Figure 3.12. For this figure, the 6.2 liter V-8 gasoline engine is considered to be the baseline, and the other two engines are compared to it. The 3.5 V-6 results provide a look at the benefits of downsizing and boosting, compared to a larger naturally aspirated engine. On lightly loaded duty cycles, such as the CARB cycle and the CILCC cycle, the smaller gasoline engine has a large advantage over the bigger V-8 (10 – 13%). However, on the most highly loaded cycle, 65 MPH cruise, there is no advantage at all for the smaller engine. The diesel comparison shows the benefit of converting a medium-duty truck from gasoline V-8 to diesel. On lightly loaded cycles, the diesel has about a 20% fuel consumption advantage. At high loads, the diesel's advantage approaches 30%. Remember that gasoline has about 16% less energy per gallon, so the thermal efficiency of the gasoline engines is not as poor as this comparison makes it appear. Also, keep in mind that these comparisons are all for the baseline engines, without any potential improvement technology.

There is one oddity in the results shown in Figure 3.12. This is the relatively poor performance of the diesel engine on the Parcel Delivery cycle. This cycle includes a lot of accelerations that are more aggressive than those of the CILCC cycle, which should tend to favor the diesel. The key to the poor performance of the diesel on this cycle, however, is the high percentage of time spent at idle on the Parcel cycle, where the baseline truck does not include the feature "auto neutral at stop". Typically, a diesel engine will have lower fuel consumption at idle than a gasoline engine. However, once the parasitic power demand of the transmission torque converter at idle is taken into account, the diesel has a higher idle fuel consumption than the

gasoline engines. The diesel has a higher peak torque and a lower peak torque speed, so the converter match is tighter. As a result, the stall torque of the converter at idle speed is much higher on the diesel engine than on the gasoline engine. The diesel engine idles at 750 RPM at a stall torque of 59 Nm, while the two gasoline engines idle at 650 RPM with a stall torque of 35 Nm.

Some MD and HD automatic transmissions now have, or will soon have, a feature such as "auto neutral at stop" that unloads the torque converter at idle speed. This would give the diesel engine an advantage on all the drive cycles with idle time, and especially on the Parcel cycle. These features will be evaluated for the second report.

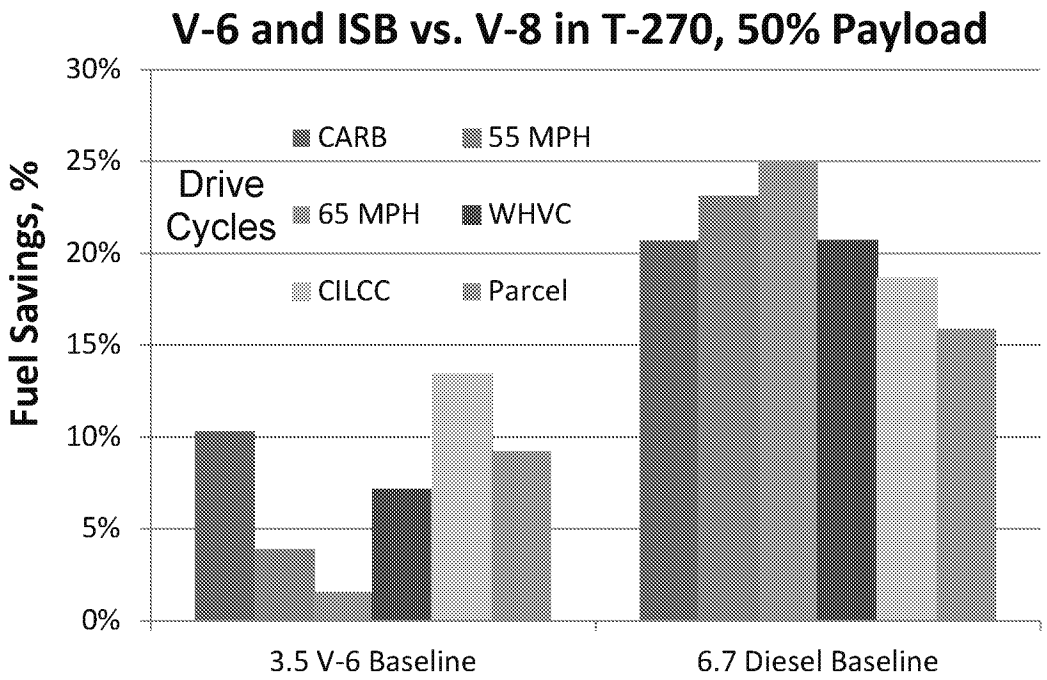


FIGURE 3.12 PERFORMANCE OF 3.5 V-6 GASOLINE AND 6.7 DIESEL BASELINE ENGINES AGAINST THE 6.2 V-8 GASOLINE ENGINE IN THE T270 TRUCK

3.3.3.2 Summary of engine technology results in T270 baseline truck

The engine technologies listed in Tables 3.17 and 3.18 above were all evaluated using the baseline T270 truck configuration. Appendix B describes the details of the ISB diesel engine model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technologies. Appendix A covers the 6.2 liter V-8 gasoline engine and the 3.5 liter V-6 gasoline engine model. Table 3.19 summarizes the fuel savings performance of all the engine technologies that have been evaluated. Each technology's performance is compared to the baseline for that engine, and all are evaluated using the baseline T270 truck. The comparison of the baseline 3.5 V-6 to the baseline diesel is highlighted in bold type, as is the comparison of the baseline 6.2 V-6 to the baseline diesel.

Note that there are some technologies available that cannot be simulated in GT-POWER. Any technology that changes combustion characteristics needs experimental data or CFD predictions to provide GT-POWER with input data. It is also difficult or impossible to handle transient operation with complex model-based controls in GT-POWER. Section 2 provides results from the literature that suggest the level of benefits that could be achieved with some of these technologies.

TABLE 3.19 FUEL SAVINGS RESULTS OF ENGINE TECHNOLOGIES, USING BASELINE T270 TRUCK

Technology	Fuel Consumption Reduction (Percent) On Drive Cycle and at Percent of Maximum Payload																	
	CARB			55 MPH			65 MPH			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
20. ISB Low Back Pres.	0.1	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.1	0.2	0.2	0.0	0.0	0.1	0.1	0.2	0.2
21. ISB Low FMEP	7.6	6.8	6.2	2.8	2.6	2.5	2.1	2.0	1.9	5.8	5.1	4.6	8.8	8.0	7.5	6.8	6.1	5.4
22. ISB No EGR	3.5	3.4	3.3	3.0	2.9	2.8	2.2	2.0	2.1	3.5	3.3	3.2	3.6	3.5	3.4	2.9	2.8	2.8
23. ISB + 5% Turbo Eff	1.6	1.6	1.6	1.7	1.7	1.7	1.4	1.4	1.4	1.7	1.7	1.7	1.5	1.5	1.5	1.4	1.4	1.5
32. 3.5 V-6 VVA / VVL	2.8	2.9	3.1	2.6	2.7	2.8	3.6	3.4	3.2	2.5	2.6	2.7	3.3	3.3	3.2	2.2	2.3	2.4
33. 3.5 V-6 Cyl. Deact.	1.7	1.4	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.5	0.4	2.8	2.2	1.8	0.9	0.7	0.5
34. 3.5 V-6 Lean GDI	9.1	7.8	7.8	3.0	2.5	2.1	2.5	2.3	1.2	7.2	6.2	5.4	11	9.8	9.3	7.2	6.2	5.7
35. 3.5 V-6 Stoich EGR	4.1	4.6	5.5	4.9	5.3	5.9	9	10	11	4.6	5.0	5.8	3.9	4.2	4.8	3.8	4.6	5.8
36. 3.5 V-6 EGR + Dwnspd	6.0	6.2	7.2	5.2	5.5	5.6	10	10	11	5.2	5.5	6.1	6.1	5.9	5.9	1.1	1.9	3.1
37. 3.5 V-6 Low FMEP	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.4	0.2	0.6	0.6	0.6	0.8	0.8	0.7	0.6	0.5	0.5
38. 3.5 V-6 + 5% Turbo Eff	0.1	0.1	0.1	0.0	0.0	0.2	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3.5 V-6 to Base ISB	**9.7**	**12**	**14**	**19**	**20**	**21**	**23**	**24**	**25**	**13**	**15**	**16**	**4.0**	**6.0**	**7.9**	**5**	**7.3**	**8.7**
40. 6.2 V-8 GDI	-0.1	-0.1	-0.1	0.0	-0.3	-0.3	0.3	0.4	0.5	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.1	0.1
41. 6.2 V-8 Lean GDI	11	9.8	9.7	8.0	8.2	8.6	11	12	11	9.7	9.3	9.1	10	10	11	8.5	8.2	7.8
42. 6.2 V-8 VVA / VVL	5.2	4.4	4.1	3.0	2.9	2.8	3.3	3.0	2.7	3.9	3.5	3.3	5.8	5.2	4.8	3.5	3.2	2.9
43. 6.2 V-8 Cyl. Deact.	5.7	4.2	3.5	-0.1	-0.1	-0.1	0.0	0.0	0.0	2.7	2.0	1.5	7.4	6.1	5.2	3.1	2.4	1.8
44. 6.2 V-8 EGR	4.4	4.3	4.9	5.0	5.3	5.8	9.0	10	11	4.4	4.8	5.4	3.5	3.8	4.2	3.3	3.9	4.8
45. 6.2 V-8 Low FMEP	1.3	1.2	1.2	1.0	0.9	0.9	1.1	1.0	0.9	1.2	1.1	1.1	1.4	1.3	1.3	1.0	1.0	0.9
6.2 V-8 to Base ISB	**21**	**21**	**20**	**23**	**23**	**23**	**25**	**25**	**25**	**21**	**21**	**21**	**19**	**19**	**18**	**15**	**16**	**16**

The data provided in Table 3.19 can also be presented in graphical form. Figures 3.13, 3.14, and 3.15 below show the performance of the various engine technologies on the 6.7 liter diesel, the 6.2 liter gasoline engine, and the 3.5 liter gasoline engine. In each figure, the fuel saving benefit of a given technology is listed relative to that specific engine's baseline performance.

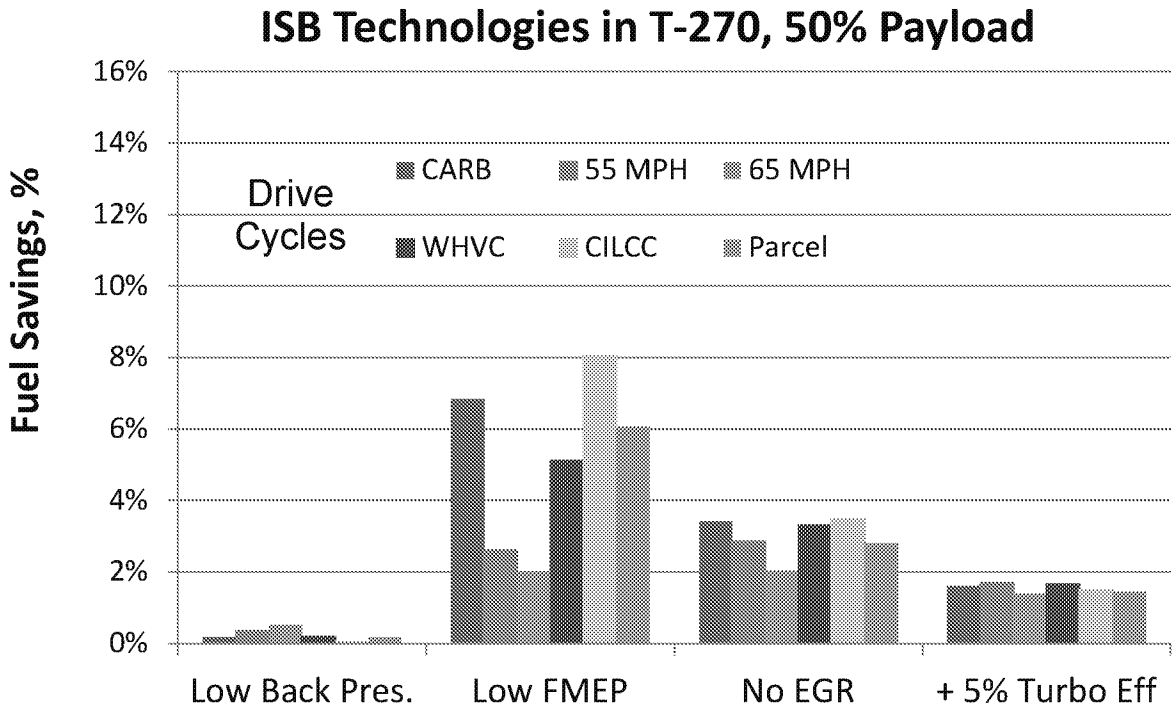


FIGURE 3.13 FUEL SAVINGS RESULTS OF 6.7 LITER DIESEL TECHNOLOGIES IN THE BASELINE T270 TRUCK

3.3.3.3 Technology #20, ISB Reduced Exhaust Restriction (Low Back Press)

Modern aftertreatment systems impose higher back pressure on the engine than the muffler-only systems used before 2007. For this technology simulation, exhaust back pressure was reduced by about 60%. Similar to the results found on the DD15 engine in the T-700 tractor-trailer, reduced exhaust restriction has only a slight impact on efficiency (see section 5.3.1.9). The simulated fuel savings were 0.1% to 0.5%, with the largest benefits coming at high speeds and high payloads.

3.3.3.4 Technology #21, ISB Reduced Engine Friction (ISB Low FMEP)

Assuming a reduction in FMEP ranging from 10% at high speed and load, to 35% at low speed and light load (see Appendix B for a complete listing of the technologies included in this friction reduction assessment), significant benefits were found. The benefits are duty cycle and payload dependent. Low speed, low average power demand cycles such as the CARB and CILCC cycles show the biggest benefit, with a range of 6% to 8% fuel savings. High average power demand cycles such as 65 MPH cruise show just a 2% benefit for low FMEP, which is less than a third of the benefit found on the CARB cycle. For all drive cycles, the largest benefit occurs with zero payload, and the smallest benefit at 100% payload. This result is to be expected, since at light load the FMEP makes up a greater portion of overall engine output.

3.3.3.5 Technology #22, ISB EGR Removed (ISB No EGR)

Driving EGR flow in an engine requires pumping work. The exhaust manifold pressure must be maintained higher than the intake manifold pressure in order for EGR to flow. Removing EGR has two benefits: pumping work can be reduced, and combustion heat release rates will increase. As a result, removing EGR provides a fuel savings of 2.7 – 3.7%, with the largest benefit coming on the most lightly loaded cycles. Note that this no-EGR technology involves very high engine-out NOx, which in turn requires a very high SCR conversion efficiency and high urea consumption, which make OBD much more challenging.

3.3.3.6 Technology #23, ISB High Efficiency Turbo (+5% Turbo Eff)

SwRI applied an assumption of a 5% increase in both compressor and turbine efficiency, under all operating conditions, resulting in an overall turbocharger efficiency increase of 10%, not 10 points (for example, from 50% to 55% overall efficiency). This technology provides a fuel savings of 1.4 – 2% across all drive cycles and payload levels. In this case, it was possible to maintain EGR flow with the higher efficiency turbo, so no impact on NOx emissions is expected. The exhaust manifold pressure remained higher than the intake manifold pressure across the operating range. It should be noted that on many engines, an increase in turbocharger efficiency will reduce or eliminate EGR flow in certain operating conditions. This issue was also experienced on the DD15 engine without turbocompound (see Section 5.3.1.6).

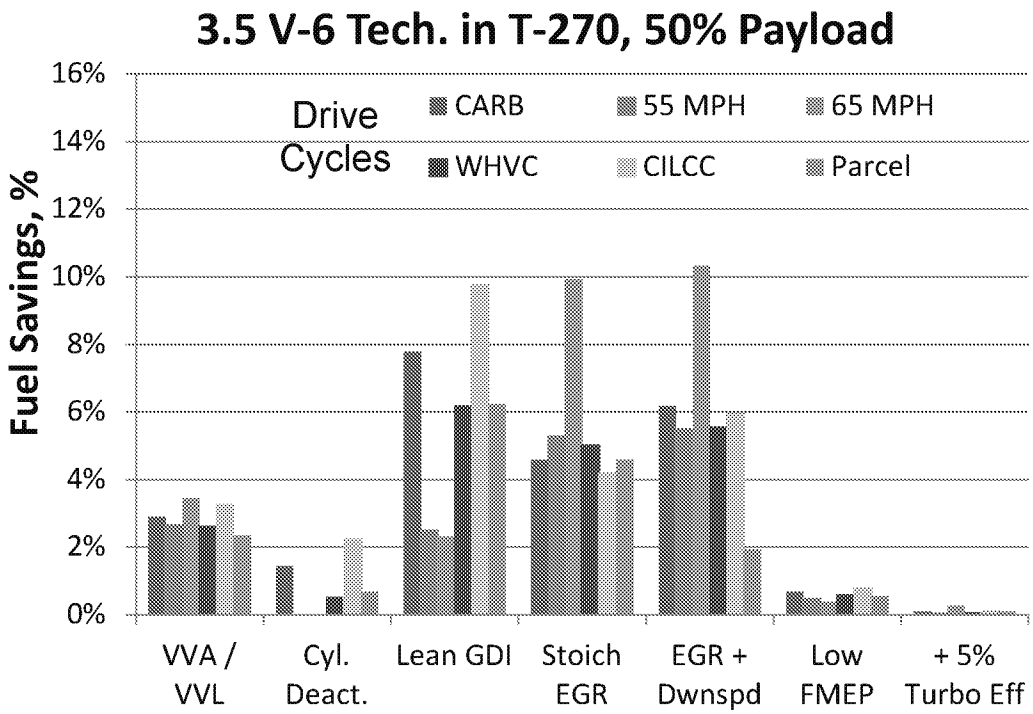


FIGURE 3.14 FUEL SAVINGS RESULTS OF 3.5 LITER V-6 GASOLINE ENGINE TECHNOLOGIES IN THE BASELINE T270 TRUCK

3.3.3.7 Technology #32, 3.5 V-6 Variable Valve Train with Cam Phaser (VVA/VVL)

The use of variable valve timing and lift is a well-known method for improving the efficiency of stoichiometric, spark-ignited engines. The application of VVA/VVL eliminates the need for a throttle, and for its associated pumping losses. In addition, engine breathing can be optimized over the wide speed range typical of spark-ignited engines (in this case, 600 to 5,500 RPM). See Section 1.2 of Appendix A for more details. In the case of this relatively small engine, however, throttling losses are small. As a result, the benefits of a VVA/VVL system are fairly modest but still significant, with a range of 2.2% to 3.6% over all the drive cycles and payloads.

3.3.3.8 Technology #33, 3.5 V-6 Cylinder Deactivation (Cyl. Deact.)

Cylinder deactivation is used to reduce pumping losses. By running the remaining cylinders at a higher BMEP, less throttling is required. This technology works best on light duty cycles and with low payloads. Given the small displacement of the 3.5 liter V-6, there isn't much opportunity to actually use cylinder deactivation in a medium-duty truck. Fuel savings benefits vary with drive cycle and payload. Cylinder deactivation does not occur on the cruise cycles at all, but benefits up to 2.8% were found on the very lightly loaded CILCC cycle.

3.3.3.9 Technology #34, 3.5 V-6 Lean Burn GDI (Lean GDI)

Lean burn GDI provides two efficiency advantages. First, it reduces pumping losses from throttling at light loads. The second advantage is that lean GDI does not require timing retard at low speed and higher loads to prevent knock. The disadvantage of lean GDI is a big one: it results in high engine-out NOx (which was not predicted in this project). Because of lean operation, a 3-way catalyst cannot be used to reduce NOx. Therefore, lean GDI requires a very effective NOx aftertreatment, such as SCR, lean NOx trap (LNT), or a combination of the two. We limited the lean GDI exhaust temperature in order to allow for aftertreatment durability and conversion efficiency. This requires going rich at loads above 14 bar BMEP, so the full load efficiency of this engine is comparable to the base engine. The largest benefits for lean burn are found on lightly loaded cycles. Up to 11% savings was recorded on the CILCC cycle, but only 1.2% was obtained at 65 MPH cruise with 100% payload.

The improvements shown here from the GT-POWER simulation results do not include the fuel penalty for regenerating an LNT, or account for the urea required by an SCR aftertreatment. These penalties can increase fuel or DEF consumption on the drive cycle and potentially cancel part or all of the benefits of lean operation. See Appendix A for more detail.

3.3.3.10 Technology #35, 3.5 V-6 Stoichiometric EGR (Stoich EGR)

Stoichiometric EGR in a spark-ignited engine has benefits similar to lean burn (which is described in the subsection above). EGR flow reduces throttling losses, eliminates the need for rich operation, and greatly reduces the need to retard spark to avoid knock. Stoichiometric EGR

avoids the need for NOx aftertreatment, because a conventional 3-way catalyst can be used. Challenges that come with EGR include the need for higher ignition system energy to avoid misfire, and the difficulty of controlling EGR rates adequately in transients to avoid misfire. EGR also has the effect of slowing combustion rates. This effect is accounted for in the simulation by using combustion data from a 3.5 liter EGR engine. SwRI has been developing EGR technology for spark-ignited engines for about 10 years now under the HEDGE program. This acronym stands for High Efficiency Dilute Gasoline Engine, although the technology is also applicable to other fuels, such as natural gas.

Unlike the lean technology, EGR provides the largest benefit at high load, where enrichment is avoided entirely. At 65 MPH, fuel savings of 9% to 11% are obtained. On the lightly loaded drive cycles, the benefit is in the 4 – 6% range.

3.3.3.11 Technology #36, 3.5 V-6 EGR + Downspeed (EGR + Dwnspd)

One advantage of turbocharged engines is that (within reason) the power level becomes independent of both displacement and speed. Engines tend to have poor efficiency at high speed, so modifying the engine to allow higher BMEP (higher torque) enables the same power to be developed at lower engine speed. The primary limitation on BMEP is cylinder pressure, which increases with BMEP. The technology evaluated here involves reducing rated speed from 6,000 RPM to 4,500 RPM, and increasing BMEP to retain power and vehicle performance. The axle ratio is modified by a factor of 4500/6000 to keep vehicle performance identical.

Under light load conditions, the engine operates at higher BMEP, reducing pumping losses and thus increasing efficiency. At high load, the engine operates at lower RPM, which generally helps efficiency. On the 65 MPH cruise cycle, benefits of 10% to 11% are obtained, with the largest benefit coming at 100% payload. The remaining cycles except the Parcel cycle show benefits that are mostly in the 4% to 7% range. The Parcel cycle results are disappointing – less than the benefits of the EGR-only technology. The reason for this disappointing performance is that the downspeed engine comes with a tighter torque converter match. The tight converter causes a higher torque converter stall torque at idle, and thus a higher load on the engine when the vehicle is stationary. The Parcel cycle includes a significant portion of time spent with the vehicle stationary.

3.3.3.12 Technology #37, 3.5 V-6 Reduced Engine Friction (Low FMEP)

Gasoline engines have seen much more effort on friction reduction than diesel engines over the past 20 to 30 years. As a result, the scope for improvement in gasoline engines is less than for diesel engines, so a target of 10% reduction in FMEP was selected for this study. Reducing friction is of greatest benefit in light load operation, where friction makes up a larger portion of the power produced. Given the small displacement of the 3.5 liter V-6, the average BMEP on a drive cycle is relatively high, which limits the potential benefit of reduced friction. Fuel savings benefits vary with drive cycle and payload, ranging from 0.2% at 65 MPH and 100% payload up to 0.8% on the CILCC cycle at zero payload.

3.3.3.13 Technology #38, 3.5 V-6 High Efficiency Turbo (+5% Turbo Eff.)

SwRI applied an assumption of a 5% increase in both compressor and turbine efficiency, under all operating conditions, resulting in an overall turbocharger efficiency increase of 10%, not 10 points (for example, from 50% to 55% overall efficiency). Because the gasoline engine is throttled, the potential fuel savings benefit is relatively small compared to the diesel engine case. The high efficiency turbo provides a fuel savings of only 0.1 – 0.3% across all drive cycles and payload levels. This benefit does not match the benefit found on the two diesel engines. In the case of gasoline engines, however, the turbocharger works against an engine throttle, in order to maintain transient response. The throttle cancels most of the benefit obtained by the more efficient turbo.

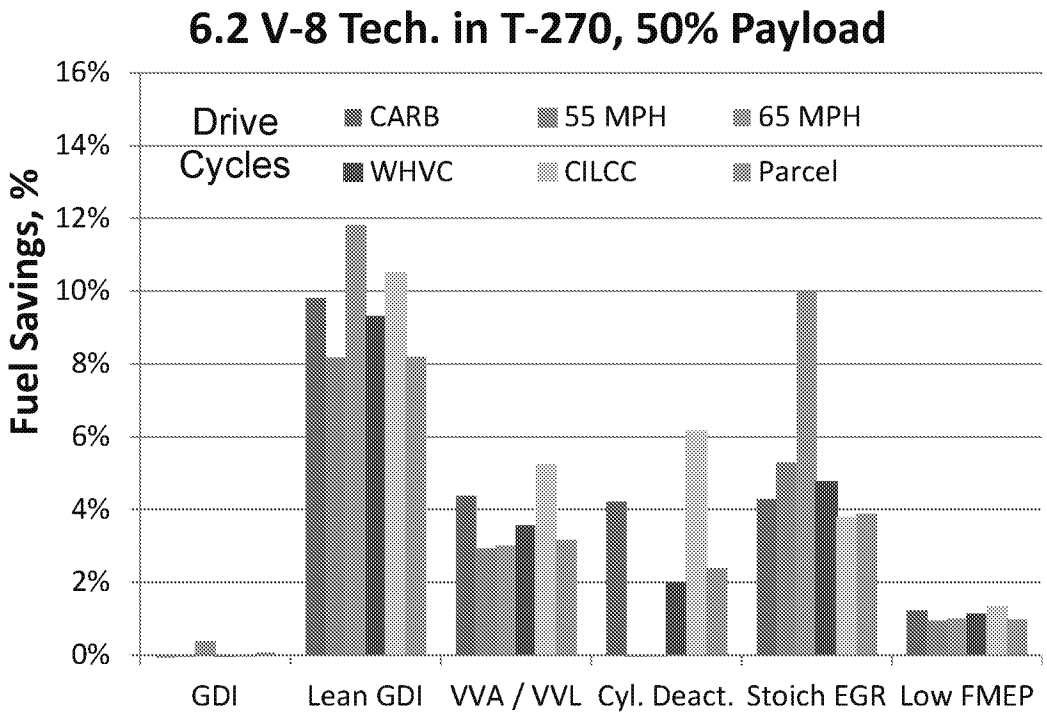


FIGURE 3.15 FUEL SAVINGS RESULTS OF 6.2 LITER V-8 GASOLINE ENGINE TECHNOLOGIES IN THE BASELINE T270 TRUCK

3.3.3.14 Technology # 40, 6.2 V-8 Convert to GDI (GDI)

Unlike the 3.5 V-6, which uses gasoline direct injection (GDI) in its baseline form, the 6.2 liter V-8 is a port injected engine in its baseline form. The addition of GDI is normally used to extract slight power and torque increases, but that was not done for this project. The original torque curve was retained to maintain constant vehicle performance. The other impact of GDI is that the cylinder charge cooling effect of direct injection reduces the tendency to knock. This typically allows an increase in compression ratio, which leads to a slight efficiency improvement. In this study, the original compression ratio was increased by 1.5 points. The benefit from the compression ratio increase is partly offset by a reduction in combustion

efficiency and the parasitic power demand of the high pressure GDI fuel pump. Over most of the range of drive cycles and payloads evaluated in the T270 truck, the change in fuel consumption was negligible, and in many cases slightly negative. At 65 MPH, a benefit of 0.3 to 0.5% was found.

3.3.3.15 Technology #41, 6.2 V-8 Lean Burn GDI (Lean GDI)

Lean burn GDI provides two efficiency advantages. First, it reduces pumping losses from throttling at light loads. The second advantage is that lean GDI does not require timing retard at low speed and higher loads to prevent knock. The disadvantage of lean GDI is a big one: it requires a very effective NOx aftertreatment. We limited the exhaust temperature in order to allow for aftertreatment durability and conversion efficiency. This requires going rich at loads above 9 bar BMEP below 4,000 RPM and 8 bar BMEP above 4,000 RPM, so the full load efficiency of this engine is comparable to the base engine. Lean GDI on a large naturally aspirated engine is fairly insensitive to drive cycle and payload, with fuel savings of 7.8% to 12%. The largest benefits come on the 65 MPH cruise cycle. This cycle imposes a relatively high load on the engine, but not full load.

The improvements shown here from the GT-POWER simulation results do not include the fuel penalty for regenerating an LNT, or account for the urea required by an SCR aftertreatment. These penalties can increase fuel or DEF consumption on the drive cycle and potentially cancel part or all of the benefits of lean operation. See Appendix A for more detail.

3.3.3.16 Technology #42, 6.2 V-8 Variable Valve Train with Cam Phaser (VVA/VVL)

The use of variable valve timing and lift is a well-known method for improving the efficiency of stoichiometric, spark-ignited engines. The application of VVA/VVL eliminates the need for a throttle, and for its associated pumping losses. In addition, engine breathing can be optimized over the wide speed range typical of spark-ignited engines (in this case, 600 to 6,000 RPM). Section 1.2 of Appendix A describes the approach used to evaluate the potential of VVA/VVL. Compared to the results for the 3.5 liter engine (see Section 5.3.3.7), the 6.2 V-8 has a larger displacement and thus larger pumping losses. As a result, the benefits of a VVA/VVL system are in the 2.7% to 5.8% range, with the largest benefits coming at zero payload on a light drive cycle (the CILCC), and the smallest benefit appearing at a highly loaded condition: 65 MPH and 100% payload.

3.3.3.17 Technology #43, 6.2 V-8 Cylinder Deactivation (Cyl. Deact.)

Cylinder deactivation is used to reduce pumping losses. By running the remaining cylinders at a higher BMEP, less throttling is required. This technology works best on light duty cycles and with low payloads. The larger displacement of the 6.2 liter V-8 offers more potential for cylinder deactivation than is available for the smaller V-6. Fuel savings benefits vary with drive cycle and payload. Cylinder deactivation does not occur on the cruise cycles at all, but benefits up to 7.4% were found on the very lightly loaded CILCC cycle. On the CARB, Parcel Delivery, and WHVC cycles, fuel savings from 1.5% to 5.7% were obtained.

3.3.3.18 Technology #44, 6.2 V-8 Stoichiometric GDI EGR (EGR)

Stoichiometric EGR in a spark-ignited engine has benefits similar to lean burn (which is described in Subsection 5.3.3.15). EGR flow reduces throttling losses, eliminates the need for rich operation, and greatly reduces the need to retard spark to avoid knock. Stoichiometric EGR avoids the need for NOx aftertreatment, because a conventional 3-way catalyst can be used. Challenges that come with EGR include the need for higher ignition system energy to avoid misfire, and the difficulty of controlling EGR rates adequately in transients to avoid misfire. SwRI has been developing EGR technology for spark-ignited engines for about 10 years now under the HEDGE program. This acronym stands for High Efficiency Dilute Gasoline Engine, although the technology is also applicable to other fuels, such as natural gas.

Unlike the lean technology, EGR provides the largest benefit at high load, where enrichment is avoided entirely. At 65 MPH, fuel savings of 9% to 11% are obtained. On the lightly loaded drive cycles, the benefit is in the 3.3% – 4.9% range.

3.3.3.19 Technology #45, 6.2 V-8 Reduced Engine Friction (Low FMEP)

Gasoline engines have seen much more effort on friction reduction than diesel engines over the past 20 to 30 years. As a result, the scope for improvement in gasoline engines is less than for diesel engines, so a target of 10% reduction in FMEP was selected for this study. Reducing friction is of greatest benefit in light load operation, where friction makes up a larger portion of the power produced. For the 6.2 liter V-8, the average BMEP on a drive cycle is lower than for the 3.5 liter V-6, and so the potential benefit of reduced friction is larger. Fuel savings benefits vary with drive cycle and payload, ranging from 0.9% at 65 MPH and 100% payload up to 1.4% on the CILCC cycle at zero payload.

3.3.4 T270 Delivery Truck Vehicle Technology Results

The vehicle technologies listed in Table 3.7 were all evaluated using the baseline version of the ISB diesel engine. Appendix G describes the details of each vehicle technology, including parameters and assumptions. Performance of the baseline vehicle is described above in Figures 3.10, 3.11, and 3.12, as well as Table 3.20 and Figure 3.16.

Table 3.20 above summarizes the simulation results for all of the vehicle technologies. Results are provided for each technology on 6 drive cycles. Each drive cycle is run at 3 payloads, to provide information on how sensitive a given technology is to payload. As a result, the table provides 15 data points for each of the 8 technologies that were evaluated. The results shown are in terms of percent reduction in fuel consumption compared to the baseline production T270 box delivery truck. Figure 3.16 provides the same information in graphical form.

TABLE 3.20 RESULTS OF T270 VEHICLE TECHNOLOGY SIMULATIONS, USING THE BASELINE ISB DIESEL ENGINE

Technology	Fuel Consumption Reduction (Percent) On Drive Cycle and at Percent of Maximum Payload																	
	CARB			55 MPH			65 MPH			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
N. A/C -40%	1.9	1.7	1.5	0.6	0.6	0.6	0.4	0.5	0.4	1.4	1.3	1.1	2.2	2.0	1.8	2.4	2.2	2.5
O. Cd - 15%	1.6	1.4	1.3	7.4	7.1	6.8	8.7	8.5	8.4	3.9	3.6	3.3	1.6	1.4	1.3	1.3	1.2	1.2
P. Crr - 30%	5.5	6.2	6.9	6.6	8.0	9.2	5.7	6.9	8.1	6.2	7.2	7.8	6.4	6.6	6.8	3.8	4.4	5.7
Q. 8-Spd Auto	1.8	2.1	2.3	0.4	0.2	0.1	0.1	0.1	0.0	2.1	2.0	2.0	7.1	7.2	7.0	2.6	2.7	3.9
R. 6-Spd AMT	4.3	3.9	3.8	3.7	3.5	3.3	3.3	3.2	3.1	5.1	4.5	4.0	11	10	9.2	11	9.5	9.7
R. 10-Spd AMT	4.5	4.4	4.4	3.7	3.5	3.3	5.4	4.1	2.8	5.2	4.8	6.4	6.9	6.4	5.9	9.6	8.9	9.2
S. Wght - 1000 lb.	2.6	2.5	2.3	1.5	1.5	1.4	1.3	1.3	1.2	2.2	2.1	2.0	2.2	1.9	1.8	2.2	2.1	3.0
T. Chassis Fr - 30%	0.7	0.8	0.9	0.9	1.0	1.1	0.9	1.0	1.1	0.8	0.9	1.0	0.7	0.7	0.8	0.6	0.6	1.4

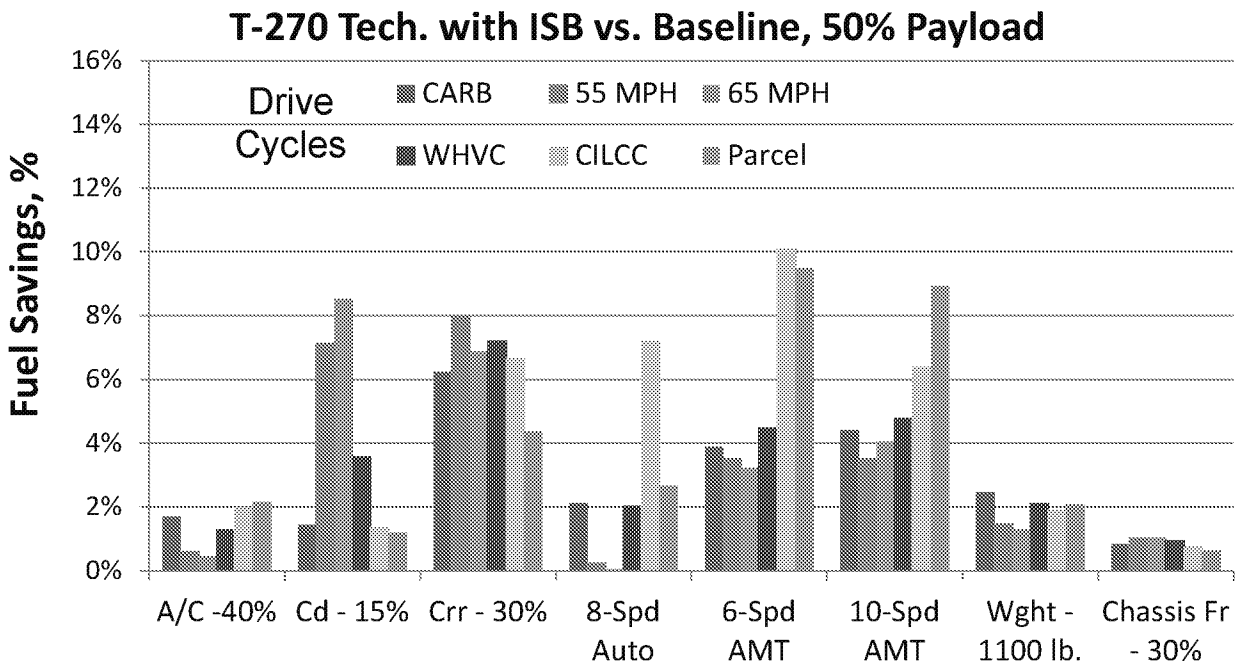


FIGURE 3.16 PERFORMANCE OF T270 TRUCK TECHNOLOGIES WITH BASELINE DIESEL ENGINE

3.3.4.1 Technology N. T270 Reduced A/C Power Demand (A/C -40%)

For all duty cycles evaluated in this project, the air conditioner is operating. Average A/C power demand is assumed to be 1.5 kW. The reduced A/C power demand technology set is assumed to reduce power demand by 40% to 900 watts. This provides a 0.4% to 2.4% benefit, with the largest benefit occurring on the CILCC and Parcel Delivery cycles at zero payload,

where the average engine operating loads are the lowest. The smallest benefit is observed on the 65 MPH cruise cycle, where vehicle power demand is high.

3.3.4.2 Technology O. Improved Cd (Cd – 15%)

This technology involves a reduction in aerodynamic drag for straight truck with a large cargo box. Several features will be required to achieve a 15% reduction in Cd. Detailed assumptions about the features required to achieve a given level of Cd improvement are provided in Appendix C. The simulation results reported here do not evaluate any specific aerodynamic feature. This study evaluates the effect of reduced vehicle power demand on a range of duty cycles. Note that different features may be required for a range of vocational segments such as refuse, utility, cement mixers, dump trucks, etc., and the level of potential improvement will vary with application type. As indicated by the results in Figure 3.7, fuel efficiency benefits over a sweep of Cd values appear to be relatively linear and can be interpolated for various Cd improvements. For the 15% reduction in Cd evaluated, the results vary widely, from a 1% benefit on the Parcel Delivery cycle up to a more impressive 8.7% at 65 MPH with zero payload. The results are also dependent on payload. Light payloads reduce the power demand from tire rolling resistance and the requirement to accelerate the vehicle inertia, and this makes aerodynamic drag a larger portion of the total power demand. Aerodynamic features will provide a significant benefit on any vehicle that runs a significant portion of its mileage at high road speeds.

3.3.4.3 Technology P. Improved Crr (Crr – 30%)

This technology assumes an improvement in tire rolling resistance by 30%. As indicated by the results in Figure 3.8, fuel efficiency benefits over a sweep of Crr values appear to be relatively linear and can be interpolated for various Crr improvements. Tire rolling resistance is most important at moderate speeds in steady state operation, such as the 55 MPH cruise cycle, where a benefit of up to 9.2% fuel savings was found. At higher speeds, aerodynamic drag grows, which reduces the rolling resistance share of total vehicle power demand. In highly transient cycles such as the Parcel Delivery cycle, the power required to accelerate the vehicle inertia overshadows the rolling resistance power demand. As a result, on the Parcel cycle the fuel savings ranges from 3.9% to 6.1%. The benefit of lower Crr is payload dependent. At 100% payload, rolling resistance plays a larger share in overall vehicle power demand than at 0% payload.

3.3.4.4 Technology Q. Automatic Transmission Upgrade (8-Spd Auto)

The baseline 5-speed automatic transmission was replaced with a more efficient 8-speed automatic. The efficiency data for the 8-speed transmission was based on that of the most efficient pickup truck automatic measured by SwRI to date. The benefits are about 2% on most duty cycles. On the very lightly loaded (gradual accelerations) CILCC cycle, benefits up to 6.4% were achieved. The ~1% benefit on most cycles came from improved transmission efficiency when the vehicle is moving. The 5- and 8-speeds share a torque converter, so there is no difference at idle. On the CILCC, the engine appears to gain some benefit from the closer gear

ratio spacing, but this does not show up in the other cycles. The 8-speed was geared to have the same cruise RPM as the 5-speed. If the 8-speed would be geared taller (i.e., use a lower numerical axle ratio) to take advantage of its wider ratio range, a larger benefit can be expected.

3.3.4.5 Technology R. AMT Alternatives (6-Spd AMT and 10-Spd AMT)

Automated manual transmissions offer higher mechanical efficiency than torque converter automatic transmissions. On the other hand, AMTs require a power interrupt for every shift event. Also, drivability with AMT is an issue in this application. Given two otherwise identical vehicles, the vehicle with an automatic transmission will accelerate faster and operate more smoothly than the vehicle with an AMT.

The 6-speed AMT was geared for the same cruising RPM as the automatic, so the benefits of 3.1 to 3.7% that are observed at 55 and 65 MPH are the result of higher mechanical efficiency of the AMT compared to the automatic. There are larger benefits provided by the AMT on the transient cycles, and especially on the Parcel delivery cycle and CILCC cycle. Additional evaluation of the results revealed that the primary culprit for the high fuel consumption of the automatic transmission on these cycles is due to the high input torque of the torque converter when the vehicle is stationary and the engine is at its idle speed of 750 RPM. The AMT imposes no drag torque on the engine at idle. Thus, at idle, the fuel consumption with an AMT is significantly lower than that of the automatic. This issue is particularly potent with the diesel engines and downspeed gasoline engines, which require a tighter converter match, and thus high engine torque at idle with the vehicle stationary. Technologies for unloading the torque converter at idle will be explored later in this project, and are expected to diminish, but not eliminate, the advantage enjoyed by AMT transmissions.

The 10-speed AMT was geared taller (lower engine speed in top gear) to take advantage of its wider ratio range. Thus, the 10-speed AMT provided a benefit of up to 5.4% at 65 MPH. On most cycles, the 10-speed provided similar efficiency benefits to the 6-speed AMT.

3.3.4.6 Technology S. Weight Reduction (Wght – 1100 lb.)

The baseline T270 box truck has an empty weight of 17,140 pounds. This technology simulation looked at the effect of a 1,100 pound weight reduction (6.4%). The payload weight was left unchanged, so the weight of the loaded vehicle decreased by the same amount as the empty weight. Benefits range from 1.2% on the 65 MPH cruise cycle to 2.7% on the highly transient CARB cycle at zero payload.

3.3.4.7 Technology T. Chassis and Driveline Friction (Chassis Fr – 30%)

This simulation evaluates the potential for features such as improved axle efficiency, improved wheel bearings, and synthetic lubricants used in the driveline. Benefits of 0.6% to 1.1% are achieved, with the larger benefits on the high speed cruise cycles (55 and 65 MPH).

3.3.5 Ford F-650 Truck Engine Technology Results

Three engines are included in the evaluation of The Ford F-650 for this study: the Cummins ISB 6.7 liter diesel, a 6.2 liter V-8 gasoline engine that is currently offered in Class 2b and 3 vehicles, and which may in time replace the older V-10 in heavier vehicles, and a Ford 3.5 liter turbocharged V-6 which is currently offered in Class 2a vehicles. The ISB diesel is considered the baseline engine for these vehicles. The Cummins ISB is the standard engine sold in the F-650 truck, although there is also a 6.8 liter V-10 gasoline engine option. Data for modeling the Ford F-650 truck came from the example shown in the photographs below.

The biggest difference between the F-650 and the T270 truck covered above is that the cargo box is replaced by a flatbed for towing purposes. Vehicle parameters for the F-650 can be found in Appendix C. The flatbed greatly reduces the frontal area of the truck, which will reduce aerodynamic drag. At high road speed, the F-650 can be expected to require significantly less power than the T270. For example, at 65 MPH, the baseline F-650 has a power requirement of 88 kW, while the T270 demands 129 kW, a 47% increase.

FIGURE 3.17 FORD F-650 ROLL-OFF TOW TRUCK

3.3.5.1 Baseline Engine and Vehicle Results for F-650 Truck and Engines

Figure 3.18 below shows the *fuel economy* performance of the F-650 truck with the three engines in their baseline form, all evaluated at 50% payload. Figure 3.19 shows the *fuel consumption* results for the same engines and payload. The same data is provided in tabular form in Tables 3.21 and 3.22 below the figures.

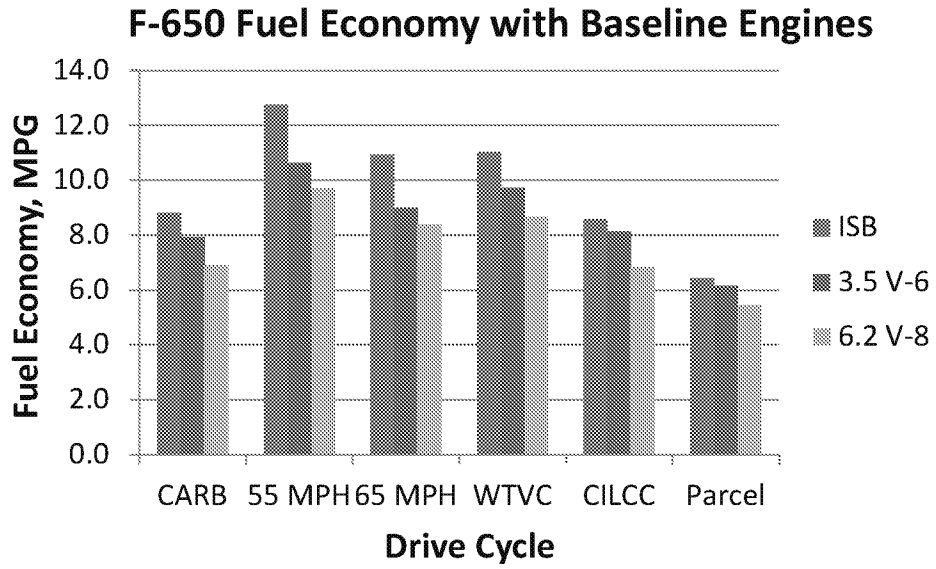


FIGURE 3.18 FUEL *ECONOMY* OF THE BASELINE F-650 AT 50% PAYLOAD, WITH THREE ENGINE OPTIONS

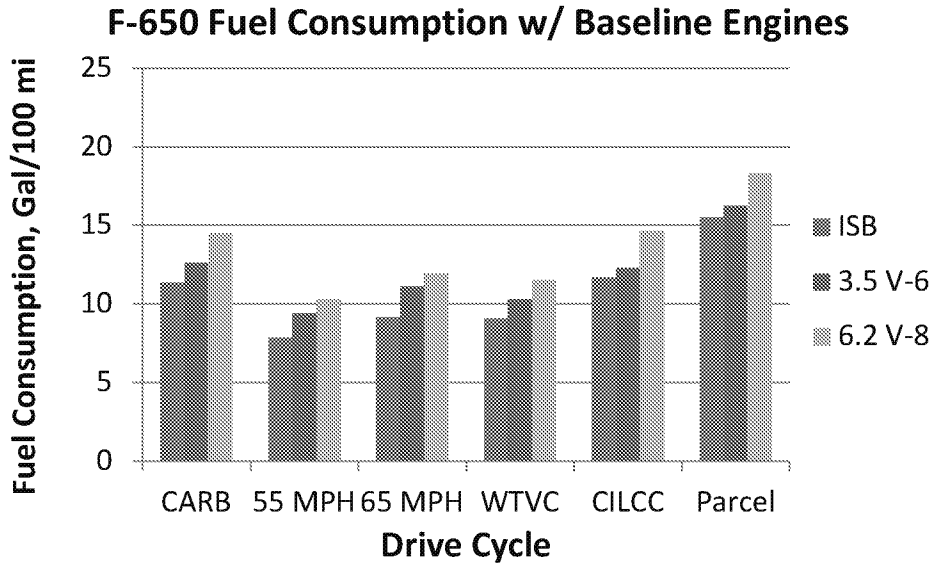


FIGURE 3.19 FUEL *CONSUMPTION* OF THE BASELINE F-650 AT 50% PAYLOAD, WITH THREE ENGINE OPTIONS

There is one oddity in the results shown in Figures 3.18 and 3.19. This is the relatively modest performance of the diesel engine on the CILCC and Parcel Delivery cycles, particularly when compared to the gasoline V-6. These cycles include a lot of accelerations, which should tend to favor the diesel. The key to the relatively high fuel consumption on the diesel on these cycles, however, is the percentage of time spent at idle in the two cycles, especially on the Parcel cycle, where the baseline truck does not include the feature "auto neutral at stop". Typically, a diesel engine will have lower fuel consumption at idle than a gasoline engine. However, once the parasitic load from the transmission torque converter at idle is taken into account, the diesel

TABLE 3.21 FUEL *ECONOMY* (MPG) OF THE BASELINE F-650 AT 50% PAYLOAD, WITH THREE ENGINE OPTIONS

Drive Cycle	ISB	3.5 V-6	6.2 V-8
CARB	8.8	7.9	6.9
55 MPH	12.8	10.6	9.7
65 MPH	10.9	9.0	8.4
WTVC	11.0	9.7	8.7
CILCC	8.6	8.1	6.8
Parcel	6.4	6.2	5.5

TABLE 3.22 FUEL *CONSUMPTION* (GAL/100 MI) OF THE BASELINE F-650 AT 50% PAYLOAD, WITH THREE ENGINE OPTIONS

Drive Cycle	ISB	3.5 V-6	6.2 V-8
CARB	11.4	12.6	14.5
55 MPH	7.8	9.4	10.3
65 MPH	9.1	11.1	11.9
WTVC	9.1	10.3	11.5
CILCC	11.7	12.3	14.7
Parcel	15.5	16.2	18.3

has more idle fuel consumption than the gasoline engines. The diesel has a higher peak torque and a lower peak torque speed, so the converter match is tighter. As a result, the stall torque of the converter at idle speed is much higher on the diesel engine than on the gasoline engine. The diesel engine idles at 750 RPM at a stall torque of 59 Nm, while the two gasoline engines idle at 650 RPM with a stall torque of 35 Nm.

Some MD and HD automatic transmissions now have, or will soon have, a feature such as "auto neutral at stop" that unloads the torque converter at idle speed. This would give the diesel engine an advantage on all the drive cycles with idle time, and especially on the Parcel cycle. These features will be evaluated for the second report.

An alternative way of comparing the three engine options in the F-650 is provided in Figure 3.20. For this figure, the 6.2 liter V-8 gasoline engine is considered to be the baseline, and the other two engines are compared to it. The 3.5 V-6 results provide a look at the benefits of downsizing and boosting, compared to a larger naturally aspirated engine. On lightly loaded duty cycles, such as the CARB cycle and the CILCC cycle, the smaller gasoline engine has a large advantage over the bigger V-8 (13 – 17%). However, on the most highly loaded cycle, 65 MPH cruise, the advantage of the smaller engine shrinks to 9%. The diesel comparison shows the benefit of converting a medium-duty truck from gasoline V-8 to diesel. On lightly loaded cycles, the diesel has about a 22% fuel consumption advantage. On the 55 and 65 MPH cruise cycles, the diesel's advantage is 22 - 25%. Remember that E10 gasoline has about 16% less

energy per gallon, so the thermal efficiency of the gasoline engines is not as poor as this comparison makes it appear. Also, keep in mind that these comparisons are all for the baseline engines, without any potential improvement technology.

A comparison of Figure 3.20 with Figure 3.12, which compares the same three engines in the larger, heavier T270, is instructive. In the F-650, the 3.5 V-6 enjoys a larger advantage on every drive cycle than it has in the T270. The difference is particularly large on the 65 MPH cruise cycle, where the 3.5 V-6 has a 7.2% advantage over the V-8 in the F-650, while it has only a 2% advantage in the larger T270. The ISB diesel, on the other hand, retains nearly the same advantage over the V-8 in the F-650.

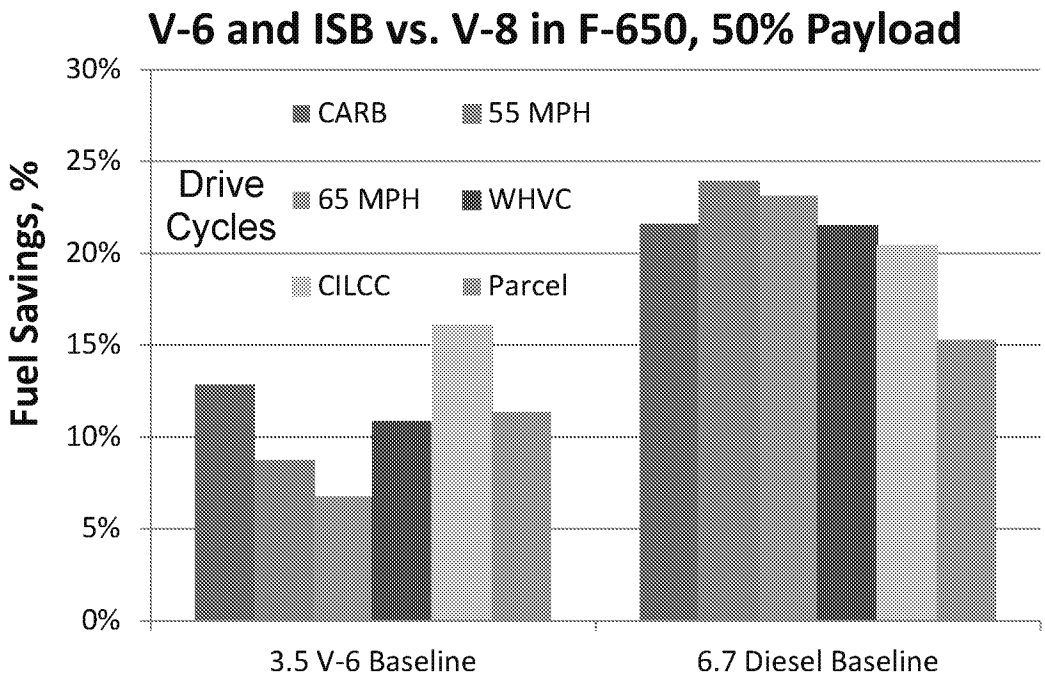


FIGURE 3.20 FUEL SAVINGS OF 3.5 V-6 GASOLINE AND 6.7 DIESEL BASELINE ENGINES AGAINST THE 6.2 V-8 GASOLINE ENGINE IN THE F-650 TRUCK

The engine technologies listed in Tables 3.2, 3.4, and 3.5 above were all evaluated using the baseline F-650 truck configuration. Appendix B describes the details of the ISB diesel engine model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technologies. Appendix A covers the 6.2 liter V-8 gasoline engine and the 3.5 liter V-6 gasoline engine model. Table 3.23 summarizes the fuel savings performance of all the engine technologies that have been evaluated. Each technology's performance is compared to the baseline for that engine, and all are evaluated using the baseline T270 truck.

TABLE 3.23 FUEL SAVINGS RESULTS OF ENGINE TECHNOLOGIES, USING BASELINE F-650 TRUCK

Technology	Fuel Consumption Reduction (Percent) on Drive Cycle @ Percent of Maximum Payload																	
	CARB			55 MPH			65 MPH			WHVC			CILCC			Parcel		
	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%	0%	50%	100%
20. ISB Low Back Pres.	0.1	0.1	0.1	0.2	0.2	0.2	0.6	0.6	0.6	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.2
21. ISB Low FMEP	8.5	7.7	7.1	4.3	4.0	3.6	3.2	3.0	2.8	7.1	6.4	5.7	10	9.4	8.8	7.3	6.8	6.2
22. ISB No EGR	3.7	3.6	3.4	3.4	3.3	3.2	4.0	3.8	3.5	3.7	3.6	3.4	3.8	3.7	3.6	2.9	2.8	2.7
23. ISB + 5% Turbo Eff	1.6	1.6	1.6	1.9	1.8	1.8	2.3	2.2	2.0	1.7	1.7	1.7	1.5	1.5	1.5	1.4	1.4	1.4
32. 3.5 V-6 VVA / VVL	2.9	2.9	2.9	2.4	2.4	2.4	3.5	3.5	3.5	2.6	2.5	2.6	3.5	3.4	3.3	2.2	2.3	2.4
33. 3.5 V-6 Cyl. Deact.	2.1	1.8	1.6	0.3	0.2	0.1	0.0	0.0	0.0	1.2	0.9	0.7	3.4	3.0	2.5	1.3	1.0	0.8
34. 3.5 V-6 Lean GDI	11	9.4	8.4	12	9.3	6.8	8.3	5.9	3.6	11	9.5	8.0	12	11	10	8.0	7.2	6.6
35. 3.5 V-6 Stoich EGR	3.8	4.0	4.3	4.1	4.3	4.4	4.2	4.3	4.3	4.0	4.3	4.5	3.6	3.8	3.9	3.4	3.8	4.3
36. 3.5 V-6 EGR + Dwnspd	8.4	7.7	7.2	8.0	7.8	7.6	9.4	9.0	8.6	7.5	7.0	6.8	8.9	8.3	7.7	1.5	1.6	2.1
37. 3.5 V-6 Low FMEP	0.8	0.8	0.7	0.9	0.9	0.8	1.0	0.9	0.8	0.8	0.8	0.7	0.9	0.9	0.8	0.6	0.6	0.6
38. 3.5 V-6 + 5% Turbo Eff	0.1	0.1	0.1	0.2	0.2	0.2	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3.5 V-6 to Base ISB	8.7	10	11	16	17	17	17	18	18	11	12	13	3.8	5.2	6.2	3.0	4.4	6.2
40. 6.2 V-8 GDI	0.0	0.0	-0.1	0.9	0.7	0.6	1.0	0.9	0.7	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1
41. 6.2 V-8 Lean GDI	11	10	10	13	11	10	8.7	8.6	8.4	12	11	10	11	11	11	8.6	8.5	8.3
42. 6.2 V-8 VVA / VVL	5.2	4.8	4.6	4.1	3.7	3.4	4.6	4.4	4.2	4.7	4.3	3.9	6.4	6.0	5.6	3.9	3.6	3.3
43. 6.2 V-8 Cyl. Deact.	6.3	5.4	4.6	3.4	2.4	1.4	0.6	0.2	0.0	4.7	3.7	2.9	8.8	7.8	6.9	3.9	3.3	2.7
44. 6.2 V-8 EGR	3.7	3.9	4.1	4.2	4.3	4.4	4.7	5.0	5.2	3.9	4.1	4.4	3.2	3.3	3.6	2.9	3.3	3.7
45. 6.2 V-8 Low FMEP	1.4	1.3	1.3	1.6	1.5	1.3	1.5	1.4	1.3	1.4	1.3	1.3	1.5	1.4	1.4	1.0	1.0	1.0
6.2 V-8 to Base ISB	22	22	21	24	24	24	23	23	23	22	21	21	21	20	20	16	15	15

The data provided in Table 3.23 can also be presented in graphical form. Figures 3.21, 3.22, and 3.23 below show the performance of the various engine technologies on the 6.7 liter diesel, the 6.2 liter gasoline engine, and the 3.5 liter gasoline engine. In each figure, the fuel saving benefit of a given technology is listed relative to that specific engine's baseline performance.

3.3.5.2 Engine Technology Performance in the F-650 Truck

Because these technologies have already been reviewed in the T270 truck section, this section will only describe situations where there are significant differences in the performance of engine technologies between the two trucks.

For the ISB diesel, the friction reduction technology provides somewhat better benefits on the smaller F-650. This is because when vehicle power demand is lower, friction makes up a greater percentage of the vehicle power demand.

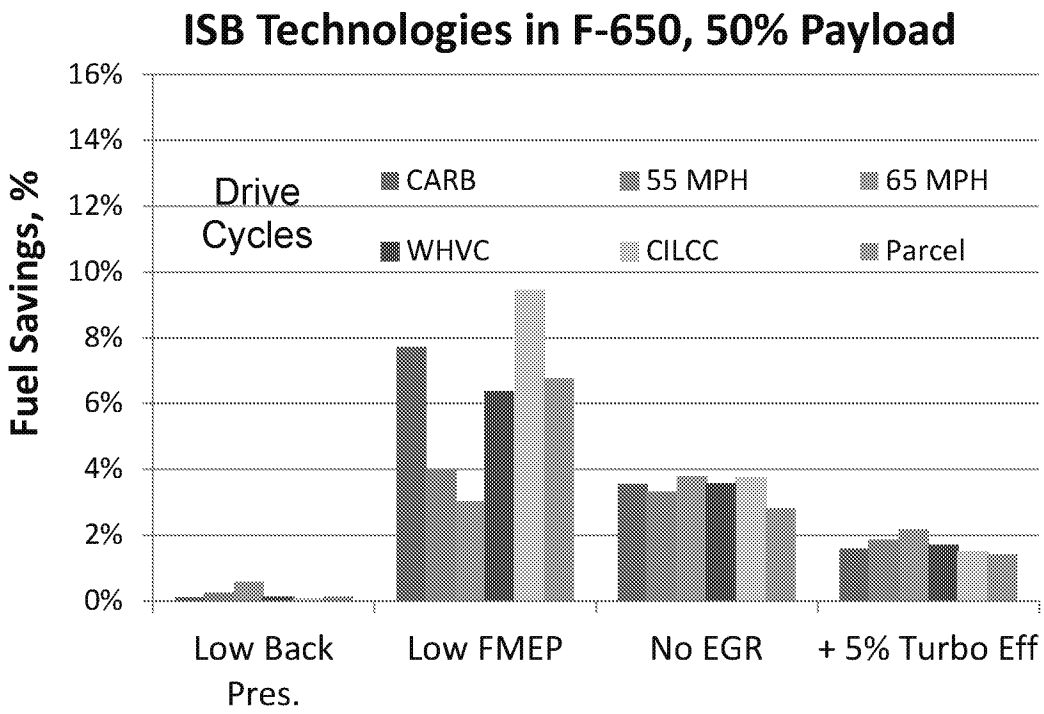


FIGURE 3.21 ISB DIESEL TECHNOLOGIES IN THE F-650 AT 50% PAYLOAD

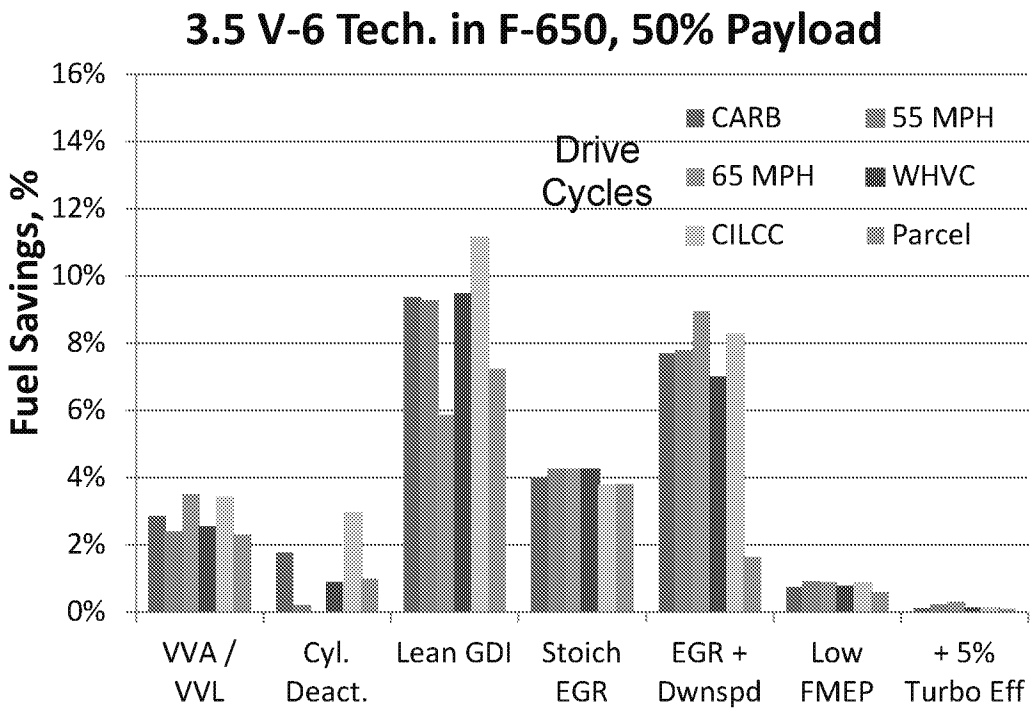


FIGURE 3.22 3.5 V-6 GASOLINE ENGINE TECHNOLOGIES IN THE F-650 AT 50% PAYLOAD

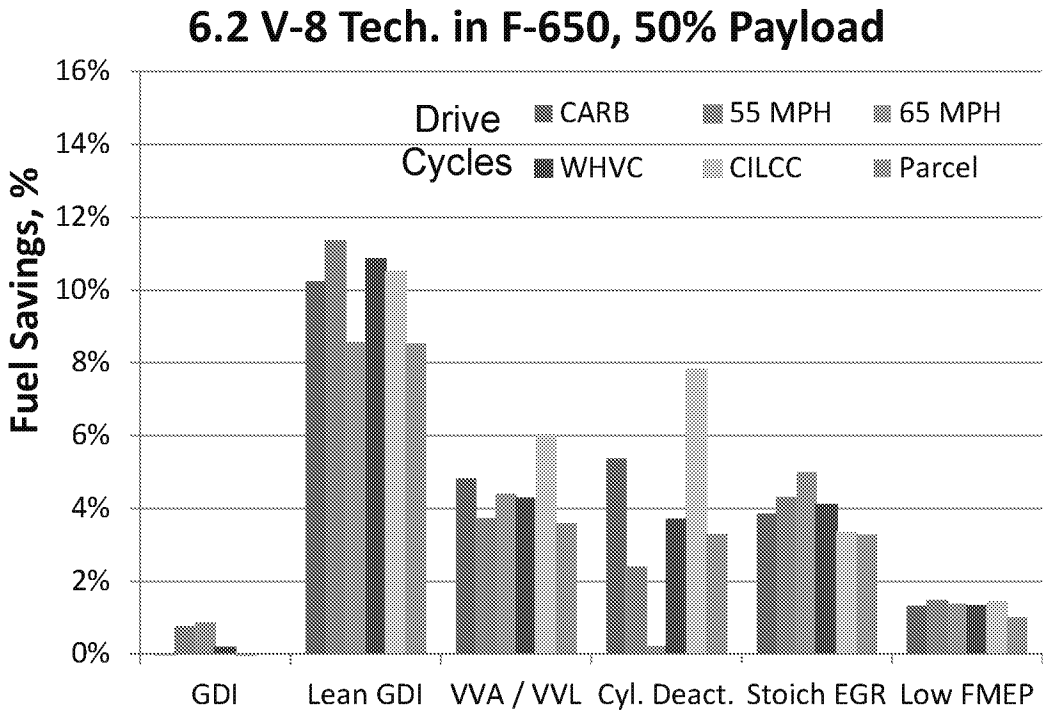


FIGURE 3.23 6.2 V-8 GASOLINE ENGINE TECHNOLOGIES IN THE F-650 AT 50% PAYLOAD

3.3.5.3 Vehicle Technology Performance in the F-650 Truck

Because these technologies have already been reviewed in the T270 truck section, this section will only describe situations where there are significant differences in the performance of engine technologies between the two trucks.

Drag reduction technology has less benefit on the F-650 than on the T270. There are two reasons for this. First, because there is less opportunity to improve the Cd of the flatbed F-650, only a 10% Cd reduction was simulated, vs. 15% for the T270 box truck. Second, since the frontal area of the F-650 is much less than that of the T270, a given change in Cd provides less benefit.

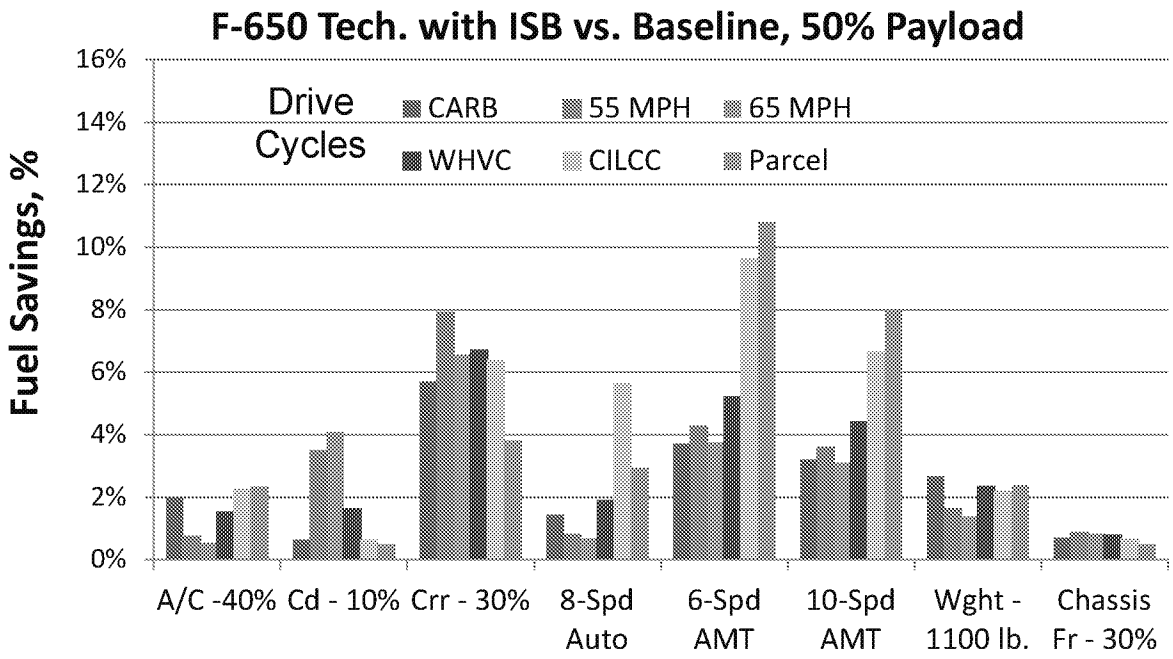


FIGURE 3.24 VEHICLE TECHNOLOGIES WITH THE DIESEL ENGINE IN THE F-650 AT 50% PAYLOAD

3.3.6 Ram Pickup Engine and Vehicle Technology Performance

Class 2b and 3 trucks and vans offer a mixture of gasoline and diesel engines. Gasoline V-8 engines of 5.7 to 6.4 liters are offered along with diesel engines of 4.5 to 6.7 liters. Diesel engines hold the largest market share, but there is a significant market for gasoline engines in this segment.

Three engines are included in the evaluation of Class 2b – 3 vehicles for this study: the Cummins ISB 6.7 liter diesel, a 6.2 liter V-8 gasoline engine that is currently offered in Class 2b and 3 vehicles, and a Ford 3.5 liter turbocharged V-6 which is currently offered in Class 2a vehicles. The ISB diesel is considered the baseline engine for the Ram. The Cummins ISB is also the standard diesel engine sold in the Ram, and it is offered in three different ratings for 2014. The lowest rating of 350 HP and 660 lb-ft is offered with a manual transmission. This is the only manual transmission identified by SwRI among the three high volume pickup and van makers. There is a 370 HP / 800 lb-ft rating offered with Chrysler-built 6 and 8-speed automatic transmissions, and a 385 HP / 850 lb-ft rating offered with an Aisin 6-speed automatic. All of these ratings are chassis certified. SwRI modeled the top diesel rating with the 6-speed automatic. The Ram also offers 5.7 and 6.4 liter V-8 gasoline engines with 6-speed automatics. For 2014, the 6.4 liter gasoline engine offers EGR, which is advertised as a fuel saving technology. Chassis cab models offered by Ram use engine dynamometer certified gasoline and diesel ratings.

For this study, the 385 HP / 850 lb-ft top rating of the ISB was modeled. See Appendix B for details of this engine, and for the differences between this version and the medium truck version of the ISB that was used in the T270 and F-650. The gasoline engine models for the pickup are described in Appendix A. They are identical to the models used in the medium duty trucks.

From the engine's point of view, the biggest difference between the pickup truck and the medium duty trucks is the lower vehicle power demand of the pickup truck. The drag coefficient is lower, frontal area is lower, and vehicle mass is lower. The pickup has a wider range of vehicle masses across the payload options, however. The zero payload mass of the pickup is 6,876 pounds, while the mass at GCW with a loaded trailer is 25,000 pounds, almost as much as the T270 at full load.

FIGURE 3.25 RAM PICKUP TRUCK

3.3.6.1 Baseline Engine and Vehicle Results for Ram and Engines

Figure 3.26 below shows the *fuel economy* performance of the Ram truck with the three engines in their baseline form, all evaluated at 50% payload. Figure 3.27 shows the *fuel consumption* results for the same engines and payload. The same data is provided in tabular form in Tables 3.24 and 3.25 below the figures.

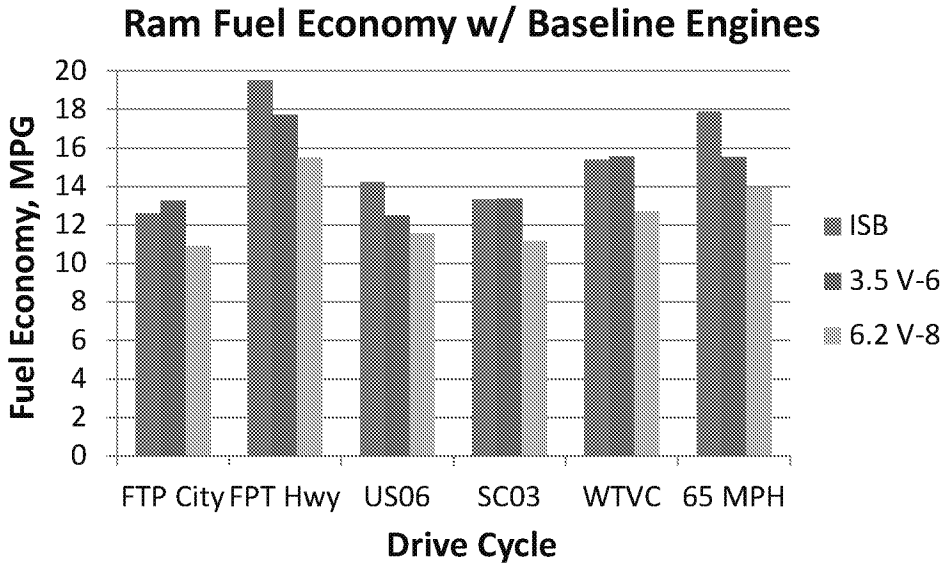


FIGURE 3.26 FUEL ECONOMY OF THE RAM WITH 3 ENGINES, ON 6 DRIVE CYCLES, AT ALVW

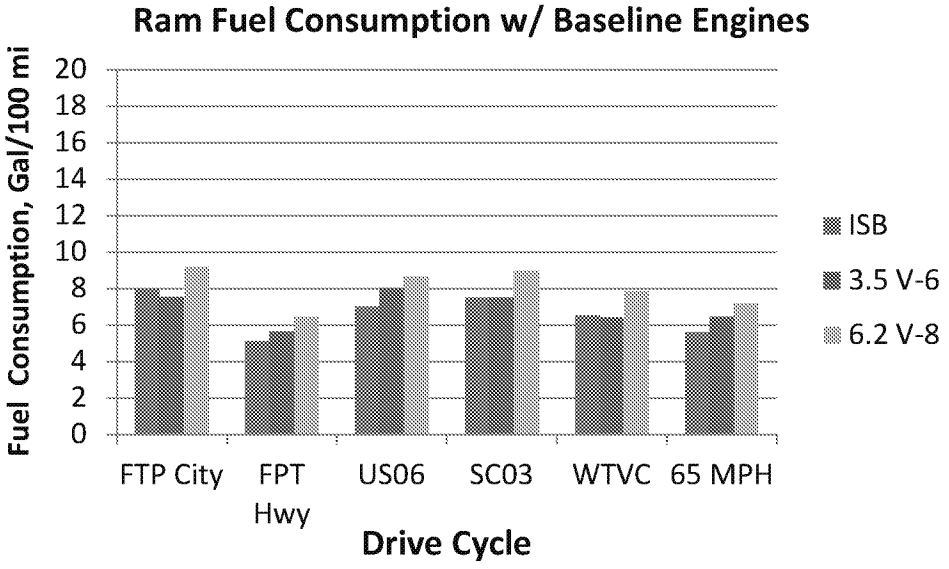


FIGURE 3.27 FUEL CONSUMPTION OF THE RAM WITH 3 ENGINES, ON 6 DRIVE CYCLES, AT ALVW

TABLE 3.24 FUEL ECONOMY OF THE RAM WITH 3 ENGINES, ON 6 DRIVE CYCLES, AT ALVW

Drive Cycle	ISB	3.5 V-6	6.2 V-8
FTP City	12.6	13.3	10.9
FTP Hwy	19.5	17.7	15.5
US06	14.2	12.5	11.6
SC03	13.3	13.4	11.2
WTVC	15.4	15.6	12.7
65 MPH	17.9	15.5	13.9

TABLE 3.25 FUEL CONSUMPTION OF THE RAM WITH 3 ENGINES, ON 6 DRIVE CYCLES, AT ALVW

Drive Cycle	ISB	3.5 V-6	6.2 V-8
FTP City	7.9	7.5	9.2
FTP Hwy	5.1	5.6	6.5
US06	7.0	8.0	8.7
SC03	7.5	7.5	9.0
WTVC	6.5	6.4	7.9
65 MPH	5.6	6.4	7.2

One surprise of the results shown above is that the 3.5 V-6 actually outperforms the diesel on some of the lower speed drive cycles. These cycles include time at idle, and as noted in the medium truck sections above, the diesel engine suffers from higher torque converter power absorption at idle. In the second phase of the project, the benefits of an idle neutral feature for the automatic transmission will be evaluated. Another factor is that the large diesel engine is not very efficient when running at very low loads.

An alternative way of comparing the three engines in the Ram pickup is provided in Figure 3.28 below. This compares the 3.5 liter V-6 and the diesel engine against a baseline of the 6.2 liter V-8. All engines are compared in their baseline form. The V-6 performs 8 to 18% better than the V-8. This is primarily due to the fact that for any given vehicle power demand, the V-6 engine is running at almost twice the BMEP as the larger displacement V-8. This means that the V-6 is often near the sweet spot of the fuel map, while the V-8 is often running at a relatively inefficient low BMEP point. It should be noted that in real life drive cycles where loads are heavy or the driver is aggressive, this advantage for the smaller V-6 will disappear. At high speeds and loads, the baseline V-6 runs in the enrichment portion of the map, which greatly reduces efficiency.

The ISB diesel performs 11 to 24% better than the baseline V-8, depending on the drive cycle. The ISB has a slightly larger displacement than the V-8, which is a small BMEP disadvantage. On the other hand, the lower speed range of the diesel makes it operate at lower RPM for a given vehicle power demand, which increases BMEP and (at lighter loads) improves

efficiency. The diesel also enjoys a lower minimum BSFC than either of the gasoline engines (see Appendix A and B).

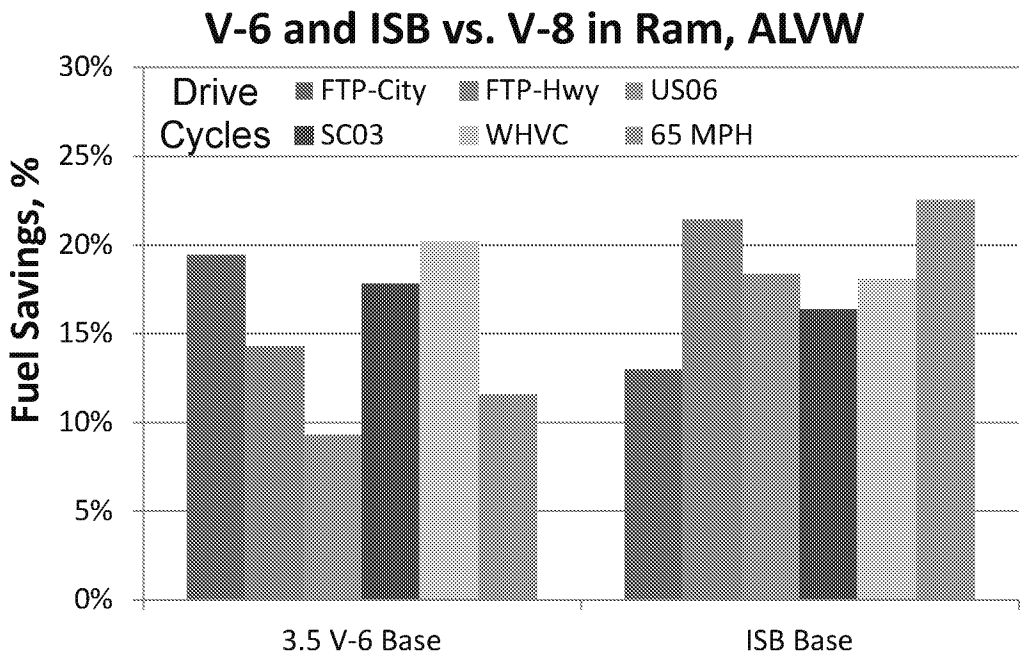


FIGURE 3.28 PERFORMANCE OF 3.5 V-6 GASOLINE AND 6.7 DIESEL BASELINE ENGINES AGAINST THE 6.2 V-8 GASOLINE ENGINE IN THE RAM TRUCK AT ALVW

3.3.6.2 Engine Technology Performance in the Ram Truck

The engine technologies listed in Tables 3.24, and 3.25 above were all evaluated using the baseline Ram truck configuration. Appendix B describes the details of the ISB diesel engine model, its calibration, as well as the assumptions and parameters involved in simulating each of the considered technologies. Appendix A covers the 6.2 liter V-8 gasoline engine and the 3.5 liter V-6 gasoline engine model. Table 3.26 summarizes the fuel savings performance of all the engine technologies that have been evaluated. Each technology's performance is compared to the baseline for that engine, and all are evaluated using the baseline Ram truck.

TABLE 3.26 FUEL SAVINGS RESULTS OF ENGINE TECHNOLOGIES IN THE RAM TRUCK. THE COLUMN OF RED NUMBERS UNDER THE US06 DRIVE CYCLE AT GCW INDICATES SIMULATIONS WHERE THE VEHICLE WAS UNABLE TO FOLLOW THE DRIVE CYCLE

Technology	Fuel Consumption Reduction (Percent) on Drive Cycle @ Payload																	
	FTP-City			FTP-Highway			US06			SC03			WHVC			65 MPH		
	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW
ISB + 5% Turbo Eff	2.5	2.4	1.6	2.5	2.4	1.5	1.7	1.6	0.9	2.2	2.1	1.3	2.4	2.4	1.7	1.8	1.8	1.2
ISB Low FMEP	8.0	7.6	4.1	7.2	6.7	3.1	4.2	3.8	1.7	7.4	6.8	3.4	8.5	8.0	4.6	4.6	4.5	2.4
ISB Low Back Pres.	0.9	0.8	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.5	0.4	0.3	0.6	0.5	0.2	0.0	0.0	0.4
No EGR	3.6	3.6	2.2	4.7	4.5	2.0	2.9	2.5	1.1	3.4	3.2	1.8	3.8	3.9	2.5	4.6	4.2	1.2
ISB 4-Cylinder	13	12	6.8	8.5	8.3	3.7	4.9	4.0	8.1	11	11	5.0	13	13	7.8	6.1	5.8	0.3
3.5 V-6 VVA / VVL	3.4	3.1	2.8	2.7	2.5	2.8	2.6	2.7	2.7	3.2	3.0	2.8	3.3	3.1	2.6	2.1	2.1	3.0
3.5 V-6 Cyl. Deact.	3.4	2.8	0.6	1.5	1.1	0.1	0.6	0.5	0.1	2.8	2.2	0.4	3.2	2.6	0.5	0.3	0.1	0.0
3.5 V-6 Lean GDI	13	12	5.5	15	13	3.9	8.7	7.3	1.5	13	11	4.6	15	14	6.1	15	13	0.8
3.5 V-6 Stoich EGR	3.5	3.7	7.9	4.0	4.2	7.7	4.8	6.0	17	3.6	3.9	11	3.5	3.6	5.2	3.4	3.6	6.4
3.5EGR + Downspd	7.2	7.0	7.0	10	9.5	7.9	7.5	8.0	20	8.1	7.5	10	7.4	7.4	5.7	8.2	8.0	5.6
3.5 V-6 Low FMEP	0.9	0.9	0.6	0.9	0.9	0.5	0.7	0.7	0.7	0.9	0.8	0.6	1.0	0.9	0.6	1.0	0.9	0.5
3.5 + 5% Turbo Eff	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
3.5 V-6 to Base ISB	-8.0	-5.3	11	8.3	9.2	20	10	12	25	-1.8	-0.2	16	-2.7	-1.2	11	12	13	22
6.2 V-8 GDI	0.0	0.0	0.2	0.3	0.3	0.0	0.3	0.3	1.3	0.0	0.0	0.4	0.1	0.1	-0.3	0.8	0.7	-0.1
6.2 V-8 Lean GDI	11	11	8.4	14	13	7.8	11	10	4.3	11	11	7.4	12	12	9.3	15	14	8.5
6.2 V-8 VVA / VVL	7.0	6.5	3.4	6.5	5.7	2.6	4.3	3.8	1.6	6.8	6.3	3.0	7.3	6.6	3.3	4.7	3.8	2.2
6.2 V-8 Cyl. Deact.	9.4	8.2	2.2	6.6	5.4	0.7	3.2	2.4	0.3	8.5	7.1	1.7	10	8.4	1.9	4.7	3.5	0.0
6.2 V-8EGR	3.0	3.2	6.4	4.2	4.4	7.0	4.6	5.6	11	3.3	3.5	7.5	3.2	3.5	4.9	4.4	4.6	6.5
6.2 V-8 Low FMEP	1.6	1.5	1.1	1.7	1.6	1.0	1.3	1.2	1.0	1.6	1.5	1.1	1.7	1.6	1.0	1.7	1.6	1.1
6.2 V-8 to Base ISB	13	14	16	21	21	22	18	19	30	16	16	20	18	17	16	23	22	21

The data provided in Table 3.26 can also be presented in graphical form. Figures 3.29, 3.30, and 3.31 below show the performance of the various engine technologies on the 6.7 liter diesel, the 6.2 liter gasoline engine, and the 3.5 liter gasoline engine. In each figure, the fuel saving benefit of a given technology is listed relative to that specific engine's baseline performance.

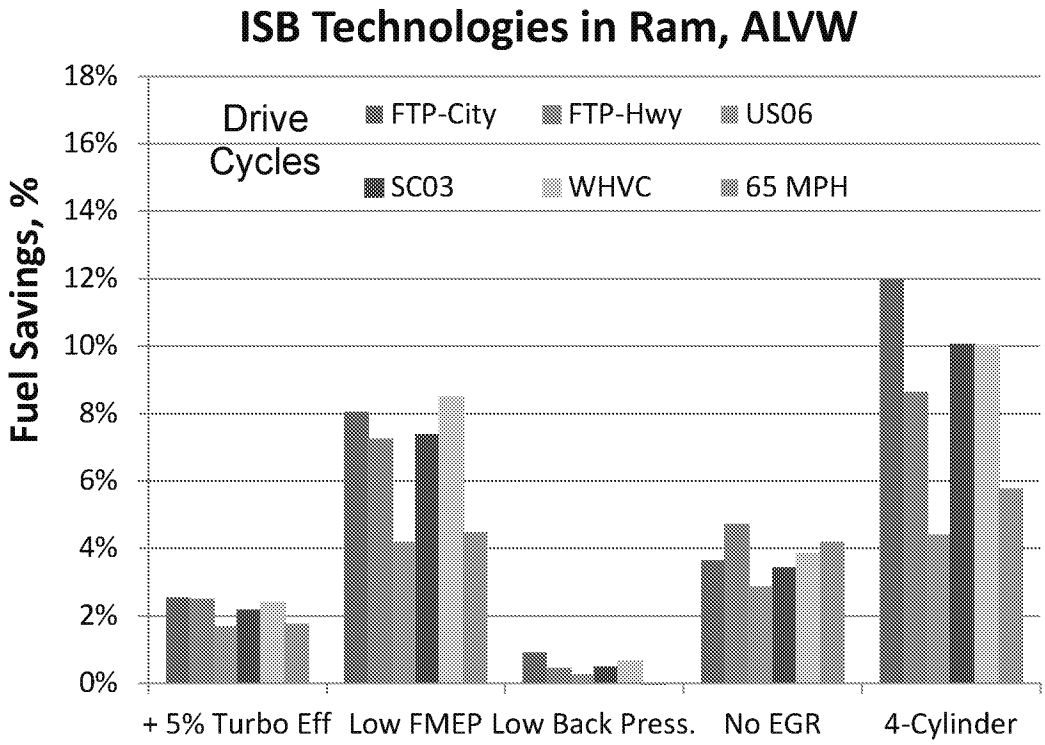


FIGURE 3.29 PERFORMANCE OF DIESEL TECHNOLOGIES IN THE RAM TRUCK

An increase in turbocharger efficiency provides about a 2% fuel consumption reduction for the diesel, at the expense of losing control of EGR rate (and thus NOx) at low RPM. The benefit declines with more aggressive drive cycles and at higher payloads. Reduced engine friction provides a 4% to 8% benefit, depending on drive cycle. The benefit of reduced friction is somewhat greater on the Ram than for the larger medium duty trucks. This makes sense: if vehicle power demand is reduced, friction becomes a larger portion of total power demand. As with the medium duty applications, low back pressure provides only marginal benefits. The benefit of removing EGR in the diesel is generally in the 3% to 4% range, which is a bit higher than was observed in the medium duty trucks. The BSFC benefit of eliminating EGR tends to be larger at light loads. The 4-cylinder diesel option provides substantial fuel savings, particularly on the more gentle drive cycles. The smaller engine operates at a higher BMEP, which makes it more efficient under light load conditions. Note that the 4-cylinder engine has only 2/3 of the power and torque of the 6-cylinder engine, so this option will not meet the needs of customers who want high power.

It is worth mentioning, however, that the 4-cylinder has more power and torque than any pickup diesel sold in the 1990s. Twenty years ago, the Cummins engine sold in Ram pickups had 160 HP and 400 lb-ft of torque, compared to the current top rating of 385 HP an 850 lb-ft. There has been quite the HP race among the pickup diesel engines. The performance of the 4-cylinder alternative shows that trading some of this increased performance for fuel consumption may be attractive to at least some customers.

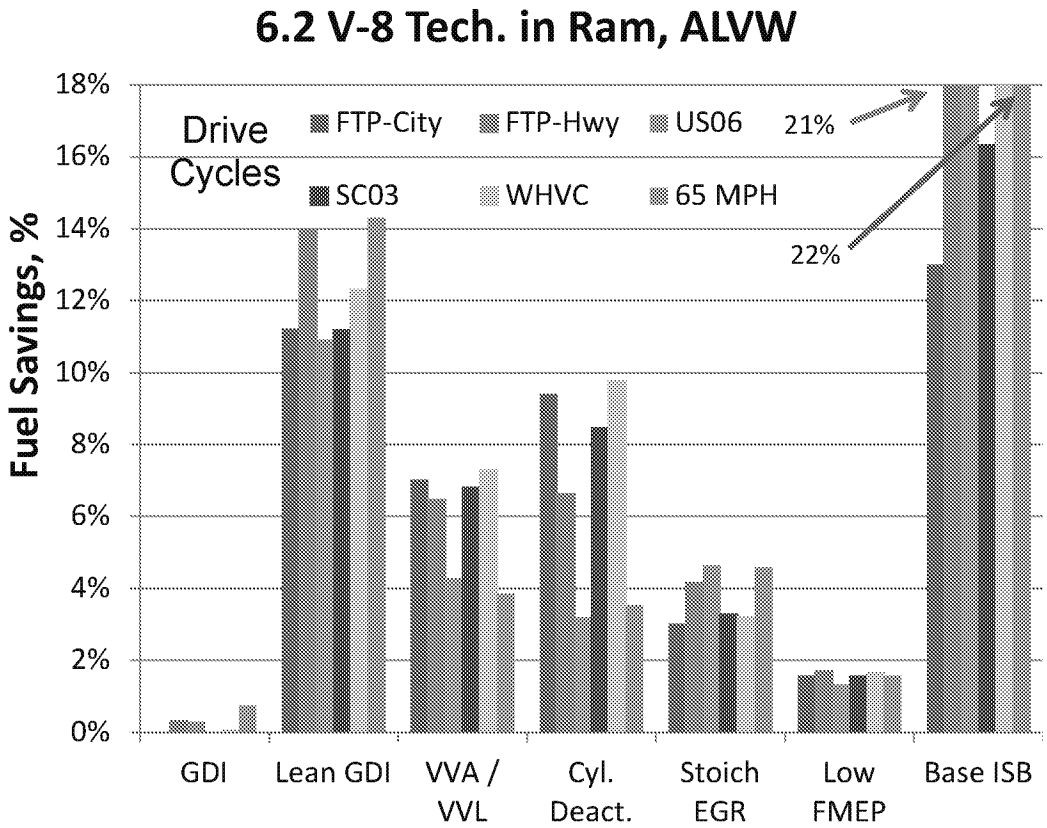


FIGURE 3.30 PERFORMANCE OF 6.2 V-8 GASOLINE TECHNOLOGIES IN THE RAM TRUCK, AND COMPARISON TO THE BASELINE DIESEL

As with the medium duty vehicles, GDI on its own provides little or no fuel consumption benefit for the V-8. The GT-POWER simulation showed that the higher efficiency provided by increased compression ratio is mostly canceled by the higher power demand of the high pressure fuel pump. (The fuel pump power demand was experimentally determined.) Lean GDI provides substantial benefits in the V-8, but there are extensive issues that would need to be resolved in order to come up with NOx aftertreatment that is reliable, durable, and which does not eliminate much of the fuel savings. The benefit of lean GDI is reduced when the vehicle runs at full GCW. At moderately high loads, a lean GDI engine runs stoichiometric, and at high speed and load, the engine runs rich, which eliminates the advantage compared to the baseline engine.

On this relatively large V-8 engine, reductions in pumping work are more important than on a smaller engine like the 3.5 V-6. As a result, VVA/VVL and cylinder deactivation provide significant benefits, especially on the more gentle drive cycles where the engine spends most of its time at light load. Lower friction also is a larger factor for the big V-8, but the benefits are still under 2%. EGR provides a 3% to 4% benefit with zero payload and at ALVW, but more when the vehicle is run at full GCW. At high loads, EGR allows the engine to avoid enrichment. The differences between the V-8 and the diesel show one of the reasons that the diesel is a popular option. Especially on highly loaded drive cycles, the diesel shines in comparison to the big V-8.

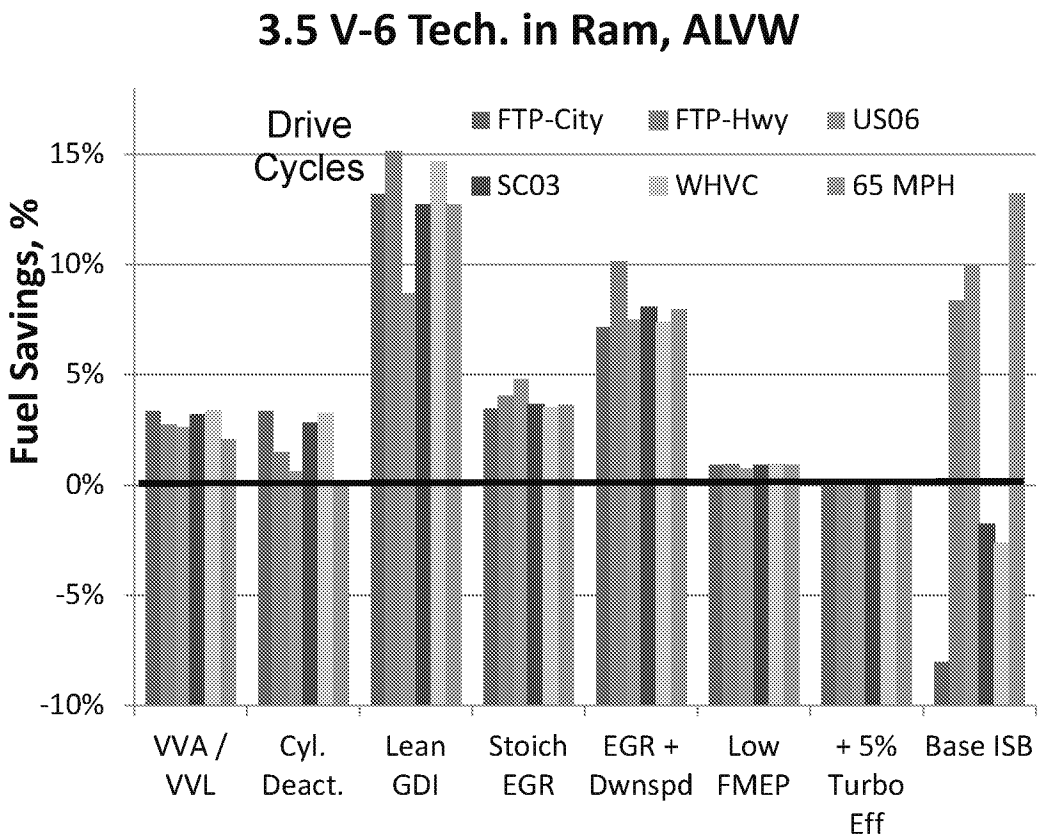


FIGURE 3.31 PERFORMANCE OF 3.5 V-6 GASOLINE TECHNOLOGIES IN THE RAM TRUCK, AND COMPARISON TO THE BASELINE DIESEL

Note that zero percent fuel savings is near the center of the plot in Figure 3.31. VVA/VVL and cylinder deactivation provide a smaller benefit on the 3.5 V-6 than on the larger V-8, because the smaller engine needs to run at higher BMEP to deliver a given power requirement. Lean GDI provides impressive benefits in the V-6, but has the same implementation issues as are described for the V-8. The benefit of lean GDI is greatly reduced when the vehicle runs at full GCW with the 3.5 V-6. At moderately high loads, a lean GDI engine runs stoichiometric, and at high speed and load, the engine runs rich, which eliminates the advantage compared to the baseline engine. EGR provides around a 4% benefit in the V-6 at zero payload and at ALVW, but substantially more at full GCW. For the downspeeding option, the engine maximum speed was reduced from 5,500 RPM to 4500 RPM, and the torque curve was increased to provide identical vehicle performance at the lower engine speed. The higher BMEP would require upgrade to the engine so it can tolerate higher cylinder pressure. In practice, this is likely to be an all-new engine. The benefits of EGR + downspeeding are substantial, however, at 7% to 10%.

Low friction contributes less than a 1% benefit on this small V-6 engine. The comparison to the diesel engine is a mixed bag. The V-6 has a fuel consumption advantage on drive cycles that involve low speed and idle operation. Two factors work in favor of the V-6 on these drive cycles: higher BMEP due to having little over half the displacement of the diesel, and

the fuel sapping torque converter power demand on the diesel at idle. On the higher speed drive cycles, the diesel retains a significant advantage.

3.3.6.3 Vehicle Technology Performance in the Ram Truck

The performance of fuel saving vehicle technologies is summarized in Table 3.27 and Figure 3.32 below.

TABLE 3.27 PERFORMANCE OF VEHICLE TECHNOLOGIES ON THE RAM TRUCK USING THE BASELINE 6.7 DIESEL ENGINE. RESULTS ON THE US06 CYCLE AT GCW ARE MARKED IN RED, BECAUSE THE VEHICLE WAS UNABLE TO FOLLOW THE CYCLE

Technology	Fuel Consumption Reduction (Percent) On Drive Cycle @ Percent of Maximum Payload																	
	FTP-City			FTP-Highway			US06			SC03			WHVC			65 MPH		
	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW	0%	ALVW	GCW
A/C -40%	2.2	2.2	1.2	1.5	1.4	0.7	1.1	1.0	0.5	2.1	2.0	1.1	2.4	2.2	1.4	0.9	0.9	0.5
Cd - 10%	0.7	0.6	0.4	2.6	2.5	1.3	2.7	2.4	1.2	0.7	0.6	0.4	3.2	3.1	1.6	3.8	3.5	2.1
Crr - 30%	2.6	2.7	4.6	4.0	4.4	7.0	2.6	2.9	4.3	2.2	2.8	4.3	2.8	3.3	6.7	3.4	4.0	7.0
8-Spd Auto	4.8	4.1	3.7	3.7	3.3	1.4	0.8	1.0	1.9	2.4	2.7	2.7	3.5	3.3	1.6	1.9	1.7	0.2
Wght - 500 lb.	2.0	1.7	1.3	2.2	2.1	1.2	2.5	2.6	1.3	2.2	2.3	1.6	1.5	1.5	1.1	1.8	1.7	1.0
Chassis Fr - 30%	0.5	0.3	0.7	0.5	0.6	0.8	0.6	0.6	0.7	0.4	0.4	0.8	0.4	0.4	0.8	0.6	0.6	0.8

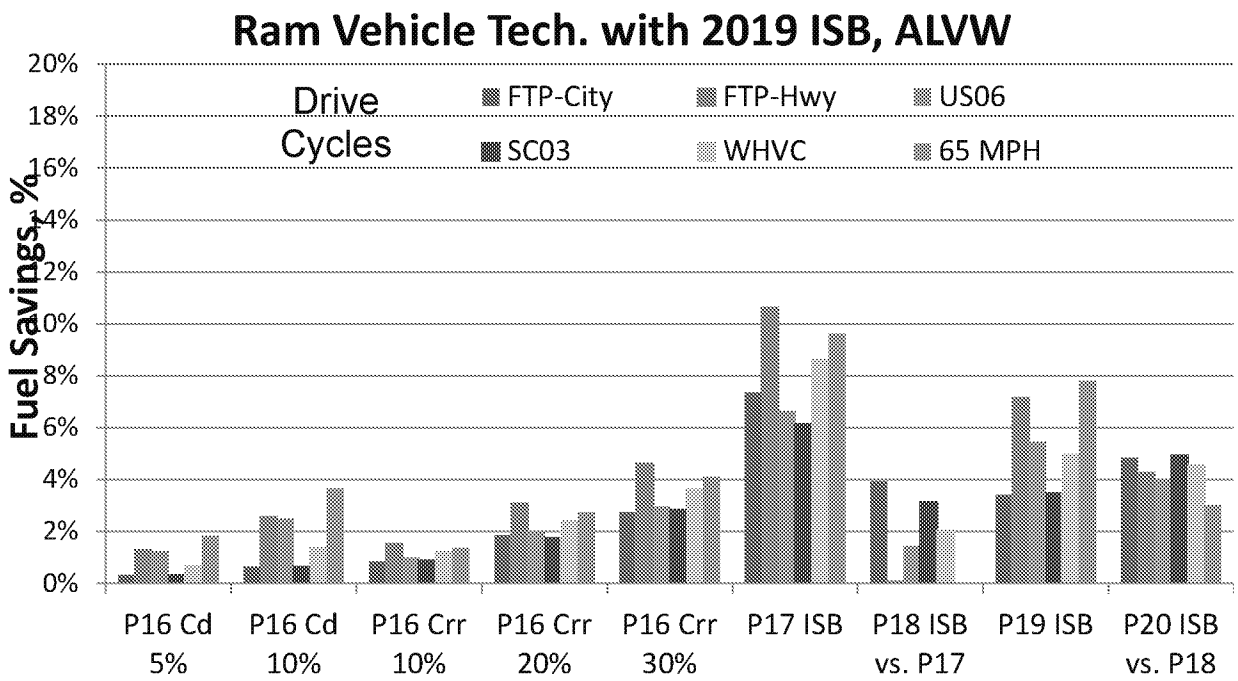


FIGURE 3.32 PERFORMANCE OF VEHICLE TECHNOLOGIES IN THE RAM TRUCK WITH THE BASELINE 6.7 LITER DIESEL ENGINE

The value of a 600 Watt reduction in air conditioning power demand is largest on lightly loaded drive cycles, and at zero payload. Aerodynamic drag reduction plays a relatively small role, for two reasons. First, an improvement of only 10% was projected. Second, the frontal area of a pickup truck is much lower than that of a larger truck, so aerodynamic drag is a smaller portion of overall power demand. A 30% reduction in rolling resistance provides a 2.2% to 4% benefit at zero payload and at ALVW, but larger improvements at GCW. Note that the trailer tire rolling resistance was also improved in this simulation.

An 8-speed automatic transmission provides a 1% to 4% improvement over the baseline transmission. Most of this improvement is due to higher mechanical efficiency of the 8-speed unit, rather than any benefit from closer matching of gear ratios to the engine fuel map. In this study, the 8-speed transmission was geared to cruise at the same engine RPM as the baseline transmission. In some cases, the OEM might gear the 8-speed taller, to take advantage of the wider ratio range from first gear to the top gear. The second report will look at this opportunity.

A 500 pound weight reduction provides a benefit of about 2% at zero payload and at ALVW. At the full GCW, the benefit of a 500 pound weight reduction is about 1%. Reduced chassis friction provides a benefit of less than 1%.

3.4 Trade-Offs Between Fuel Consumption / CO2 and Future Emissions Standards

For many years, developers of diesel engines have struggled with trade-offs between NOx emissions and two other parameters: PM emissions and fuel consumption. Historically, steps taken to lower engine-out NOx have tended to increase both PM and fuel consumption. The introduction of diesel particulate filters (DPF) in 2007 greatly reduced the trade-off with NOx and tailpipe PM. The DPF is so effective that engine-out PM can run at very high levels without exceeding the tailpipe requirement. The primary downside of high engine-out PM is the need for more frequent DPF regeneration, which costs fuel.

All of the figures in this section show data for 12 to 15 liter long-haul truck engines. This section will focus on heavy-duty engines, for which more data is available. Figure 3.33 below shows the trade-off between NOx and fuel consumption, using data acquired by SwRI over a number of years on several different projects. These engines were equipped with unit injector fuel systems, which are capable of only single-shot injection. Unit injectors also have high injection pressure at rated speed, but injection pressure falls off as engine speed goes down. These engines represent a variety of combustion chamber designs. Best point fuel consumption is shown in the figure, not the SET fuel consumption result, which will be higher. At 0.2 g/bhp-hr engine-out NOx, SwRI has determined the typical best point BSFC to be about 225 g/kW-hr. Fuel consumption drops in an exponential fashion as NOx is increased, with a value of 188 g/kW-hr at about 10 g/bhp-hr NOx (14 g/kW-hr). The total fuel consumption penalty for reducing engine-out NOx across this range is almost 20%.

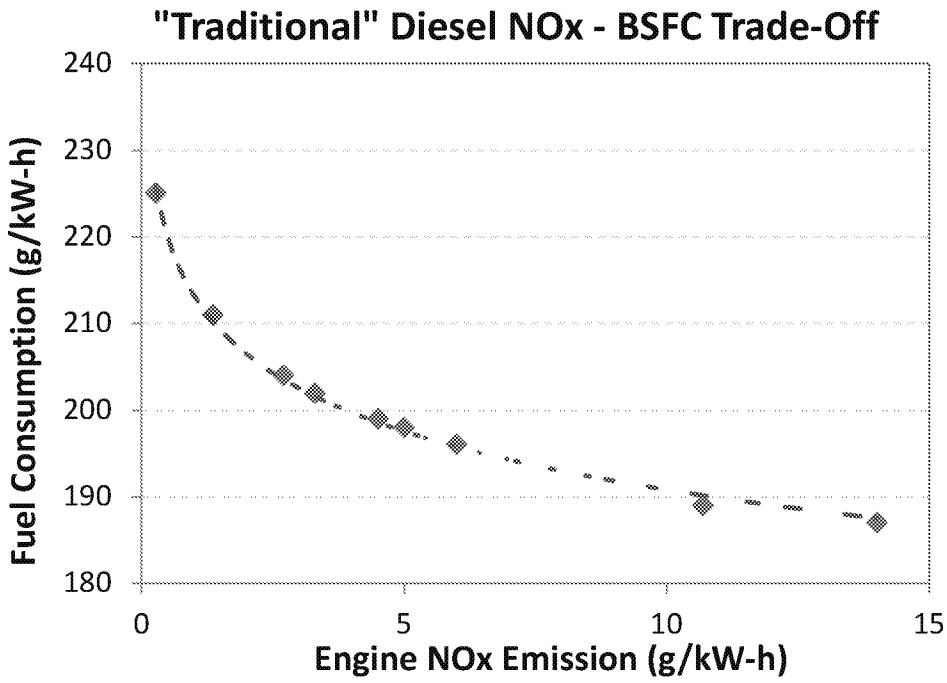


FIGURE 3.33 NOX / BEST POINT BSFC TRADE-OFF WITH TRADITIONAL ENGINE TECHNOLOGY

Over time, researchers and engine manufacturers have learned to drive the NOx / BSFC trade-off curve down a bit, and make the "elbow" of the curve much steeper. Figure 3.34 shows 13-mode SET fuel consumption data taken by SwRI on production engines complying with 2004, 2007, and 2010 emissions requirements. The thick red curve represents the trade-off for 2004 compliant engines. The thick blue curve shows the NOx / BSFC trade-off for 2007 and 2010 compliant engines. Finally, there is also a thin blue curve representing the possible future direction of development, and how that will improve the NOx / BSFC trade-off.

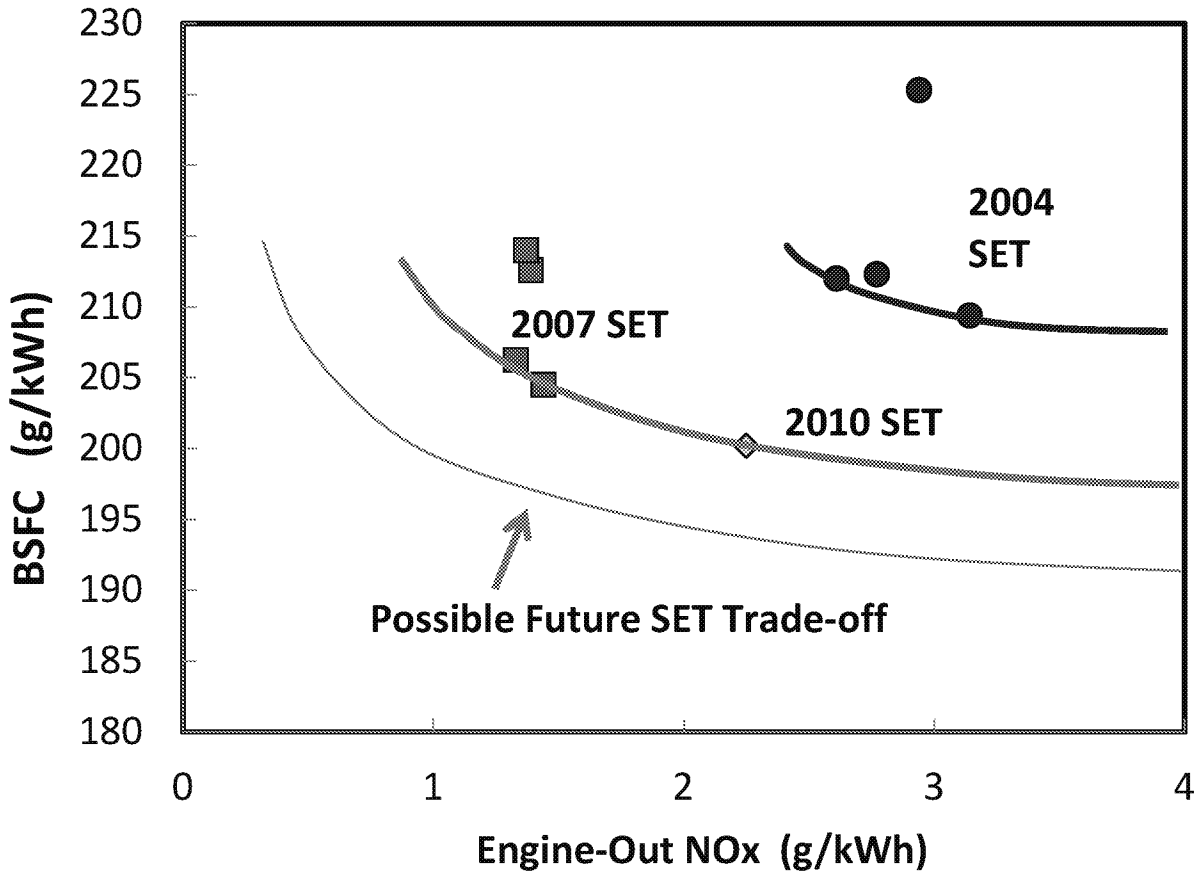


FIGURE 3.34 EVOLUTION OF NOX / BSFC TRADE-OFF OVER TIME, USING SET RESULTS

In order to enable the production implementation of new fuel saving technologies, some key limiting-issues must be addressed, including:

1.) "Best-point" fuel efficiency may not scale to full-operating range fuel efficiency. A significant part of production-development work is devoted to unavoidable tradeoffs in best local-optimum operation versus best drive-cycle operation and best regulatory cycle operation. These three targets are often mutually-exclusive to some degree. It is important that regulatory cycles be as similar as possible to real-world use, in order to limit this discrepancy. Sections 4.4.3 and 4.5.2 expand on this issue.
2.) An engine designed to provide the highest fuel efficiency may not meet other production requirements, such as NVH, durability, cost, etc.
3.) OBD requirements have not been considered and will play a key role in selection of producible, saleable engines. For example, if a very high efficiency SCR system is applied, diagnosing failures at the required level becomes very difficult.

As will be explained below, there isn't much that can be done to improve fuel consumption at very low engine-out NOx levels approaching the current tailpipe regulatory limit of 0.2 g/bhp-hr. There does appear to be scope for improving upon the trade-off curve shown in

Figure 3.34 at higher levels of engine-out NOx, such as in the 1 to 3 g/bhp-hr range. Research is under way in the engine industry to determine how much improvement is possible in the 1 to 3 gram NOx range.

The cause of high fuel consumption at low engine-out NOx levels is primarily due to the combination of pumping losses (driven by high dilution/EGR for low NOx) and extended combustion duration. High EGR rates (high dilution) lead to slower combustion and thus longer combustion duration. As combustion duration gets longer, less of the expansion stroke is available to extract energy from the combustion event. This leads to a decline in fuel efficiency.

As diesel combustion begins, the dominant combustion reaction path depends on formation of an alkyl peroxyl radical that becomes less stable as the temperature increases. These reactions start slowly, and because of reduced stability actually slow down further as the temperature increases. But with a further increase in temperature another reaction mechanism becomes predominant. In this second reaction path, hydrogen peroxide is formed, each molecule of which easily breaks into two hydroxyl radicals (OH). This chain branching reaction path rapidly increases the combustion rate, and continues to speed up with increased temperature. It is this chain branching reaction path that is critical to the rapid energy release required for efficient operation. These two reaction paths, and the change in importance of each with temperature, were reported by Professor James Keck at MIT, and his graduate student [ET-30].

Based on these reaction paths, Flynn and his colleagues at Cummins demonstrated the impact of flame temperature in the diesel engine combustion chamber [ET-31]. In practical terms, at lower in-cylinder temperatures the slower initiation reaction scheme predominates, and it is only at higher temperatures that the much faster, branching reaction path takes over. The transition in dominance between these reaction paths occurs at flame temperatures that correspond to the knee shown in the NOx/BSFC curves of Figures 3.33. As the flame temperature is reduced further, the fuel consumption penalty gets continually worse, with combustion becoming prohibitively slow as the engine approaches 0.2 grams in-cylinder NOx production.

Since 2010, most truck engines sold in the USA use SCR to reduce tailpipe NOx levels, and this approach will soon be universal. SwRI has measured the performance of several 2010 to 2013 engines and SCR systems. On the composite FTP transient cycle, NOx conversion efficiencies of 90 to 92% are common. This has allowed compliance with the current NOx standard using an engine-out NOx level of 1.5 to 2 g/bhp-hr, allowing some margin for production compliance. Under the steady-state SET test cycle, conversion efficiencies reach 98% or more. This would in theory allow very high engine-out NOx levels, but manufacturers have tended to limit engine-out NOx to around 2 – 3 g/bhp-hr in order to limit urea consumption. Urea consumption increases linearly with engine-out NOx. Even though urea consumption has a small contribution to CO_2 emissions compared to using diesel fuel, the cost of urea to operators is significant.

Figure 3.35 below shows the engine-out NOx vs. BSFC data from Figure 3.33, along with urea consumption (DEF or Diesel Exhaust Fluid) and total fluid consumption. This figure suggests a minimum total fluid consumption at around 3 to 4 grams engine-out NOx per bhp-hr.

In Figure 3.35, if the cost of diesel fuel and DEF is the same ($/gallon), then the green curve representing total fluid consumption would also represent the operating cost for fuel and DEF. In practice, DEF prices vary widely, with lower prices for bulk delivery by tanker truck, and much higher prices when purchased in 1 gallon jugs. On March 4, 2014, Flying J Truck Stops web site quoted a price of $2.79 per gallon for DEF from the pump at their stations, with diesel fuel costing $3.79 to $3.99 per gallon. Large fleets that buy DEF in bulk will pay less than a driver at a truck stop. At the other extreme, automotive web sites quote $6/gallon for DEF in 2.5 gallon jugs. If the lower per gallon price of DEF for many operators is factored in, and fluid consumption is replaced by fluid cost, then the optimum engine-out NOx level is somewhat higher – around 5 to 6 grams at early 2014 diesel fuel prices.

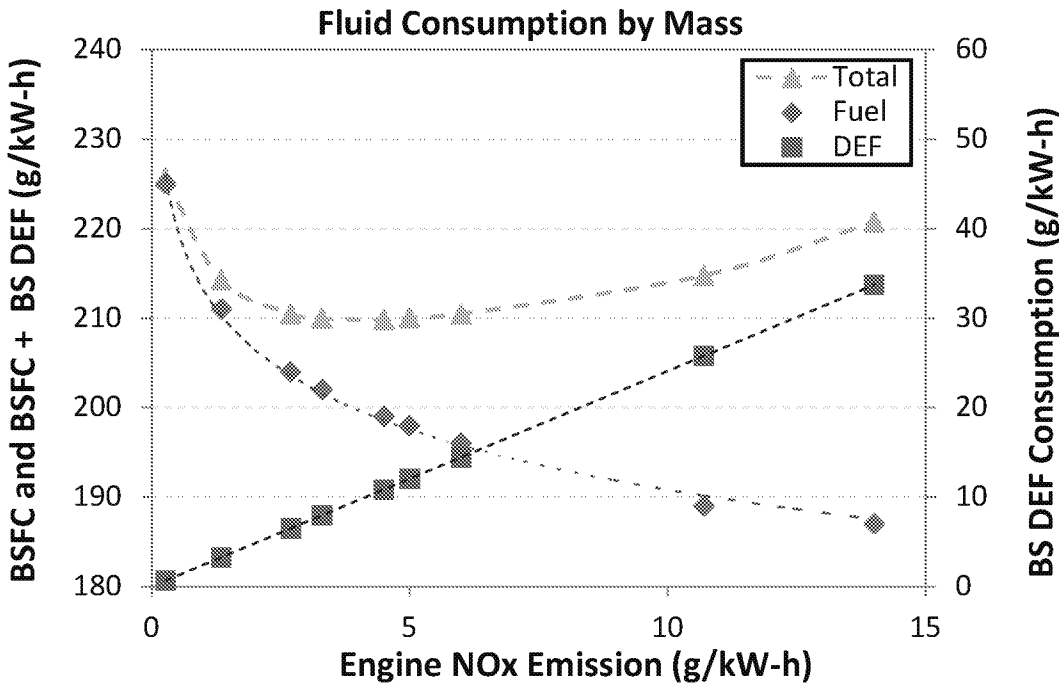


FIGURE 3.35 FUEL CONSUMPTION AND TOTAL FLUID CONSUMPTION (LEFT AXIS) AND DEF CONSUMPTION (RIGHT AXIS) AS A FUNCTION OF ENGINE-OUT NOX

Figure 3.36 below shows the same data, but assuming a future, improved NOx vs. BSFC trade-off. Because these results are speculative, the actual values have been removed. In this situation, the minimum fluid consumption occurs at an engine-out NOx level of about 1.5 to 2 g/bhp-hr. The minimum fluid cost point at current diesel fuel and DEF prices would be around 2 to 2.5 grams NOx, assuming $2.80 for DEF and $3.90 for diesel fuel.

If the tailpipe NOx standard is reduced using current SCR systems, engine-out NOx may have to be reduced from current levels in order to maintain tailpipe NOx compliance. Other alternatives include improved SCR system efficiency and/or thermal management of the SCR.

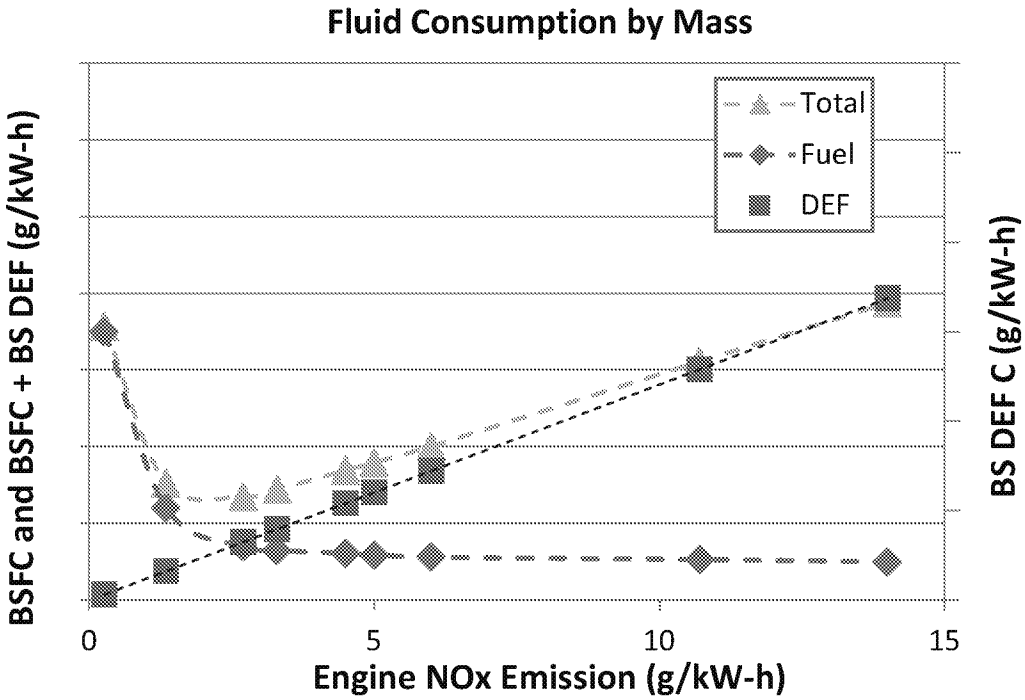


FIGURE 3.36 FUEL CONSUMPTION AND TOTAL FLUID CONSUMPTION (LEFT AXIS) AND DEF CONSUMPTION (RIGHT AXIS) AS A FUNCTION OF A POTENTIAL FUTURE NOX / BSFC TRADE-OFF

Note that thermal management usually entails a fuel consumption penalty. As the figures above show, this could cause an increase in fuel consumption and CO2 emissions. In order to bring the fuel consumption penalty of lower NOx standards down to a more acceptable level, more efficient SCR systems will be required, and OBD issues will need to be overcome.

There has been rapid progress in SCR conversion efficiency over the last 10 years, since these systems first went into production for European trucks around 2004. In fact, one of the major sources of reduced fuel consumption in 2014 model year GHG certified engines compared to their 2010 predecessors is higher engine-out NOx, enabled by more efficient SCR systems. SwRI's expectation is that for 2017 Phase 1 GHG compliance, engine manufacturers are likely to take advantage of improving SCR systems to push up engine-out NOx to some degree. This will enable a modest reduction in fuel consumption and CO_2 emissions.

It can be anticipated that further increases in SCR system efficiency will occur. However, cycle-weighted conversion efficiencies may have to increase by an order of magnitude (from 90 – 92% to over 99% on the composite FTP) in order to allow a factor of 10 decrease in the NOx standard, if there is to be no fuel consumption penalty compared to today's engines. Similarly, if the NOx standard is reduced by a factor of 4 (to 0.05 g/bhp-hr), SCR efficiencies may need to increase by a factor of 4 to avoid an increase in fuel consumption. Even if these more efficient SCR systems become available, OBD issues may prevent OEMs from taking full advantage of them.

4.0 EVALUATION OF TESTING AND SIMULATION APPROACHES

4.1 Fuel Efficiency Metrics

As part of this project, SwRI evaluated the fuel efficiency metrics used in the current GHG / fuel consumption regulations, and considered potential alternatives or additions. The units used in the current regulations are based on emissions or fuel consumption per unit work, and are summarized in Table 4.1 below:

TABLE 4.1 FUEL EFFICIENCY AND GHG METRICS IN CURRENT REGULATIONS

Regulated System	Type of Regulation	Metric Used
2b/3 Trucks	GHG	Grams of CO_2 /mile
2b/3 Trucks	Fuel Consumption	Gallons/100 mile
Vocational and Tractor Vehicles	GHG	Grams of CO_2 per ton-mile
Vocational and Tractor Vehicles	Fuel Consumption	Gallons per 1000 ton-miles
Engines	GHG	Grams of CO_2 per bhp-hr
Engines	Fuel Consumption	Gallons per 100 bhp-hr

EPA and NHTSA set standards for HD pickups and vans based on the proposed "work factor" attribute that combines a portion of the vehicle payload capacity and vehicle towing capacity, in pounds, with an additional fixed adjustment for four-wheel drive (4wd) vehicles. This adjustment accounts for the fact that 4wd, critical to enabling the many off-road heavy-duty work applications, adds roughly 500 lb to the vehicle weight. **Citation: 76 FR 57162**

For heavy-duty trucks, both combination and vocational, the agencies adopted standards expressed in terms of the key measure of freight movement, payload ton-miles or, more simply, ton-miles. Hence, for EPA the final standards are in the form of the mass of emissions from carrying a ton of cargo over a distance of one mile (g/ton-mi). Similarly, the final NHTSA standards are in terms of gallons of fuel consumed over a set distance (one thousand miles), or gal/ 1,000 ton-mile. Finally, for engines, EPA is adopting standards in the form of grams of emissions per unit of work (g/ bhp-hr), the same metric used for the heavy-duty highway engine standards for criteria pollutants today. Similarly, NHTSA is finalizing standards for heavy-duty engines in the form of gallons of fuel consumption per 100 units of work (gal/100 bhp-hr). **Citation: 76 FR 57115**.

[NRC 2010, pages 20 - 28] devoted significant effort to a discussion of metrics for fuel efficiency. This report pointed out that the most popular metric for fuel efficiency in North

America, miles per gallon, has a number of disadvantages. First, MPG is a non-linear metric. A 2 MPG improvement from a baseline of 6 MPG represents a huge benefit, while a 2 MPG improvement from a baseline of 50 MPG is almost insignificant. Another issue is that a 100% increase in MPG only represents a 50% reduction in fuel consumption, fuel cost, and GHG emissions. These factors make it easy for people to make incorrect decisions when dealing with a complex data set.

As discussed in Section 2.2, fuel consumption is inversely proportional to fuel economy. Fuel consumption can be measured in units of gallons per 100 miles traveled or, in metric units, liters per 100 km. Fuel consumption is a linear metric. If the fuel consumption of a vehicle is reduced by 2 gallons per 100 miles, the cost of driving 100 miles is reduced by a fixed amount (2 gallons times the fuel price), regardless of whether the vehicle started with a fuel consumption of 3 gallons or 30 gallons per 100 miles. Also, a 50% change in fuel consumption will translate directly into a 50% reduction in fuel cost and GHG emissions. For vehicles that perform work, such as the delivery of goods or passengers, units of work-specific fuel consumption are desirable [NRC 2010]. The units used in the current GHG regulations conform with the NRC's recommendations.

Metrics for units of work include ton-miles, but there are other types of work that vehicles can perform. A bus could be evaluated in terms of passenger-miles. Depending on cargo density, many trucks can be completely full but below the legal weight limit (i.e., cube-out). This fact suggests the possibility of a work unit in terms of gallons per cubic volume-mile, resulting in a work specific metric such as gallons consumed per million cubic foot - miles.

A passenger and luggage load can be readily converted into a mass-based metric such as tons, so a metric in terms of gallons per 1000 passenger-miles is probably redundant. However, it is more risky to completely avoid a volume-based metric. Some truck configurations lend themselves to efficiently moving low-density freight, while others favor high-density freight. For example, when moving high-density freight, it would be easy to reduce frontal area (and thus aerodynamic drag), because the cargo space can be relatively small. Low-density freight, on the other hand, is moved most efficiently in a vehicle with a high cargo volume. The use of both mass and volume-based metrics would seem particularly useful in situations where potential changes to vehicle length and weight regulations are being considered. If there is no intention to consider changes in vehicle cargo capacity (either mass or volume), then the existing mass-based metrics should be adequate. In the cases of vehicle mass reduction or increased payload with existing payload volume, the existing mass-based metric will capture the benefit.

Consider the example of a vehicle configuration being used to a limited extent in Canada today: turnpike doubles. A turnpike double consists of a standard tractor pulling two 53-foot box van trailers. This configuration has a total of nine axles, four of which support the second trailer. If the current US axle weight limits are retained, this vehicle could operate at a GCW of 148,000 pounds. However, to limit loading of bridges and for safety reasons, such a vehicle might be limited to 120,000 pounds (in Canada, the limit is 140,000 pounds, or 63,500 kg). Assume an empty weight of the turnpike double vehicle of 48,000 pounds, compared to 34,000 pounds for a standard 53-foot single trailer configuration. The change in payload possible at a 120,000 or 140,000-pound limit would be:

TABLE 4.2 COMPARISON OF PAYLOADS FOR LONG COMBINATION VEHICLES

Vehicle Configuration	Weight Limit	Empty Weight	Payload	Payload Increase, %
53 foot single	80,000	34,000	46,000	N/A
53 foot double	120,000	48,000	72,000	56.5%
53 foot double	140,000	48,000	92,000	100.0%

While the available payload increases by 56.5% for a 120,000-pound turnpike double, the volume available for cargo increases by exactly 100%. For operators carrying low-density freight who cube-out rather than gross-out, the appropriate efficiency metric would be fuel consumption per volume-mile, because these operators would double the amount of freight they can deliver with a single vehicle. Weight limited operators would see a smaller but still substantial benefit. At a 140,000-pound weight limit, there would be no difference between the increase in cargo mass and volume. Note that in the case of these large doubles, the fuel consumption of a given vehicle does increase compared to a traditional single trailer configuration. However, fuel consumption increases by much less than payload mass or payload volume increases, so there is a substantial increase in fuel efficiency [NESCCAF, 2009].

Another issue is that not all medium- and heavy-duty vehicles transport goods or passengers. Some trucks simply deliver a capability to a job site, usually in the form of some sort of equipment. These capabilities include examples such as towing, well drilling, or bringing maintenance tools and parts to a job site. A utility bucket truck is another example of a vehicle used to bring a capability to a job site, rather than to deliver freight. Despite the lack of a "cargo", the best efficiency metric for these vehicles may still be units of gallons per 1000 ton-miles. In this case, cargo mass is replaced with the mass of the equipment installed on the vehicle, including, if appropriate, a typical load of replacement parts and other removable equipment or tools that are needed to perform the job.

It is possible to quibble with the units of fuel consumption now used for engine fuel consumption certification. Gallons per 100 bhp-hr is not a unit familiar to any engine development engineer (or to any member of the public). Mass-based fuel consumption units are typically used in engine development: brake specific fuel consumption is measured in terms of grams of fuel per kW-hr in metric units, or pounds per bhp-hr for English units. One reason for using mass based units is that volume based units are very sensitive to fuel density. For example, a gallon of gasoline has about 13% less energy content than a gallon of diesel. On the other hand, gasoline and diesel fuel have similar energy content per unit mass, because of the higher density of diesel fuel. If a switch from the current volume-based units to more familiar mass-based units is considered, the regulators must keep in mind the different densities (and energy content and carbon content) of fuels such as gasoline and diesel. Note that ethanol (used in E10 gasoline) has a lower energy content both on a per unit volume and per unit mass basis, compared to gasoline and diesel fuel.

The units used for GHG certification of engines are an odd mix of metric and English units (grams per bhp-hr), but at least these units are familiar from their use in criteria pollutant regulations.

4.2 Matching Test and Simulation Procedures to Technologies

Many engine and vehicle technologies that can have an effect on vehicle fuel consumption. It is important to match the test or simulation procedure to the technology being evaluated in order to accurately account for the performance of the technology under consideration.

As a first step, the technologies can be separated into two categories:

1. Technologies that affect the efficiency of generating power
2. Technologies that affect the vehicle's demand for power

Or, the issue can be expressed using very simple terms:

1. How efficiently can I make power?
2. How much power do I need to do the job?

Generally, the first category includes engine technologies, but things like waste heat recovery and hybrid systems can fall into this category as well. The second category encompasses any feature that has an influence on vehicle power demand. This basic split fits well with the current regulatory approach of having an engine efficiency standard and a separate vehicle efficiency standard. Unfortunately, not every technology can be effectively evaluated using the same testing or simulation approach. In this section, we will consider the range of fuel saving technologies, and look at the available approaches for evaluating technology performance.

It is also worth noting that some technologies perform best at full payload, while others perform best at zero payload, and some technologies are insensitive to load. As a result, it is best to evaluate technologies over a range of payload, to ensure that real-world performance is captured.

4.2.1 Engine (Powertrain) Efficiency

The current regulatory approach for evaluating engine efficiency is an engine dynamometer test. This test provides results in terms of fuel consumption or CO_2 emissions per unit of work. Engine (or powertrain) efficiency can also be predicted using simulation, as we have done in this study. Simulation is very helpful for evaluating technology options and for specifying hardware to be used in a development project. However, a lot can happen between a simulation and a finished product, so we do not recommend using engine simulations to certify engine efficiency. A dynamometer test on an appropriate duty cycle is a more reliable way to determine efficiency.

On which technologies does the current engine test certification procedure perform well? Generally, it does a good job on the following technologies:

- Engine friction reduction, including lubricants, bearings, etc.

- Combustion systems
  - Combustion chamber shape
  - Fuel injection characteristics, including injection timing
  - Swirl, tumble
  - Ignition system characteristics, including ignition timing
  - Control of heat release rate
  - Engine-out emissions strategy
- Turbochargers
- EGR systems (or the lack of one)
- Turbocompound systems
- Downsizing (but not downspeeding, see the discussion below)
- Reduced restrictions (intake, charge air cooler, exhaust)
- Variable valve actuation
- Cylinder cutouts

One area where the current engine dynamometer test approach falls short is when we would like to accurately determine the performance of a feature that only makes a very small difference in overall fuel consumption. In some cases, these technologies would be better evaluated using an alternative approach. For example, there are a number of power consuming accessories on an engine that could be improved, but where the magnitude of improvement is small enough to result in a large measurement uncertainty if an engine level test is used. Examples of these technologies include:

- Engine water pump
- Engine oil pump
- Engine high pressure fuel pump
- Friction reduction features, where individual features typically provide less than a 1% benefit
- Vacuum pump
- Air compressor
- Power steering pump
- Air conditioner compressor
- Active control of accessory power demand, such as on/off piston cooling nozzles

For technologies like these, we recommend two different approaches. For components that are part of the base engine, and which operate over the current regulatory dynamometer test cycle (for example, the water, oil, and fuel pumps, plus friction reduction features), any improvement can simply be considered part of the overall engine recipe. In these cases, the existing regulatory cycle is sufficient to capture the benefit, even if the engine dynamometer test is not sensitive enough to capture the benefit of a specific technology change. Other technologies (such as the vacuum pump, air compressor, power steering pump, and A/C compressor) will not be part of the normal certification test, so a different approach is required. The power consumption of the accessory can be very accurately measured in a test rig ("bench test") across a range of simulated engine operating conditions. Next, the change in accessory

power demand for each portion of the engine test cycle can be determined, and that data is used to determine the change in engine efficiency on its test cycle.

As an example, let us consider the idea of adding a clutch to an engine driven air compressor. The purpose of the clutch is to disengage the compressor from the drive at any time compressed air is not needed, similar to the way an air conditioner compressor clutch is used. According to data published by Cummins [Secrets of Better Fuel Economy, 2007], the compressor absorbs about 0.4 HP at cruising RPM when it is not active. It is very difficult to measure the change in fuel consumption or CO_2 from a 0.4 HP improvement with any certainty, if we use an engine dynamometer test. We are looking for approximately a 0.2% benefit, which is a smaller change than can be reliably measured using an engine dynamometer test.

However, measuring the power demand of the air compressor on a test rig can be accomplished to within 1% or so. Combined with vehicle duty cycle data, (what percent of the time is the compressor idle?) a very accurate estimate of the fuel savings from a compressor clutch can be generated. The technology provides a small benefit (0.2% in our example), but that small benefit can be very accurately determined with a combination of rig testing, duty cycle evaluation, and data analysis. The same basic approach can be applied to all the engine accessory technologies listed above. To cover the full list of technologies, a range of test setups and data evaluation approaches will be required. Since it would be very difficult for the regulator to cover all of the possibilities, we recommend that it be left to industry groups such as SAE to develop approaches for validating the performance of fuel saving technologies that fall into this realm. The regulators could develop a checklist for manufacturers. The checklist would require the manufacturer to show that their method of evaluating a technology properly takes duty cycle into account, and that their evaluation achieves an acceptable accuracy or error band size when estimating the technology's benefit.

There is one technology listed above where the effect would only be partially described by a rig test. On/off piston cooling nozzles would reduce oil pump power demand during times when piston cooling is not required. This benefit can be measured on a rig. However, turning piston cooling off has other effects that a rig test would not capture. The piston would run hotter under light loads, when the cooling is turned off. This will have two benefits: exhaust temperatures will go up slightly, which is a benefit to the turbo and to the aftertreatment, and there will be a (tiny) improvement in engine efficiency from increased piston power. These benefits may be too small to be measured directly in an engine dynamometer test, but they can be captured on the existing dynamometer test cycle as part of the overall engine efficiency result. As an alternative, since on/off piston cooling nozzles would be active on the current regulatory cycle, this technology could just be considered part of the base engine.

There is another group of technologies that are not amenable to either an engine test or a component level test. For example, the vehicle-level benefits of a downspeeding strategy may not show up, at least in full, on an engine-only certification cycle. The engine certification cycle is run at fixed speed and load points. However, with downspeeding, the engine operates at lower speed, and thus at a higher BMEP, for a given vehicle power demand. When power demand is below roughly 60%, an increase in BMEP will lead to higher efficiency. A powertrain efficiency

test cycle or vehicle simulation could determine the true vehicle level performance of a downspeeding strategy.

Also, as transmissions become increasingly computer controlled, there is an opportunity to improve the efficiency of power delivery by integrating the control of the engine and transmission. If you add vehicle electrification or other forms of hybrid such as hydraulic hybrids into consideration, this is another opportunity to provide power more efficiently. For these technologies, the best approach is a powertrain efficiency test, which is also referred to as a powerpack or powertrain test that includes both the engine and transmission. The powertrain is exercised over a defined power demand and road speed cycle (including, for hybrids, defined periods of negative power demand where regenerative braking can be performed). The powertrain test cycle would include specification of the powertrain output shaft speed and torque as a function of time, to simulate a given vehicle drive cycle chosen by the regulators. This test would be run on a dynamometer, and the powertrain controller would be left to determine how best to meet the power and speed demand. Just as with the existing engine test cycles, the result would be in terms of fuel consumption and GHG emissions per unit of work performed. Selection or development of a realistic vehicle power demand cycle is the key to getting appropriate results with this approach.

Note that there are issues that need to be resolved in order to create a powertrain test cycle. Existing engine cycles do not represent any specific vehicle drive cycle. A number of assumptions need to go into a powertrain cycle, such as vehicle configuration and mass, gear ratios, etc. Choices for these parameters will dictate the output shaft speed and torque as a function of time.

There are also issues that need to be addressed to keep a powertrain test cell test as realistic as possible. These issues are shared with chassis dynamometer testing. All the aftertreatment must be present in a realistic configuration, and heat losses from the exhaust system components need to reflect real-world conditions. The engine cooling system and charge air cooling must accurately represent the conditions found in real-world driving. A fair amount of test development is required to make the engine and aftertreatment perform in a test cell environment the same way that it performs in the vehicle.

4.2.2 Vehicle Power Demand

The current Phase 1 regulatory approach for evaluating vehicle power demand is the GEM model. For tractor-trailer trucks, the inputs to the GEM model are:

- Aerodynamic drag coefficient, determined by
  - Coastdown testing,
  - Wind tunnel testing,
  - CFD analysis, or
- Constant speed testing
- Steer and drive tire rolling resistance coefficients, determined by an ISO test procedure

- Vehicle empty weight reduction from a baseline value
- Road speed governor (vehicle speed limiter, or VSL) setting (if used, and if factory set for the life of the vehicle or for a defined time or mileage)
- Extended idle reduction feature, also called automatic engine shutdown, or AES (if used, and if factory set for the life of the vehicle or for a defined time or mileage)

In discussions with OEMs, SwRI was told that some customers resist taking advantage of the vehicle speed limiter (VSL) and automatic engine shutdown technology (AES) features that are factory set to qualify for GHG / fuel consumption credits, even though most tractors are used by fleets with these features active. Many fleets use VSL and AES features, but they want the flexibility to adjust vehicle speed limits or disable AES, depending on the application. To retain resale value, original purchasers want to allow the second owner to be able to decide whether and how to use these features. In the case of VSLs, to qualify for GHG/FC credit, the maximum speed must be factory set for the useful life of the truck or for expiration after a predetermined number of miles. If the maximum vehicle speed can be adjusted by the owner, rather than being preset by the factory, then the VSL does not qualify for credit under the regulation. The VSL's value is prorated based on the speed setting, with no credit given for a setting at 65 or above. Temporary increases in maximum speed (soft top) are allowed for safety purposes related to maneuvering and passing on-road. To get credit for AES, a feature that automatically shuts off the main engine after 300 seconds or less must be installed for the useful life of the vehicle or for expiration after a predetermined number of miles. If the AES feature can be turned on and off by the owner, rather than being preset by the factory, then the AES feature does not qualify for credit.

The simplified approach to estimating vehicle power demand that is implemented in GEM in Phase 1 means some vehicle technologies are not directly captured in the GEM model (though manufacturers may request innovative technology credits for technologies not in common use with heavy-duty vehicles before model year 2010 that are not reflected in the GEM simulation tool). Examples of potential fuel saving technologies not reflected by GEM in Phase 1 include:

- Matching of axle ratio to the powertrain and vehicle requirements
- Power transmission efficiency of the transmission, driveline, and axles
- Number of transmission ratios, control of shift events, efficiency features
- Power demand of vehicle accessories, such as
  - Air compressors (which can be clutched to reduce power demand)
  - Hydraulic pumps
  - Air conditioner systems
  - Electrical systems
  - Cooling fans
  - APUs and other anti-idle "hotel load" systems
- "Driver management" features, such as
  - Gear-down protection (not allowing a vehicle speed above X unless the transmission is in top gear)
  - Progressive shift algorithms (reducing engine governed speed at lower road speed)

- Load based speed control (estimating vehicle mass and using it to set the engine speed governor)
- "Smart" cruise control (operating the engine at its best BSFC load as much as possible, allowing some variation from the set speed)
- GPS based cruise control
- Driver reward systems (tracking acceleration, deceleration, cruise speed, and shift patterns, estimating the driver's achieved efficiency compared to the best possible efficiency, and determining a driver bonus)
- Downspeeding (setting the vehicle up so that it cruises at a given road speed using a lower engine speed)
- Shift optimization (using grade and load sensors)
- Electronic E-coast feature, which disengages the transmission

Many of the technologies listed above can use the same approach described in Section 4.2.1 for engine accessories. The power demand and duty cycle of vehicle accessories can be measured and used to calculate fuel savings on a given regulatory drive cycle. The power transmission efficiency of transmissions, axles and driveline components can be measured on dynamometers and used with duty cycle data to determine fuel savings on a regulatory drive cycle. For example, it is very hard to accurately determine the contribution of an alternative axle lube from vehicle testing, because the potential benefit is within the range of test-to-test variability. However, the benefit of an alternative axle lube can be measured with great accuracy in an axle dynamometer test. It should be noted that there remain some technologies on the list above which do not fit easily into a component level test scheme. This is particularly true of the driver management features.

The match of engine rating, transmission type, and axle ratio can be optimized for any given payload and drive cycle. Unfortunately, if the vehicle duty cycle changes, the vehicle is no longer optimized for its new duty cycle. For example, if a tractor is purchased for hauling potato chips on flat terrain, the buyer could specify it in a way that minimizes fuel consumption for this type of application. However, if that tractor is later used to haul heavy loads in the mountains, the performance will be very poor. For this reason, users at the extremes (especially at the light end) of the duty cycle range tend not to fully optimize for their drive cycle, in order to preserve some flexibility for future applications. It is also not clear what regulatory approach could be used to improve the market's performance regarding vehicle powertrain and driveline specifications. OEMs have very sophisticated tools that are routinely used to optimize specifications for customer applications. These tools provide guidance with high confidence even at very small fuel consumption differences, based on specific customer payloads and driving routes. One market failure here is that smaller operators who buy only one or a few trucks at a time do not often get the benefit of an OEM analysis of their application.

Driver management features also represent a difficult area for regulators to deal with. Consider the example of gear-down protection. For example, assume that the truck has a vehicle speed limiter set to 65 MPH, and a gear-down setting of 60 MPH. This means that the truck will not be able to exceed 60 MPH unless it is in top gear (or going downhill). It is easy to quantify the fuel economy benefit of running at 65 MPH in top gear vs. one gear down. The hard part is to determine with any degree of confidence how often this would happen in the field, and

therefore the actual fuel saving performance of the feature. What percentage of the time would the average driver run over 60 MPH without being in top gear, if the gear-down feature is not in use? A lot of real-world data logging with and without the feature would be required to get a reliable estimate of the benefit.

Progressive shift is another example of this difficulty. Twenty years ago, almost every driver did upshifts only as the engine approached the high-speed governor. Given that driving style, the use of progressive shift, which lowers governed speed under many conditions, will make a big improvement for applications with a lot of transient operation. Today, however, most drivers no longer automatically rev the engine to the governor, because driver training has a strong focus on keeping the revs down to improve fuel economy. As a result, a lot of data logging would be required to determine the actual fuel saving benefit of progressive shift. A lot more data would be required to determine how often the benefits of progressive shift come into play across the vehicle population. Other features on the list above have different issues regarding quantification of benefit. For example, the performance of smart and GPS-based cruise control is extremely sensitive to the specific route being driven and to traffic conditions. On the current GEM cycles (and on some real-world routes), the value of these features is not captured. However, there are other real-world routes where smart or GPS-based cruise control will provide significant benefits. Characterizing the driving conditions of the vehicle fleet, and then determining the benefits of a specific feature, is a large challenge.

4.2.3 Alternative Approaches

The discussion in Sections 4.2.1 and 4.2.2, and the current regulatory framework, are both focused on a certification test approach. This means that the engine or vehicle is put into a specific class, and its performance is measured against a duty cycle that is intended to represent the typical use for that class of vehicle. If the actual use of the vehicle in the field diverges significantly from the certification cycle, there will be situations where the real-world benefit or penalty for a given technology is significantly different from what is measured on the regulatory cycle. This could limit regulatory incentives for certain technologies that might have a useful benefit in certain actual duty cycles, but not on the regulatory cycles. Driver management features are particularly likely to fall into this situation.

Other performance measurement approaches may be better suited for capturing some benefits. For example, the performance of a technology could be measured while the vehicle is operating in normal use, rather than on a regulatory cycle. For example, consider an OEM who would like to get credit for a GPS-based cruise control and automated transmission control. To determine the performance of the feature, the ECM could contain a model of the unimproved vehicle system (i.e., with the standard cruise control and AMT control). The ECM can then track the commanded fuel consumption for the baseline case, and compare it to the actual commanded fuel consumption with the GPS-based technology. The difference in performance between the (simulated) baseline technology fuel consumption and the actual in-use fuel consumption would form the basis for the fuel consumption and GHG credit awarded to this technology. However, in order to implement this approach, both the fuel consumption prediction model for the baseline case, and the "measured" fuel consumption for the technology case would need validation. Manufacturers could monitor and quantify the in-use benefits of difficult to measure

technologies using the method described here, and then request innovative technology credit for new vehicles that incorporate these features. The OEM would need to show the regulator that both models accurately reflect the real-world fuel consumption of the vehicle.

4.3 Assessment of Current Regulatory Testing and Simulation Approaches

4.3.1 China's Regulatory Approach

The Chinese government has developed fuel consumption regulations for medium and heavy-duty trucks. The regulations are based on fuel consumption of fully loaded vehicles, measured in liters per 100 km. [SAE Paper 2011-01-2292] describes the methods used. The test and simulation procedures used in the Chinese regulations are based on the World Transient Vehicle Cycle (WTVC). This cycle consists of three segments: an urban low-speed segment, a rural secondary road medium-speed segment, and a motorway high-speed segment that is based on the EU truck speed limit of 80 km/h (50 MPH) and the EU maximum vehicle speed limiter setting of 90 km/h (56 MPH). There are no grades in the WTVC. Because many Chinese trucks operate with a relatively low power/weight ratio, the Chinese regulators have modified the WTVC to limit acceleration and deceleration rates. The resulting modified cycle that is used in the Chinese regulation is called the C-WTVC.

The Chinese standards provide a table of fuel consumption targets by GVW/GCW for each vehicle market segment. The market segments are described in the next paragraph below. There are two steps in the current regulation. Stage 1 targets apply to existing production vehicles in July 2014. Stage 2 standards apply to new vehicles launched after July 2014, and existing vehicles after July 2015. The targets were set based on tests of a sample of over 300 different existing production vehicles. The Stage 1 targets were set at a level that would require improvement in about the worst 10% of current vehicles. The Stage 2 targets are 10 to 15% more stringent, and require improvement to almost 50% of current production vehicles [ICCT Update on China HDV, 2013, page 4]. The regulators did not describe the current product baseline vehicles in detail, but they appear to be mostly 2010 and 2011 vehicles that meet China Stage 3 and 4 (roughly Euro 3 and 4) emissions requirements.

Under the new Chinese efficiency regulation, base models of each vehicle type are required to undergo chassis dynamometer testing. Coastdown tests conducted with a fully loaded vehicle are used to determine the aerodynamic drag and rolling resistance values for the chassis dynamometer testing. Depending on the vehicle type, different weightings are applied to the three C-WTVC cycle segments. For example, large semi-tractors skip the urban cycle, and use 10% rural and 90% motorway, while city busses use 100% urban cycle. Table 1 in [SAE Paper 2011-01-2292] shows the market segmentation of MD and HD vehicles, and what proportion of urban, rural, and motorway segments apply to each market segment. The basic market segments are: semi-tractor, dump truck, straight truck, city bus, and motor coach. Some of these vehicle segments are further subdivided by weight class. Some important details of the chassis dynamometer test procedure are not spelled out in the available literature. For example, how is cooling air handled? Is there a supply provided by a wind tunnel? Does the air supply

velocity track simulated road speed? The way cooling air is handled will have a large effect on cooling fan power demand, assuming some sort of fan clutch is used in the vehicle.

The parent, or standard, configuration of a vehicle type must be certified on the chassis dynamometer test. For variants of a basic vehicle type, the manufacturer has a choice of chassis dynamometer or vehicle simulation. The simulation procedure uses the same C-WTVC test cycle. The model calculates the transient driving power demand required to follow the speed-time profile. This is translated into an engine torque and speed requirement. The regulation spells out the shifting strategy to be used with manual transmissions. Using a measured engine fuel map, fuel consumption is calculated by the vehicle simulation model. The results on the three test cycle segments are weighted in the same way as they are for the chassis dynamometer test standard.

The Chinese regulation puts an overall efficiency target on the vehicle. It is up to the OEM to set system and subsystem targets that allow the overall vehicle to meet the requirement. One OEM may decide to focus more on engine technologies, while another focuses more on aerodynamic features or weight reduction. The Chinese regulations do not address some of the issues raised in Section 4.2. Another area that the Chinese regulation does not address is that of fleet averaging. Every vehicle must comply, so there is no opportunity to use good performance on some portion of an OEM's fleet to subsidize other less efficient vehicles. This may have an effect on the vehicle market, especially in smaller niches where the engineering cost to meet the standard may prove excessive.

4.3.2 Japan's Regulatory Approach

Japanese regulators introduced MD and HD vehicle efficiency standards as part of a broader effort to improve the efficiency of all power consuming devices from trucks to refrigerators. The program is called "Top Runner," and the overall approach is to find the most efficient vehicle in a given class, and eventually require that all vehicles in the class meet the same efficiency. Top Runner went into effect in 2005, based on test results of MY 2002 vehicles [ICCT 2013]. Hybrid vehicles were not eligible for Top Runner status, since this would have the effect of forcing hybrid technology to be applied across the board. The initial regulatory requirement, which began in 2006, is that vehicle literature must prominently discuss efficiency technologies that have been implemented. All vehicles must meet the Top Runner requirement in 2015, which means that they must have efficiency equal to the best vehicle in class from MY2002. For tractors, the regulation requires an improvement of 9.7% from the 2002 average. Straight trucks and busses have targets ranging from 11 – 13% compared to the 2002 average.

The Top Runner program has goals in terms of fuel economy, measured in km/liter. As a result, the actual reduction in fuel consumption will be somewhat less than the headline increase in fuel economy. For example, a 10% increase in fuel economy is equivalent to a 9.1% reduction in fuel consumption or GHG emissions. Regulatory compliance is determined by vehicle simulation. An engine dynamometer test provides the fuel map for the vehicle simulation. Other vehicle information, such as the number of gears and gear ratios, is entered into the model. Values for Cd, Crr, and vehicle weight are pre-determined by the regulator for each vehicle class, based on average values from the 2002 model year. The simulation model has an algorithm to

determine shift points, based on the engine torque curve and vehicle gearing. The model then predicts vehicle fuel economy on two drive cycles. The first is the JE05 drive cycle, which includes a mix of mostly urban driving with a small highway segment [ICCT World Regs, 2013]. The second drive cycle is a constant 80 km/h "Interurban Mode" that includes varying grades of up to +/- 5%. The overall regulatory result is a weighted average of the two drive cycles.

Since vehicle weight, Cd, frontal area, and tire rolling resistance are all input values specified by the regulation (the values vary as a function of vehicle class), the Top Runner program basically translates into a requirement for engine efficiency (fuel map values) and the match between transmission ratios and engine torque curve (keeping the engine in a favorable part of the fuel map as often as possible). Factors that influence the vehicle power demand are deliberately left out of the regulation. Many of the technologies discussed in Section 4.2 would not play a role in determining fuel economy according to the Japanese regulations.

4.3.3 The EU Regulatory Approach

Very high fuel prices in Europe provide a strong market motivation to achieve good vehicle efficiency. Average European diesel fuel prices at the pump as of January 2, 2014 were:

- France $6.88 / gallon
- Germany $7.14 / gallon
- UK $8.60 / gallon
- Italy $8.75 / gallon
- USA $3.91 / gallon (for comparison)

These prices are driven by high taxes on fuel. Given the strong market incentives and the complexity of the truck market, with its huge range of applications and duty cycles, European regulators are taking a slow, conservative approach to regulation of MD and HD vehicle fuel consumption and GHG emissions. As a first step, the EU is developing a vehicle efficiency simulation tool. This tool will be used to meet a vehicle efficiency labeling requirement, but the introduction data for the labeling requirement has not been finalized yet. Once experience has been gained from the labeling program, the EU will consider whether regulatory requirements are needed, and whether the simulation tool provides results useful enough to drive a regulatory requirement. In other words, the EU approach is to develop a system for determining vehicle efficiency, test that system out in a labeling program, fix any deficiencies that are identified, and then determine if an efficiency regulation is justified.

As a safety measure, the EU has required trucks to have a vehicle speed limiter set to 90 km/h (56 MPH) since 1992 [EU web site]. Even though this regulation is driven by safety rather than fuel economy, it has significant fuel economy and GHG implications for vehicles that operate on long distance routes.

The EU is currently developing a program to require vehicle labeling to show CO_2 and fuel consumption performance. There has been an active research program for several years to explore ways of obtaining CO_2 and fuel consumption values that represent real-world

experience. Research organizations, universities, and the industry have been participating in this effort. The EU is developing a vehicle simulation tool called VECTO. This tool will use a range of vehicle drive cycles. The drive cycles used for a specific vehicle will be selected based on the intended application of that vehicle. The VECTO model will project fuel consumption and CO_2 emissions on the selected drive cycle(s).

The EU's VECTO model will use the following inputs [ICCT 2013]:

- Engine fuel maps from engine dynamometer testing
- Aerodynamic drag measured using a constant speed on-road test
- Tire rolling resistance, based on the ISO 18164 and 28580 test procedures
- Transmission ratios and efficiency map data from manufacturers
  - Default transmission efficiency values can also be used
- Auxiliary systems power demand from efficiency maps

According to [http://ec.europa.eu/clima/policies/transport/vehicles/heavy/index_en.htm], accessed on January 31, 2015, it is expected that regulations for the EU fuel economy and GHG labeling requirement will be proposed in 2015.

Unlike the US regulation, the proposed EU system does not regulate engines and vehicles separately. Engine efficiency maps are an input to the EU's VECTO vehicle efficiency model. One OEM may decide to focus more on engine technologies, while another focuses more on aerodynamic features or weight reduction. It can be argued that this is a cost effective way to achieve a given efficiency target, although independent engine manufacturers may face a range of efficiency expectations from different OEM customers. The EU approach uses a constant speed on-road test to determine aerodynamic drag, while the US approach is to use coast-down testing. Both test approaches can be extremely sensitive to test variables such as slight changes in grade, wind, and ambient temperature. The EU approach includes transmission ratios and transmission efficiency maps, which are not part of the current US regulation. The EU approach also includes power demand from vehicle accessories, which are not part of the current US regulation.

4.3.4 Canada's Regulatory Approach

So far, the Canadian government has followed the US EPA and NHTSA regulations for truck fuel economy and GHG, with some tweaks to accommodate differences between the US and Canadian truck market. It is too early to know if this approach will continue for the next phase of regulations.

4.4 Recommendations for Certification of Tractor-Trailer Vehicles

4.4.1 Realism of Current GEM Cycle Weightings for Sleeper Tractors

The current GEM regulatory drive cycles could be criticized for not exercising the vehicle power demand over the whole range. Addition of a cycle including grade would address this concern. While it is true that the engine certification cycle already exercises the engine over a wide speed and load range, the SET test cycle is increasingly removed from typical engine operation in tractors, as will be shown below.

It can be argued that the NESCCAF cycle is more representative of sleeper-equipped tractor-trailer operations than the blend of cycles used in the Phase 1 GEM model. Tractors with sleepers use a summation of drive cycles consisting of 86% at 65 MPH cruise, 9% at 55 MPH cruise, and 5% urban transient to determine the GEM result (95% steady-state cycles). Discussions with long haul operators have indicated that it is unusual for a vehicle to average much over 50 MPH in long haul service, and very difficult to average over 55 MPH. The lower average speed obtained in real-world operation is driven by time spent driving off the interstate network, time in congestion, and local speed limits or road conditions including grades. The NESCCAF cycle averages 54 MPH for a truck at 50% payload, with a slight reduction for 100% payload, and a slight increase in average speed when unloaded. The variations in cycle average speed are caused by the 3% grade segments, which cause the truck to lose speed. When compared to the NESCCAF cycle, the Phase 1 GEM approach tends to predict higher benefits for aerodynamic and rolling resistance technologies, as shown in Table 4.3 below. There is little difference between the NESCCAF results and GEM results for the other vehicle technologies that were evaluated in Section 3.

TABLE 4.3 COMPARISON OF TECHNOLOGY PERFORMANCE ON GEM AND NESCCAF CYCLES AT 50% PAYLOAD.

Technology	Fuel Savings Performance		GEM – NESCCAF	GEM Benefits Higher By
	GEM Cycle	NESCCAF Cycle		
25% Cd Reduction	13.74%	12.00%	1.70%	14.1%
30% Crr Reduction	7.72%	6.90%	0.85%	12.5%

If the GEM cycle was modified to the following weightings, the Cd and Crr effects come close to matching the NESCCAF cycle: 79% @ 65 MPH, 0% @ 55 MPH, and 21% on CARB cycle, which has a 15.3 MPH average speed. The reason for eliminating the 55 MPH segment from the GEM summation would be to bring the rolling resistance benefits in line with the NESCCAF results. Note that at 55 MPH cruise, the effect of a change in rolling resistance is very high, because there is no power demand related to inertia (no acceleration) and aerodynamic forces are relatively low compared to 65 MPH. Overall, the suggested GEM weighting of 79% at 65 MPH and 21% on the CARB cycle gives an average speed of 54.6 MPH, very close to the average speed of the NESCCAF cycle, and near the top of the range of typical long haul drive cycles. Results for the suggested reweighting of GEM cycles are shown in Table 4.4.

TABLE 4.4 COMPARISON OF TECHNOLOGY PERFORMANCE ON MODIFIED GEM AND NESCCAF CYCLES AT 50% PAYLOAD

Technology	Fuel Savings Performance		GEM – NESCCAF	GEM Benefits Higher By
	Modified GEM Cycle	NESCCAF Cycle		
25% Cd Reduction	11.86%	12.00%	-0.18%	-1.47%
30% Crr Reduction	6.99%	6.90%	0.13%	1.83%

Rather than simply implementing the change in GEM weighting shown above, it would make sense to take extensive field data from long-haul trucks and use that data to modify the GEM weighting parameters.

4.4.2 Value of Including the Trailer in a Regulation

In a standard 80,000 pound tractor-trailer combination with an empty weight of 34,000 pounds, the weight on the trailer axles represents 22% of the total for an empty vehicle, and 42.5% of the total for a fully loaded vehicle. (See Section 3.3.2.3 for details.) Since trailer tires have somewhat lower rolling resistance than traction tires used on the drive axles, the trailer share of rolling resistance varies from just under 20% when empty to about 40% when fully loaded. Assuming that trucks carry an average of 50% payload, leaving the trailer out of the regulation sacrifices about 30% of the fuel saving benefit that is available from the use of low rolling resistance tires. Note that some operators already take advantage of low rolling resistance trailer tires today on their own, under the SmartWay program, or under California regulations, so a regulation would only affect those who currently use higher rolling resistance tires.

Trailers have an even larger effect on vehicle aerodynamics. Compared to today's most aerodynamic tractors, there remains a potential of up to a 5% fuel consumption reduction due to improvements in tractor aerodynamics, as demonstrated in the SuperTruck program [ET-15 and ET-18]. The potential for improvement on the trailer side is much greater. A SmartWay trailer skirt or boat tail provides about a 5% savings, and the two combined are worth about 8%.

Another factor that should be considered is the question of what sort of trailer the tractor designer should work with. If tractor performance is measured using a "standard" trailer with no aerodynamic features, the tractor designers will optimize for that. If the tractor designer works with a more aerodynamic trailer, the tractor design will include different features with different dimensions, in order to work better with the more aerodynamic trailer. Including trailer aerodynamic performance in the regulation would allow tractor designers to optimize around a more aerodynamic trailer, resulting in greater overall fuel savings. Defining the "standard" trailer against which tractor performance will be judged is a topic that deserves consideration.

Since the trailer owner is often not the same as the tractor owner, the trailer owner has little or no economic incentive to invest in fuel saving technology, since the fuel savings are retained by the tractor owner. This makes a strong argument in favor of regulation of trailer rolling resistance and aerodynamic characteristics. There are typically 3 to 4 trailers per tractor [NRC 2010], so the average trailer has a much lower annual miles traveled than a tractor. This

makes achievement of a good cost/benefit ratio for trailer technologies more difficult. Consideration of trailer technologies needs to take this issue into account.

4.4.3 Comparison of SET Test Points with Long Haul Truck Duty Cycles

The SET test cycle is currently used for engine fuel consumption and CO_2 emissions certification. This was done to maintain commonality between emissions and fuel economy test cycles. Unfortunately, the SET test cycle exercises the engine in a way quite different from the way the engine is actually used in the field. This difference in duty cycle can potentially lead to efforts to optimize engine performance in parts of the speed/load range that are irrelevant to actual in-use fuel consumption. Such an approach could reduce the potential benefits of optimizing for actual applications, and misstate the benefits of many technologies. There are also issues with having the emissions test cycle operate in a way that is not representative of real-world operation.

There is another potential drawback of having an emissions and fuel efficiency test cycle that is not representative of real-world operation. Manufacturers could put a high priority on criteria emissions reductions at operating points that are rarely used in actual service, and focus on fuel efficiency at operating points extensively used in service. This sort of approach would optimize real-world fuel consumption and GHG emissions, but at the expense of higher real-world criteria emissions.

Figure 4.1 below shows the percentage of operating time spent in each speed range on the SET ramped modal cycle, compared to field data logged on current production long-haul sleeper tractors in revenue service. This data was provided to SwRI by Volvo. The tractors are equipped with a 13-liter engine and downspeeding technology. The engine cruise RPM on these trucks is set up to be 1160 RPM at 65 MPH road speed. These trucks are also equipped with AMT transmissions, which helps limit the in-use engine speed range. Note that results for other engine and transmission types will vary from the results presented here. Comparing the two data sets, it is clear that the SET test cycle emphasizes higher RPM operation, where the engine rarely operates in the field. Less than 1% of the engine's field duty cycle is at the B speed or higher, while on the SET the B and C speeds represent over half of the total duty cycle. The SET test under-represents idle speed time and time around the A speed, which for this particular vehicle configuration closely matches the highway cruise speed.

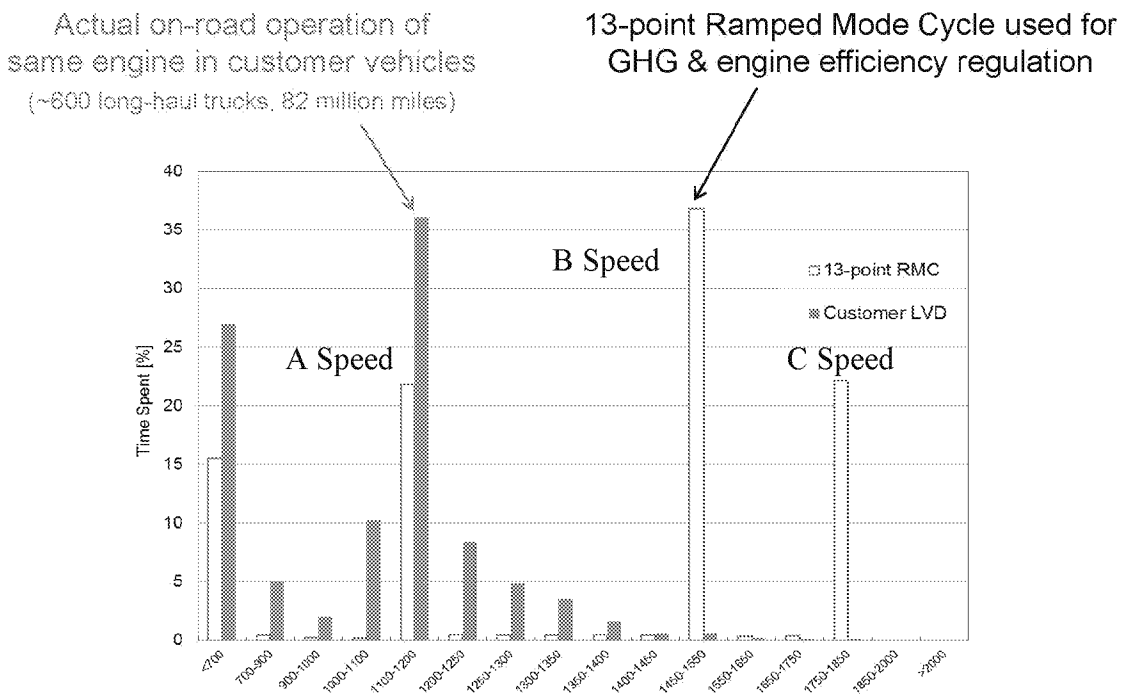


FIGURE 4.1 COMPARISON OF SET TEST CYCLE SPEEDS AND ON-HIGHWAY DUTY CYCLE SPEEDS

It must be noted that the data in Figures 4.1 and 4.2 is for a downspeeded engine with an AMT. These configurations are becoming popular on the market, and are likely to increase in market share in the future. Today, however, manual transmission applications geared to cruise at around 1300 RPM @ 65 MPH are most common. If the comparison of field data and SET data shown in Figure 4.1 was repeated for "standard" engine and transmission configurations, the results would show a large peak around 1300 PM, which is about midway between the A and B speeds. There would also be a little more high RPM operation. Even this "standard" configuration, however, would show very little real-world operation above the B speed.

Figure 4.2 below compares engine torque on the SET test cycle with actual on-road duty cycle data for the same fleet of trucks with downspeeding and AMT. The SET cycle roughly matches the actual duty cycle for the percentage of time spent at the highest torques, but the SET cycle does not accurately represent the relatively even distribution of real-world torque values across the wide range between 300 and 2200 Nm. The SET also missed the very high portion of time spent in the field at very light load (0 to 300 Nm). Combined with the wide discrepancy in engine speeds shown in Figure 4.1, the results suggest that the SET cycle is not a very good representation of an actual long-haul truck duty cycle. There is a risk that optimization of the engine to perform better on the SET cycle will need to focus on high speed, medium and high load operation that is rarely used in actual long-haul duty cycles. It is worth noting that the increasing use of aerodynamic tractors and trailers, low rolling resistance tires, and other vehicle efficiencies, driven both by regulation and customer demand, will significantly reduce the torque profile of future vehicles even further.

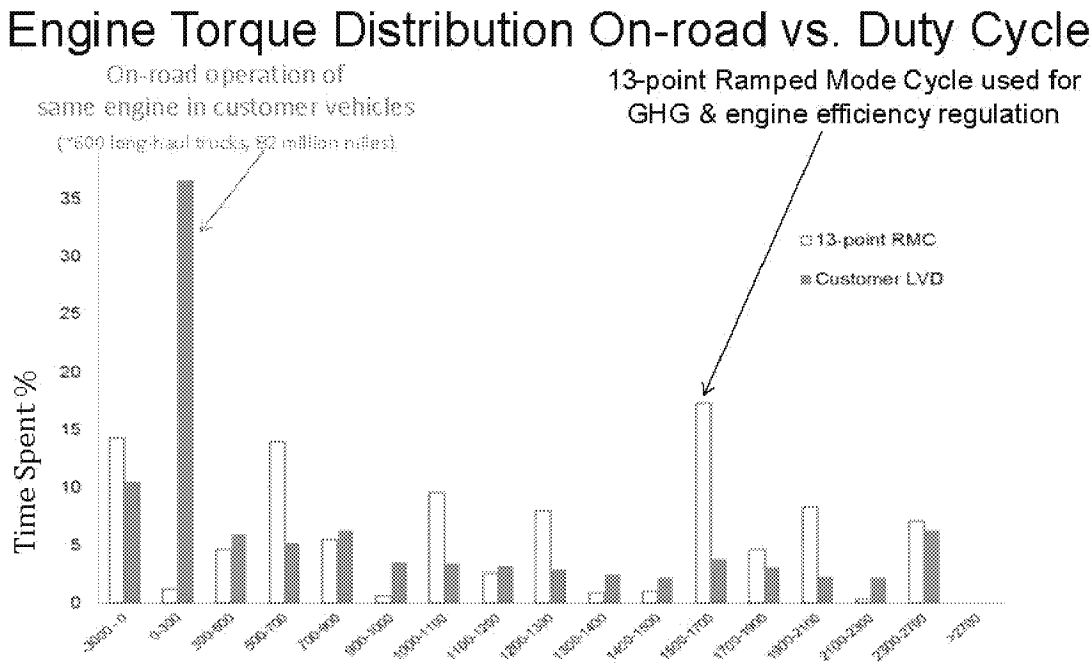


FIGURE 4.2 COMPARISON OF SET TEST CYCLE TORQUES AND ON-HIGHWAY DUTY CYCLE TORQUES

Based on a comparison of in-use duty cycle data and the regulatory certification cycle, SwRI recommends that EPA and NHTSA consider modifying the duty cycle used for certification of fuel consumption and GHG emissions.

4.5 Recommendations for Certification of Vocational Vehicles

4.5.1 Parameters Considered for Vocational Vehicle Certification

The current regulation for vocational vehicles includes only tire rolling resistance. As Figure 4.3 below shows, tire rolling resistance is a significant factor in vocational truck fuel consumption. Note that the advantages shown for the AMT transmissions on the CILCC and Parcel cycles will be reduced when a neutral idle feature is applied to the automatic transmission. Aerodynamic drag is also an important factor, but only for vehicles that drive a significant portion of their miles at high speed.

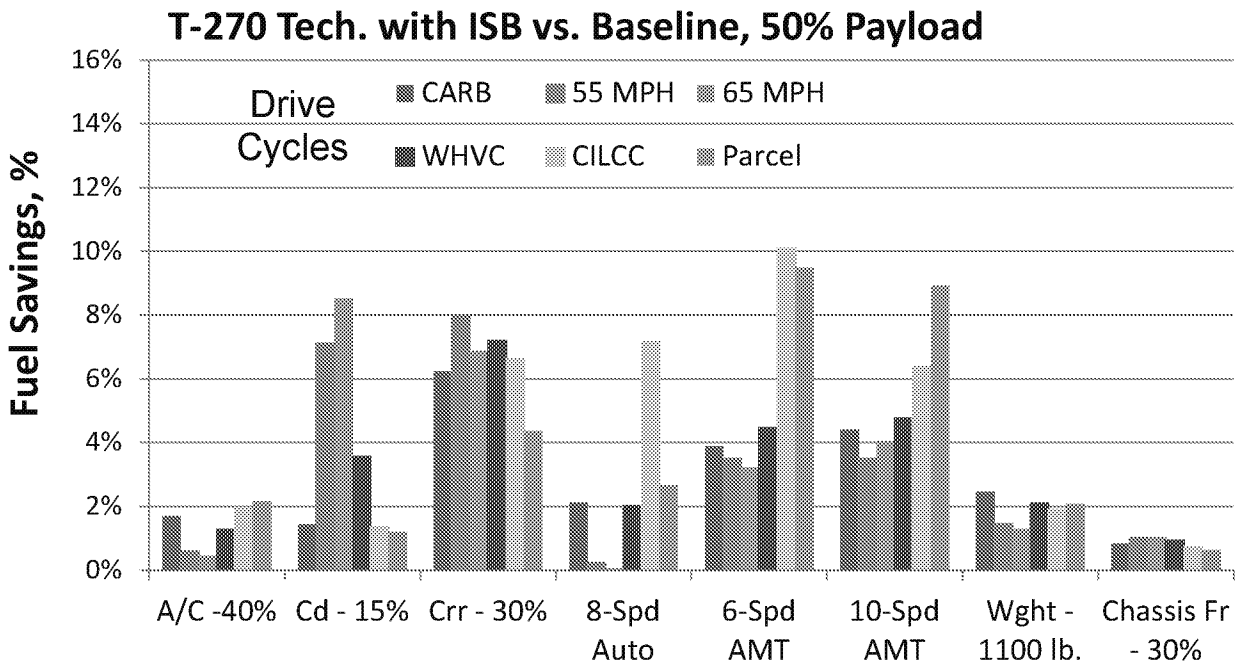


FIGURE 4.3 FUEL SAVINGS OF VEHICLE TECHNOLOGIES APPLIED TO THE T270 VOCATIONAL TRUCK

Many vocational vehicles are delivered from the OEM as a running chassis, with the bodywork and equipment added by a separate company. There are hundreds of companies in the bodybuilding business, which would make regulation very difficult. The body and equipment drive both the Cd and the weight of the completed vehicle.

It might be possible for the regulator to drive small incremental improvements through additional requirements on the chassis manufacturer. For example, some reduction in parasitic power from air conditioning, power steering, and other accessories is possible. It might be feasible to require a chassis aerodynamic skirt on most vocational trucks, although exemptions would be needed for cases where the skirts would interfere with the bodywork or with vehicle function. Modifications to the GEM model would be needed to allow these factors to be accounted for.

4.5.2 Comparison of FTP Test Points with Vocational Truck Duty Cycles

As was the case with sleeper tractor trucks and the SET certification cycle, a comparison of the FTP test cycle and actual vocational truck duty cycles can provide insight into the usefulness of the regulatory cycle for predicting real-world fuel consumption and GHG performance. As is the case with the SET cycle, there are significant discrepancies between the FTP test cycle and in-use duty cycles.

Figure 4.4 below shows the speed distribution of the FTP cycle compared to recorded in-use data for a variety of vocational trucks and transmissions using an 11-liter engine. This data comes from trucks that do not use downspeeding technology, and which use mostly manual

transmissions. These trucks are set up to cruise at engine speeds ranging from 1488 RPM to 1774 RPM at 65 MPH road speed. This data was also provided to SwRI by Volvo. Results from other manufacturers may vary. For the Volvo data, the FTP cycle clearly over-represents the time the engine spends at speeds over 1650 RPM by a factor of 2 to 5. The FTP cycle under-represents the time the engine spends in the 700 to 900 RPM range, as well as the more important 1000 to 1550 RPM range.

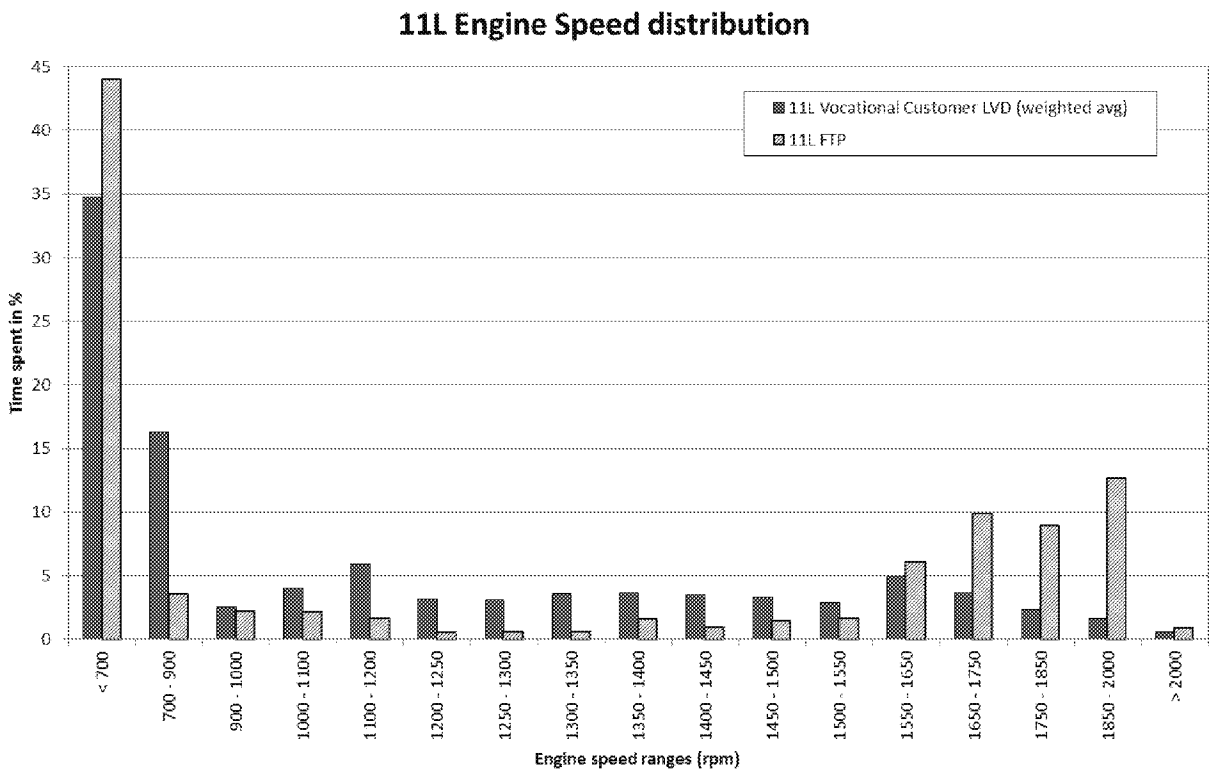


FIGURE 4.4 ENGINE SPEED DISTRIBUTION ON THE FTP CYCLE AND IN-USE OPERATIONAL DATA

Figure 4.5 shows the torques operated by the 11-liter engine on the FTP cycle and in field service. The FTP cycle over-represents the higher torques in the 1500 to 1900 Nm range, but in general, the FTP cycle gets the torque distribution approximately correct. One thing that does not show up in these figures of speed and torque is the combination of speed AND torque. The FTP includes a fair amount of high speed, low and medium torque operation that is not found in real-world duty cycles. In general, during the relatively few occasions that drivers use high engine speed, it is because they are looking for maximum power from the engine. Driver training emphasizes that high RPM, light load operation is bad for fuel economy.

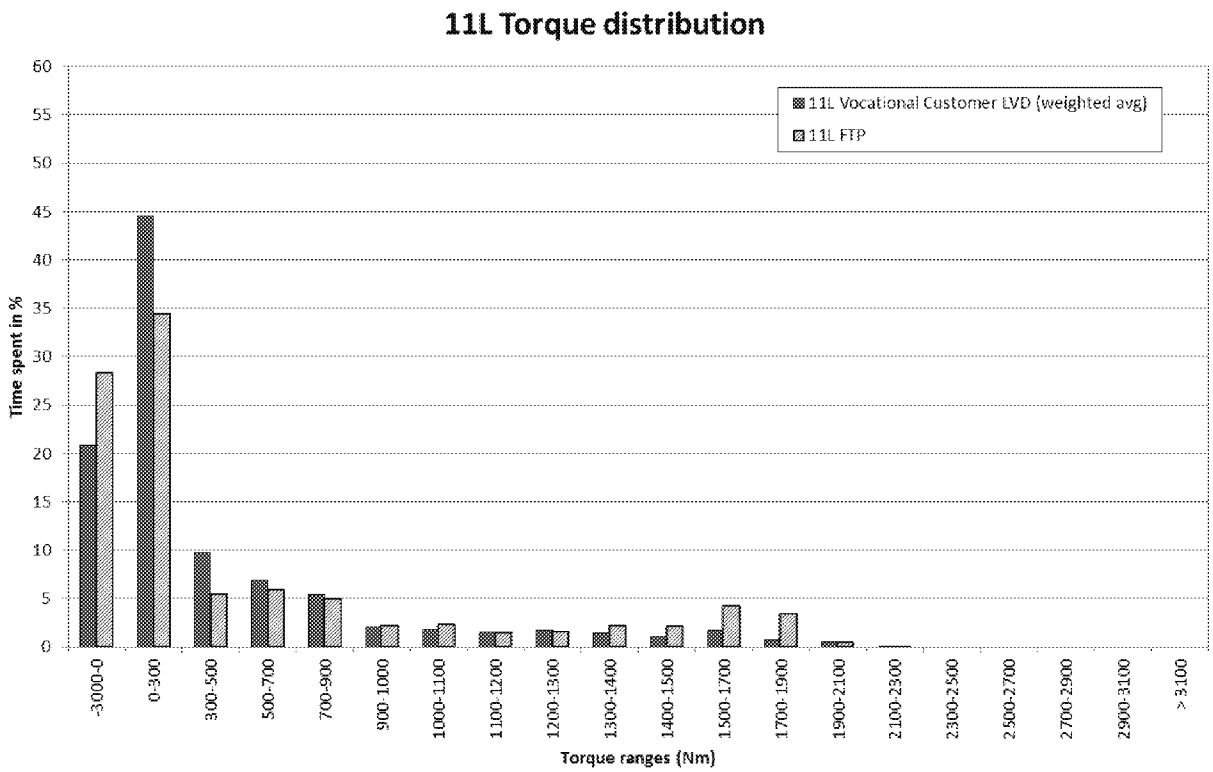


FIGURE 4.5 COMPARISON OF FTP TEST CYCLE TORQUES AND ON-HIGHWAY DUTY CYCLE TORQUES

SwRI recommends that EPA and NHTSA evaluate the usefulness of the FTP cycle for predicting the fuel consumption and GHG emissions of engines in field service.

4.6 Effect of Drive Cycle on Technology Performance

Drive cycles and payload can significantly affect the performance of vehicle and engine technologies. In this section, technologies will be evaluated over a range of payload and drive cycle.

The T-700 tractor and DD15 engine are generally intended for long haul operation, but vehicles like this can sometimes find use in low speed drayage operations. Figure 4.6 shows the performance of five technologies on the 65 MPH steady state cycle. Aerodynamic drag has a huge impact on this drive cycle, but the benefit of an aerodynamic drag improvement declines with increasing payload. Tire rolling resistance has the second largest fuel savings on the 65 MPH cycle, but its value *increases* with higher payload. There is a trade-off between the portion of vehicle power demand going to aerodynamics, which is independent of payload, and the portion of power demand going to rolling resistance, which increases with payload. The third largest benefit comes from Downspeeding, which provides around a 4% benefit. This benefit declines slightly as payload increases. The values of reduced engine friction and reduced vehicle

weight are in the 2% and 1% range respectively, and these values also decline slightly with increasing payload.

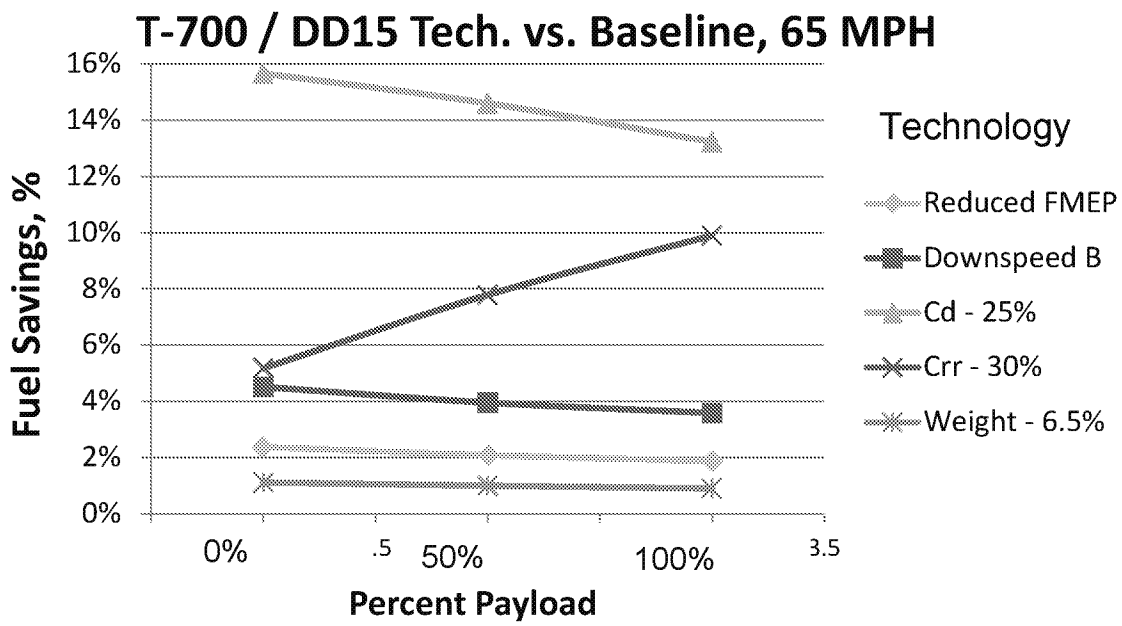


FIGURE 4.6 SENSITIVITY OF T-700 AND DD15 TECHNOLOGIES TO PAYLOAD AT 65 MPH

At the other extreme, the CARB urban cycle has an average speed of about 15 MPH, and it represents stop and go urban driving. Most technologies perform very differently on this cycle. Aerodynamic improvement, which gives the largest benefit at 65 MPH, has the smallest benefit on the CARB cycle (Figure 4.7). The load sensitivity is still the same, with aerodynamics becoming less important as payload increases. Downspeeding moves up to 2nd place in the benefit ranking, from 3rd place at 65 MPH. The benefit of downspeeding is more sensitive to payload on the low speed CARB cycle than at 65 MPH. It should be noted, however, that downspeeding is the only technology with nearly identical benefit on both drive cycles. Reduced engine friction moves up to become the #1 benefit on the CARB cycle, up from 4th place at 65 MPH. The benefit of friction is also strongly payload dependent. Weight reduction provides about twice the benefit on the CARB cycle as is found on the 65 MPH cycle. Overall, note that no technology exceeds a 6% benefit on the CARB cycle, while two technologies exceed 6% (and in one case, 15%) on the 65 MPH cycle. Results on the other drive cycles fall between the extremes defined by the 65 MPH cycle and the CARB cycle.

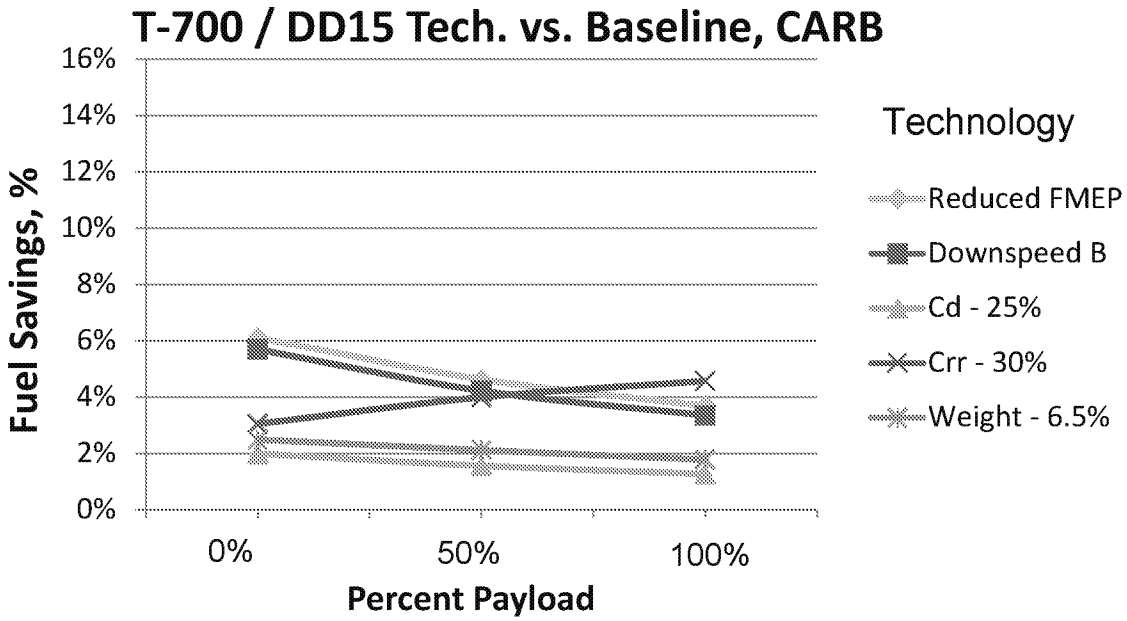


FIGURE 4.7 SENSITIVITY OF T-700 AND DD15 TECHNOLOGIES TO PAYLOAD ON THE CARB CYCLE

Vocational vehicles also see changes in technology performance depending on drive cycle and payload. Figure 4.8 shows the performance at 65 MPH of six engine and vehicle technologies on the Ford F-650 tow truck. The largest benefit is provided by the addition of EGR and downspeeding to the baseline 3.5 liter V-6 gasoline engine. The benefit of this engine technology declines slightly with higher payload. Tire rolling resistance provides the second

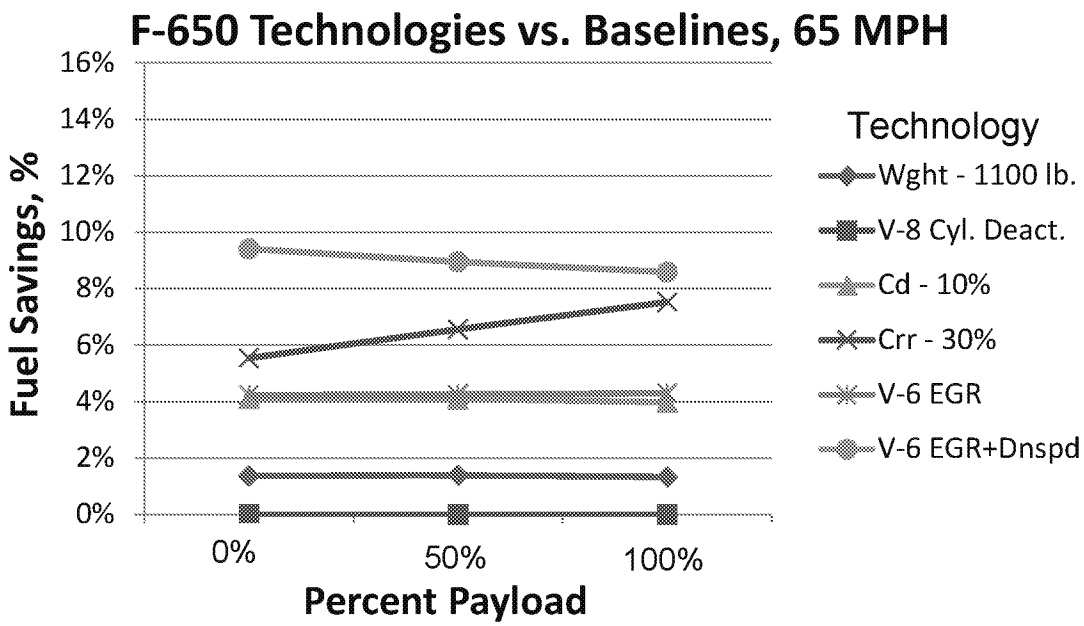


FIGURE 4.8 SENSITIVITY OF F-650 AND ENGINE TECHNOLOGIES TO PAYLOAD AT 65 MPH

largest benefit, and this benefit strongly increases with payload. Applying EGR only to the 3.5 liter V-6 provides a benefit just over 4%, regardless of payload. Reducing aerodynamic drag by 10% provides about a 4% improvement, independent of payload. Reducing vehicle mass by 1100 pounds provides a 1.3% fuel savings, independent of payload. Finally, cylinder deactivation on the 6.2 liter V-8 provides no benefit at all, because at the 65 MPH operating point, the engine needs all 8 cylinders.

The comparison between 65 MPH and the CARB cycle is not quite as dramatic with the F-650 as it was on the sleeper tractor T-700 above, but there are still a number of important differences in performance between the two cycles. On the CARB cycle, the EGR + Downspeeding technology on the V-6 engine provides the largest benefit, as it did at 65 MPH. The benefit is a bit lower on the CARB cycle, however. Cylinder deactivation on the 6.2 liter V-8, which provides no benefit at 65 MPH, comes in 2nd place on the CARB cycle, with benefits of 4 to 6 percent. The lower benefit comes at full payload. Tire rolling resistance roughly ties for 2nd on the CARB cycle. The benefit of lower rolling resistance consistently increases with higher payload. EGR on the 3.5 V-6 engine provides almost the same benefit on both drive cycles (around 4%), and is relatively insensitive to payload. Weight reduction is more important on the CARB cycle that at 65 MPH, a result that matches the T-700 results described above. Reduced Cd is the least effective technology on the CARB cycle, down substantially from its performance at 65 MPH.

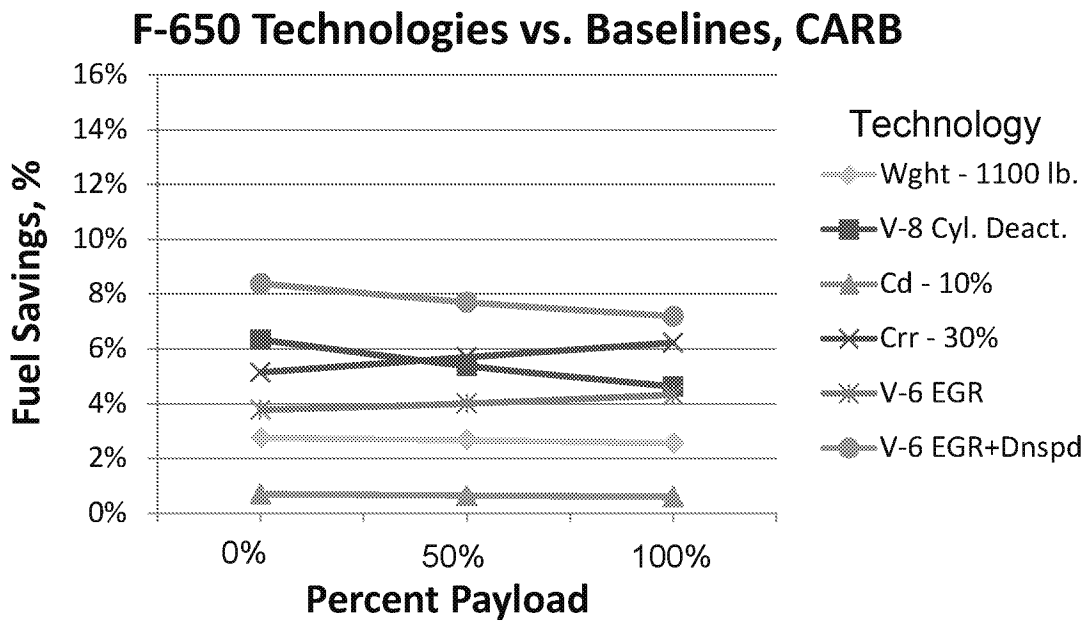


FIGURE 4.9 SENSITIVITY OF F-650 AND ENGINE TECHNOLOGIES TO PAYLOAD ON THE CARB CYCLE

Figure 4.10 below shows the performance of several technologies on the Ram 2b/3 pickup truck as a function of payload on the US06 test cycle. The US06 is an aggressive drive cycle that includes rapid accelerations and speeds up to 80 MPH. The three payload levels are not evenly distributed. The baseline vehicle weighs 6876 pounds. At ALVW, there is a 1562-pound payload, for a total vehicle weight of 8,438 pounds. At GCW, a trailer is added to provide

a total vehicle weight of 25,000 pounds, along with a 50% increase in frontal area to account for the additional aerodynamic drag of the trailer. As a very important caveat, it should be noted that the fuel savings benefits predicted for the GCW case are ***not reliable***. This is because the vehicle was unable to follow the aggressive drive cycle very well, with discrepancies in speed for 10% or more of the total drive cycle. For the 4-cylinder diesel, there was a speed discrepancy about 20% of the time. Changes that affect either engine power or vehicle power demand resulted in changes in the speed/time history on the US06. This makes the fuel consumption results unreliable.

On the US06 cycle, the most effective technology shown in Figure 4.10 is the combination of EGR and downspeeding on the 3.5 V-6 gasoline engine. This technology performs best at full GCW, where the baseline engine often has to use extensive enrichment to avoid excessive engine and catalyst temperatures. EGR alone on the 3.5 V-6 is the second most effective technology on the US06, with benefits from 5% at zero payload to over 17% at GCW. Reduced rolling resistance provides benefits from 6 to 9%. These benefits also increase with payload, but not nearly as strongly as the two EGR technologies. The 4-cylinder version of the diesel provides a 4% to 6% benefit. A 500-pound weight reduction is worth 3% at zero payload, falling to 1.3% at GCW. Cylinder deactivation on the 6.2 V-8 gasoline engine is worth 3.1% at zero payload, falling to 0.3% at GCW. A 10% improvement in Cd is worth just over 2% at zero payload, falling to 1% at GCW.

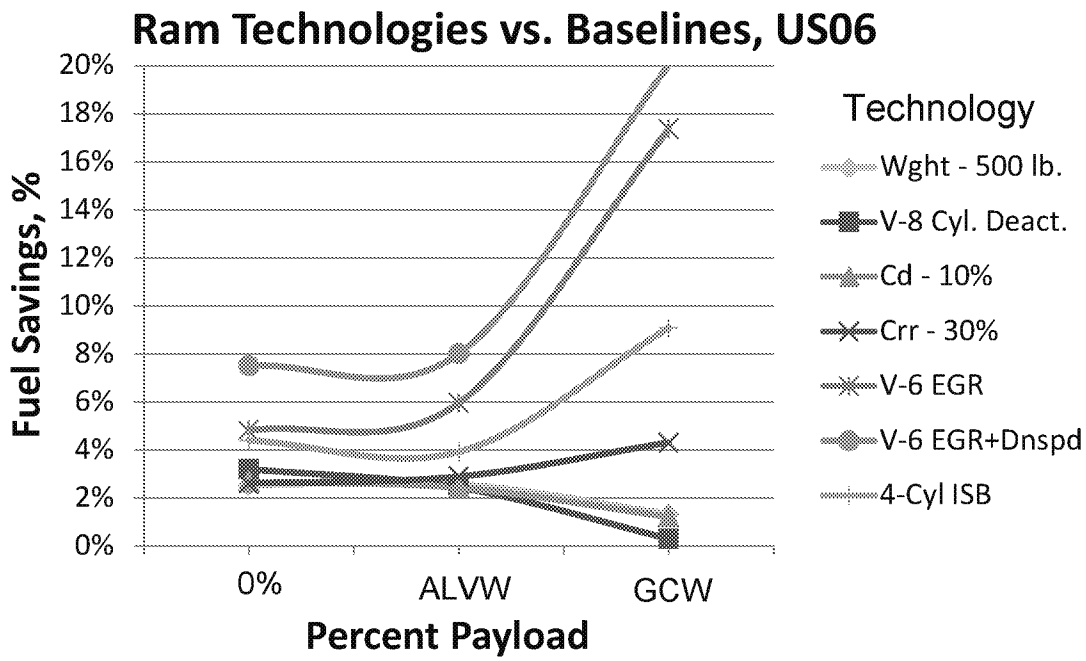


FIGURE 4.10 SENSITIVITY OF PICKUP VEHICLE AND ENGINE TECHNOLOGIES TO PAYLOAD ON THE US06 CYCLE

Figure 4.11 below shows the performance of the same set of technologies on the low speed FTP-City cycle. On this cycle, the 4-cylinder diesel is the best performing technology. The downsized diesel benefits from an increase in average BMEP compared to the baseline. This technology ranked #4 on the US06 cycle. Note that the benefit of the smaller diesel drops

off considerably at full GCW, where the engine runs near full load much of the time. The number 2 performer on the city cycle is EGR and downspeeding, applied to the V-6 gasoline engine. This technology provides a benefit of around 7% that is independent of payload. Cylinder deactivation on the V-8 gasoline engine provides over 9% benefit at zero payload, falling to 2% at GCW. At full GCW, there is little opportunity to use cylinder deactivation. The benefits of reduced rolling resistance and reduced weight are similar on the city cycle and on the US06. Finally, a reduction in Cd has almost no effect on the low speed city cycle.

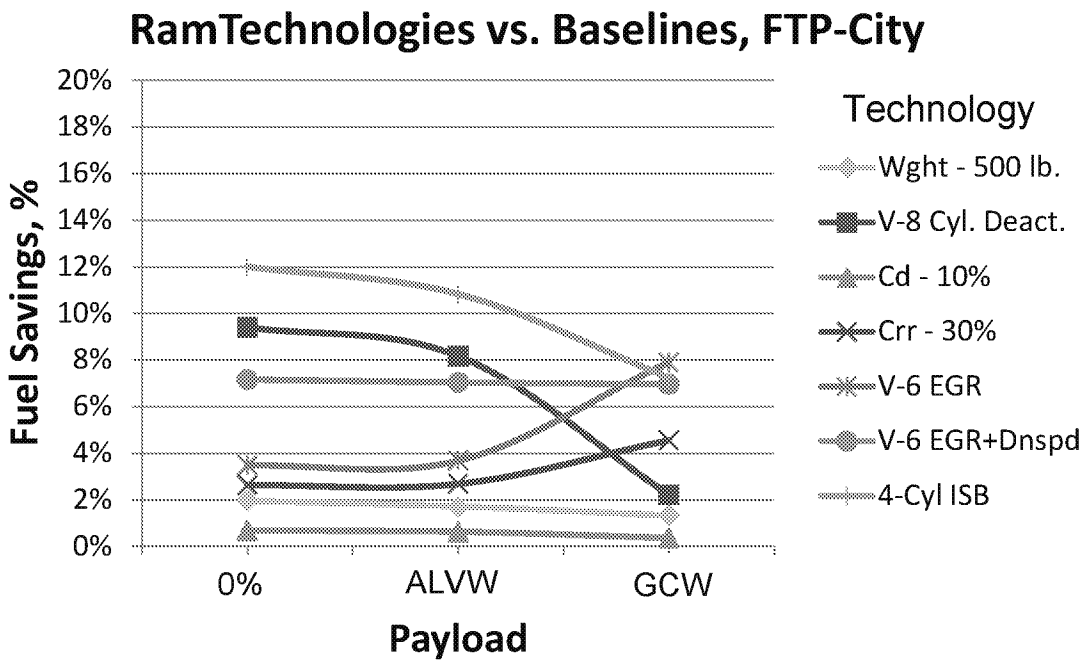


FIGURE 4.11 SENSITIVITY OF PICKUP VEHICLE AND ENGINE TECHNOLOGIES TO PAYLOAD ON THE FTP-CITY CYCLE

5.0 SUMMARY

The tractor-trailer truck shows the largest potential percentage fuel savings of any of the vehicles evaluated. This is fortunate, since tractor-trailers account for a significant portion of overall medium- and heavy-duty vehicle fuel consumption. Another factor in favor of fuel saving technologies for tractor-trailer vehicles is the high average miles traveled per year, at least for tractors. The high VMT gives an opportunity to pay back the cost of what are often expensive technologies (see the separate cost report for cost information). Since there are three to four trailers per tractor, benefits for trailer technologies accrue based on their respective VMT.

Given the technologies evaluated in this report, the most promising long haul truck engine technologies (in terms of fuel savings – cost will be considered in a separate report) are:

- Friction reduction, downspeeding, and downsizing: 2% to 4% each
- Elimination of EGR, turbo efficiency improvement: up to 2% each (note that EGR elimination requires very high conversion efficiency from the aftertreatment)
- Waste heat recovery systems: 3% to 5% on highway cycles, but little benefit in urban driving

Note that downsizing and downspeeding both have the same effect, which is to drive up the average load on the engine (BMEP), so these two technologies can only be combined to a limited extent. Also note that friction reduction is not always compatible with downsizing or downspeeding. Since both downsizing and downspeeding tend to push up cylinder pressure, the engine design must accommodate higher cylinder pressure, and this tends to increase friction.

Tractor-trailer trucks show a significant potential for vehicle power demand reduction, and thus for fuel consumption reduction. The most promising technologies here include:

- 25% Cd reduction: < 2% fuel savings in urban driving, 12% to 14% on high speed cycles
- 30% Crr reduction: ~ 4% fuel savings in urban driving, 6% to 8% on high speed cycles
- 2,200 pound empty weight reduction: 1% to 2%
- 6 X 2 axles: ~1.5% fuel savings
- Road speed governor: 1.2% per 1 MPH speed reduction (only effective when the speed would otherwise be higher than the governed limit)

The potential of medium duty truck diesel engine technologies is more limited than for tractor-trailer engines, primarily because waste heat recovery systems are not practical for use in transient operating conditions. This is due to the extremely slow transient response of waste heat systems. The high cost of WHR systems will also be an issue in medium trucks. The most promising medium duty diesel technologies are:

- Friction reduction: 2% to 8%, with larger benefits on low speed, lightly loaded cycles

- EGR elimination: 2% to 3.5% (note that this option requires very high aftertreatment conversion efficiency)
- Improved turbocharger efficiency: about 1.5%

Gasoline engines show a high potential for fuel consumption improvement in medium truck applications. The limited gasoline engine offerings in medium trucks today are large displacement, port injected, naturally aspirated engines. These engines suffer from very high fuel consumption at high loads, where they use enrichment to limit engine and exhaust temperatures. Downsizing and boosting is one option. Using today's technology, this option has a fuel savings potential of up to 16% compared to the large naturally aspirated engine, on the most lightly loaded vehicles and gentle drive cycles. Unfortunately, that benefit shrinks to zero on the most heavily loaded and aggressive cycles in the study (and none of the medium truck cycles in the study is very aggressive, since there are no grades). Gasoline engines with today's technology have a substantial fuel consumption penalty compared to a medium-duty diesel. The diesel's advantage is largest on the more heavily loaded and aggressive duty cycles, where gasoline engines run in the enrichment portion of their maps.

Compared to the naturally aspirated V-8, the diesel uses 15% to 25% less fuel than the gasoline alternative. Note that about 13% of this difference is due to the lower energy content of a gallon of gasoline compared to a gallon of diesel, while the remainder is a difference in efficiency. The CO_2 emissions from a gallon of diesel are about 14% higher than from a gallon of gasoline, so the CO_2 advantage of the diesel ranges from 1% to 11%. The following technologies can improve the fuel consumption of the naturally aspirated V-8:

- VVA/VVL: 3% to 5% fuel savings, with the largest benefits on lightly loaded cycles
- Cylinder deactivation: 0% at high speed and load, up to 8% on the most lightly loaded vehicle and cycle
- Stoichiometric EGR: 3% to 10% fuel savings on the drive cycles used in this study, with the largest savings under high load conditions. Up to 30% savings at 100% load.
- Lean GDI: 8% to 11%, with the highest benefits on lightly loaded cycles (note the lack of available, durable lean aftertreatment for spark ignited engines)

The downsized and boosted 3.5 liter V-6 evaluated in this study often has a fuel consumption advantage over the 6.2 liter V-8. For a given power demand, the V-6 runs at higher BMEP. This gives the V-6 an efficiency benefit at light load, but a penalty at high load, where enrichment causes high fuel consumption. The light load advantage of the V-6 comes from reduced pumping work (throttling loss) and lower friction (from the smaller size). Beyond the benefits of downsizing and boosting, the fuel consumption of the V-6 can be reduced significantly with the following technologies:

- VVA/VVL: 2% to 3% fuel savings (less than for the V-8, because the smaller displacement means that there is less pumping work to reduce)
- Cylinder Deactivation: 0% to 3% (much less than the V-8, because the V-6 rarely runs at a light enough load to make use of cylinder deactivation)
- Stoichiometric EGR: 4% to 10%, with the largest fuel savings under high load conditions. Up to 30% savings at 100% load.

- EGR + Downspeed: 2% to 11% fuel consumption reduction, with the smallest savings coming on the Parcel cycle, which has 50% idle time. The penalty on the Parcel cycle is due to higher idle power demand on the engine from a tighter torque converter. On the remaining drive cycles, downspeeding provides a 1% to 2% fuel savings on the large, heavy T270, and about 4% on the smaller, lighter F-650.
- Lean GDI: 2% to 11%, with the highest benefits on lightly loaded cycles (note there is a lack of available, durable lean aftertreatment for spark ignited engines)

With EGR and downspeeding, the 3.5 liter V-6 comes within 3% of the fuel consumption of the diesel in the F-650 on the CARB cycle. This means that under low speed, light load conditions, the small V-6 gasoline engine can exceed the thermal efficiency of the much larger diesel, as well as offering up to 11% lower CO_2 emissions. Note that the diesel retains an 18% fuel consumption and a 4% CO_2 advantage under higher load operation, such as at 65 MPH cruise in the larger T270. The harder the engine needs to work, the larger the diesel's advantage will be. These results do indicate that for more urban applications, an advanced technology gasoline engine can compete with a diesel on thermal efficiency. Given the huge cost advantage of gasoline engines with their simple 3-way catalyst aftertreatment, and the lower price of gasoline compared to diesel fuel, this is an important finding.

Medium trucks have less potential for vehicle power demand reduction than tractor-trailer trucks. There is less opportunity for aerodynamic improvements, so this study evaluated a potential improvement in Cd of 15% on the T270 box truck and 10% on the F-650 tow truck. However, as for the tractor trailer trucks, these trucks were evaluated with a potential 30% tire rolling resistance reduction. The largest medium truck fuel consumption reductions came from:

- 15% / 10% Cd reduction: 1% to 8% fuel savings on the T270, 0.5% to 4% on the F-650, which has less frontal area as well as a smaller Cd improvement potential. The largest benefit is at 65 MPH cruise in both trucks.
- 30% Crr reduction: about 6% fuel savings on most cycles. Higher savings at 55 MPH cruise, lower on the Parcel cycle, which has 50% idle time.
- High efficiency 8-speed automatic: 0% to 2% on most cycles, more on the very gentle CILCC cycle.
- Automated Manual Transmission (AMT): 3% to 4% fuel savings on most cycles, up to 10% on the CILCC and Parcel cycles. The advantage on the parcel cycle is mostly due to elimination of torque converter load at idle. Note that the AMT will have significantly less acceleration capability and driving smoothness in transient conditions.
- 1100 pound weight reduction: 1% to 2%, with the larger benefits on transient cycles

The pickup truck shares the same gasoline engines with the medium trucks. The diesel has the same displacement, but for the pickup truck the rated engine speed is increased to 3,000 RPM from 2,500. The pickup diesel also has more power and torque than the medium duty version: 385 HP and 850 lb-ft, compared to 300 HP and 750 lb-ft for medium trucks. In the pickup truck, the fuel savings potential of eliminating EGR and for a more efficient turbocharger are very similar to the results reported above for the medium duty version. Friction reduction is more important in the more lightly loaded pickup, with fuel savings of 4% to 8% when the truck

operates at ALVW. The benefit of friction reduction is much less when the truck operates at full GCW, because of the higher average engine load.

One additional diesel variant was considered for the pickup: a 4.5 liter 4-cylinder version of the original 6.7 liter inline-6. The 4-cylinder retained the BMEP and speed range of the larger engine, so there is a 33% reduction in available power and torque. The 4-cylinder engine still has substantially more power and torque than pickup diesels of 15 years ago, however. The 4-cylinder provides fuel savings of 0% to 13%. The 0% figure comes at 65 MPH and full GCW, while many cycles show a benefit of over 10%. The primary benefit is operation at higher BMEP for a given road load, which at light load pushes the 4-cylinder into a more efficient portion of its operating map. The 4-cylinder also benefits from lower friction. Many commercial pickup operators may be willing to trade the performance of the 6-cylinder for the substantial fuel consumption improvement of the smaller diesel, provided that they do not routinely pull large, heavy trailers.

For the 6.2 V-8 in the pickup, VVA/VVL, cylinder deactivation, and lean GDI all perform somewhat better than in medium trucks, because of the lower average vehicle power demand:

- VVA/VVL: 4% to 7%, with the largest benefits on lightly loaded cycles
- Cylinder deactivation: 0% at high speed and load, up to 10% on the most lightly loaded vehicle and cycle
- Stoichiometric EGR: 3% to 11%, with the largest savings under high load conditions (full GCW). 3% to 6% savings on most cycles, but up to 30% savings at 100% load.
- Lean GDI: 8% to 14%, with the highest benefits on lightly loaded cycles (note the lack of available, durable lean aftertreatment for spark ignited engines)

As with the V-8, the 3.5 liter V-6 engine sees slightly larger fuel savings from several of the technologies in a pickup compared to the medium truck results:

- VVA/VVL: 2% to 3% (less than for the V-8, because of the smaller displacement)
- Cylinder Deactivation: 0% to 3% (much less than the V-8, because the V-6 rarely runs at a light enough load to make use of cylinder deactivation)
- Stoichiometric EGR: 4% to 10%, with the largest savings under high load conditions. 17.4% savings on the US06 cycle at full GCW. Up to 30% savings at 100% load, due to elimination of enrichment.
- EGR + Downspeed: 6% to 10% on most cycles, with the smallest savings coming on lightly loaded cycles. 20% savings on the US06 cycle at full GCW. Downspeeding provides a 3% to 5% fuel savings over EGR only at zero payload and at ALVW, but much less at full GCW.
- Lean GDI: 8% to 15% fuel savings at zero payload and at ALVW, but only 1% to 6% at full GCW, where high power demand often pushes the engine out of the lean operating region (note the lack of available, durable lean aftertreatment for spark ignited engines).

In general, the pickup truck proved less sensitive to Cd and Crr than the larger trucks. With its smaller frontal area, the pickup will have a lower CdA value. Also, tire rolling resistance represents a smaller portion of total vehicle power demand. On the other hand, the pickup is more sensitive to empty weight reductions and auxiliary power demand. Vehicle technologies applied to the pickup truck provided the following benefits:

- 10% Cd reduction: 0.4% to 3.8% fuel savings, with the largest benefit at 65 MPH cruise.
- 30% Crr reduction: 2.2% to 4.4% at zero payload and at ALVW, and up to 7% at full GCW (assuming a 30% reduction in trailer tire Crr).
- High efficiency 8-speed automatic: 0.2% to 4.8% fuel savings, with larger savings at light load and on gentle cycles.
- 500 pound weight reduction: 1% to 2.6%, with the larger benefits with light payloads and on transient cycles
- 600 watt auxiliary power demand reduction (A/C): 0.9% to 2.2% at zero payload and at ALVW, with the largest benefit on low speed cycles. 0.5% to 1.2% at full GCW.

Auxiliary power demand reduction was also evaluated on the larger trucks, but it has the largest benefits on the pickup truck, where the average vehicle power demand is lowest.

The results presented in this report show that known technologies can provide significant fuel savings across a wide range of Class 2b through Class 8 trucks. These results can be combined with cost information (to be provided in a companion report) and VMT data to estimate cost effectiveness. A second report will evaluate technology combinations. This is an important topic, because while some technologies may be synergistic, in many cases, adding a second technology will reduce the benefit obtained from the first technology.

APPENDIX A

GASOLINE ENGINE TECHNOLOGIES

Gasoline Engine Technologies

Objective: Simulate Future Gasoline Engine Technologies to demonstrate Fuel Economy Improvement Potential in Class 2b through 7 vehicles utilizing:

3.5L V6 turbocharged, direct injected gasoline engine

6.2L naturally aspirated, port injected V8 engine

1. **3.5L V6 turbo technology evaluation plan:**
   1.1. **Baseline V6 Validation (Turbocharged, Direct Injection, Stoichiometric Operation)**
   1.2. **Explore Variable Valve Lift, Duration, and Timing**
   1.3. **Explore Cylinder Deactivation**
   1.4. **Lean Burn GDI**
   1.5. **Explore GDI with cooled EGR (HEDGE)**
   1.6. **EGR Engine Down speeding with increased BMEP and PCP**
   1.7. **Explore FMEP Improvements**
   1.8. **Explore turbo efficiency improvement**

2. **6.2L naturally aspirated V8 engine evaluation plan**
   2.1. **Baseline V8 Validation (Naturally Aspirated, Port Injected)**
   2.2. **Stoichiometric Gasoline Direct Injection**
   2.3. **Lean Burn GDI w/SCR**
   2.4. **Variable Valve Lift**
   2.5. **Cylinder Deactivation**
   2.6. **GDI with EGR**
   2.7. **FMEP Improvements**

1.1 Baseline V6 Validation

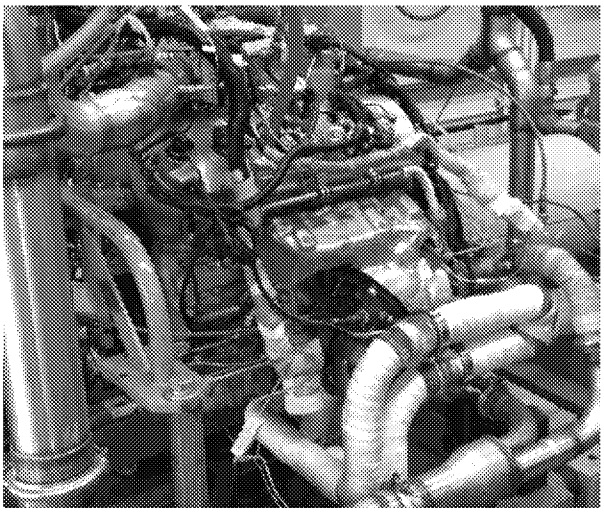


Figure A 1. Ford EcoBoost 3.5 liter engine

- **Ford EcoBoost**
  - 3.5L V6
  - Twin Turbo
  - Single Cam Phaser (Intake)
  - 4 valves per cylinder
  - Gasoline
  - 265/272 kW (car/truck)
  - 475/569 Nm (car/truck)

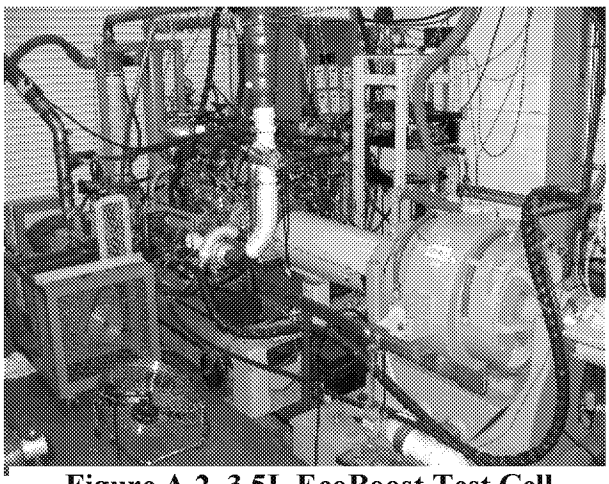


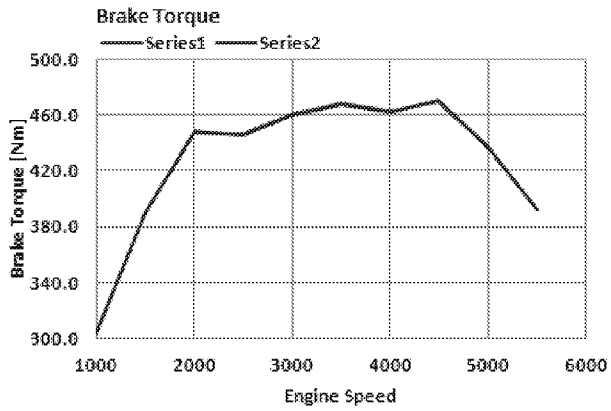
Figure A 2. 3.5L EcoBoost Test Cell

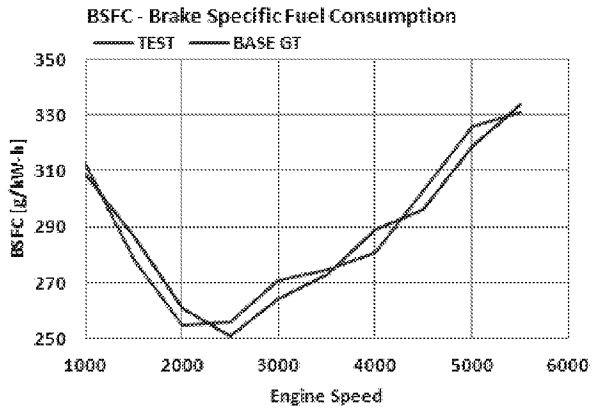
A GT Power model was built using the geometry of a 3.5L Ford EcoBoost engine currently installed in a SwRI test cell. The engine was fully instrumented, including temperatures, pressures, speed, torque and high speed cylinder pressure measurements. A test matrix that covered the entire engine operating range, consisting of 78 part and full load conditions, was run in the test cell. Engine data from the test cell, shown below, was used as model input data.

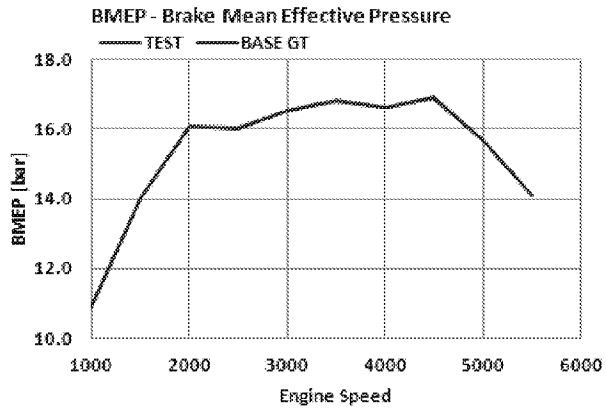
50% Mass Fraction Burned (CA50)
10-90 Burn Duration
Valve Flow Coefficients
FMEP
Cam Phaser Position
Air/Fuel Ratio

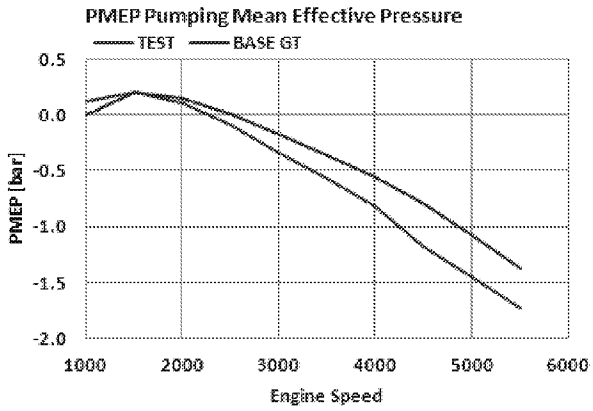
The GT Power model was then operated over the same 78-point test matrix to compare the following variables to the actual engine data. Figure A 3 shows the comparison between actual engine testing and GT Power model predictions. The following operating parameters were considered in the GT Power model validation:

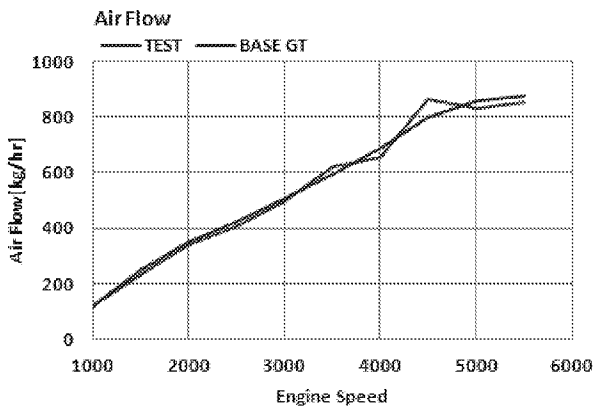
Brake Torque
BSFC
BMEP, IMEP, PMEP
Air and Fuel Flow
Pre/Post Throttle pressures and temperatures
Pre/Post Turbine pressures and temperatures
Combustion Phasing
Combustion Duration

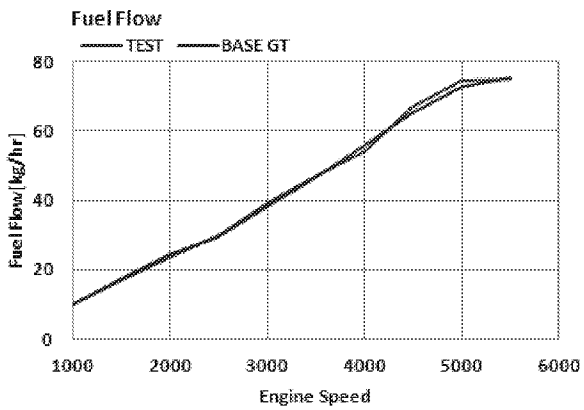

Brake Torque
Series1
Series2
Brake Torque [Nm]
500.0
460.0
420.0
380.0
340.0
300.0
1000
2000
3000
4000
5000
6000
Engine Speed

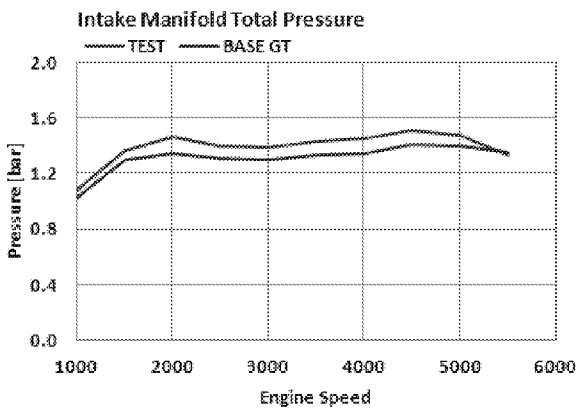

BSFC - Brake Specific Fuel Consumption
TEST
BASE GT
BSFC [g/kW-h]
350
330
310
290
270
250
1000
2000
3000
4000
5000
6000
Engine Speed

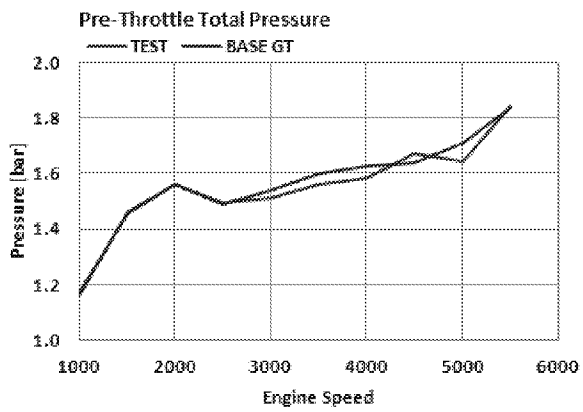

BMEP - Brake Mean Effective Pressure
TEST
BASE GT
BMEP [bar]
18.0
16.0
14.0
12.0
10.0
1000
2000
3000
4000
5000
6000
Engine Speed


PMEP Pumping Mean Effective Pressure
TEST
BASE GT
PMEP [bar]
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1000
2000
3000
4000
5000
6000
Engine Speed


Air Flow
TEST
BASE GT
Air Flow [kg/hr]
1000
800
600
400
200
0
1000
2000
3000
4000
5000
6000
Engine Speed


Fuel Flow
TEST
BASE GT
Fuel Flow [kg/hr]
80
60
40
20
0
1000
2000
3000
4000
5000
6000
Engine Speed


Intake Manifold Total Pressure
TEST
BASE GT
Pressure [bar]
2.0
1.6
1.2
0.8
0.4
0.0
1000
2000
3000
4000
5000
6000
Engine Speed


Pre-Throttle Total Pressure
TEST
BASE GT
Pressure [bar]
2.0
1.8
1.6
1.4
1.2
1.0
1000
2000
3000
4000
5000
6000
Engine Speed

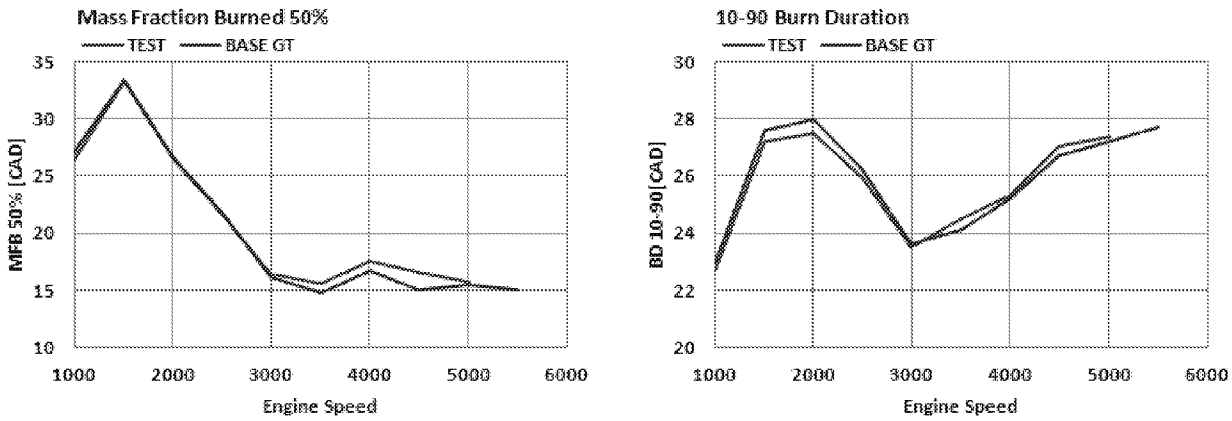


Figure A 3. Baseline Validation

Once the GT-POWER simulated conditions outside of the cylinder were close to the experimental data, the in-cylinder pressure data was compared to model data and the heat rejection was fine tuned until simulated and measured cylinder pressure shape and amplitude were similar for multiple speeds and loads.

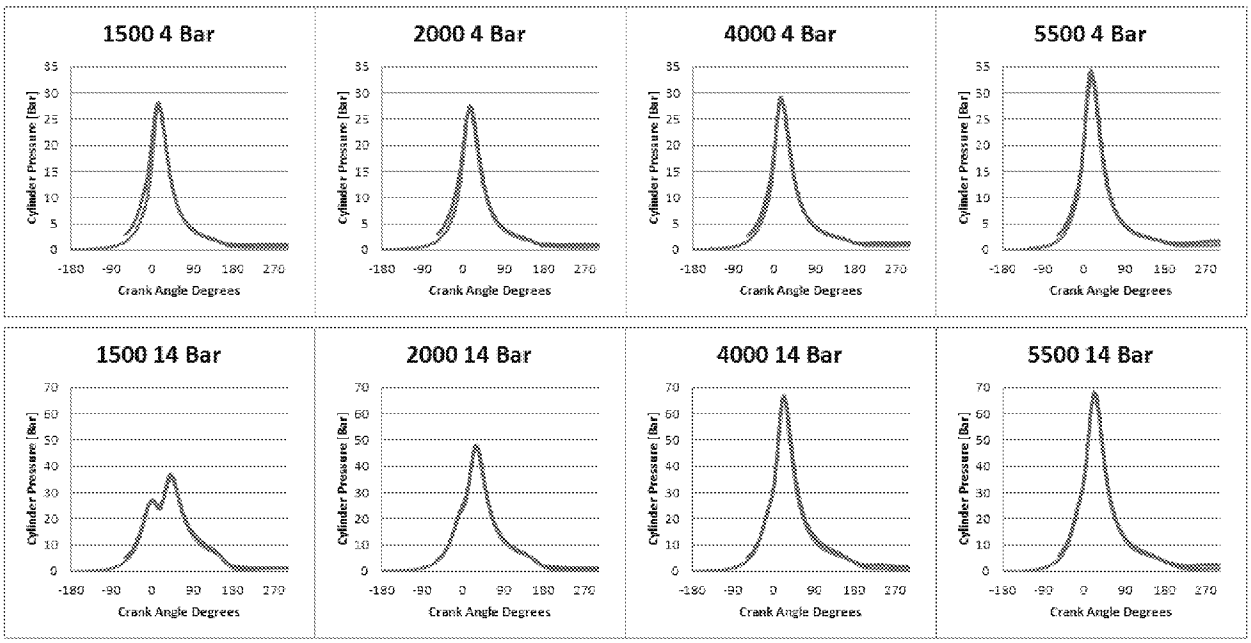


Figure A 4. In-Cylinder Pressure Data Comparison Between Simulation and Test

With the "matched" operating conditions, the 78 operating points were run again to confirm that the simulated BSFC was within +/- 3% of the experimental results. Shown below is the comparison between the engine data and model reported BSFC. Also shown in Figures A6-A7 are the full BSFC and equivalence ratio contours.

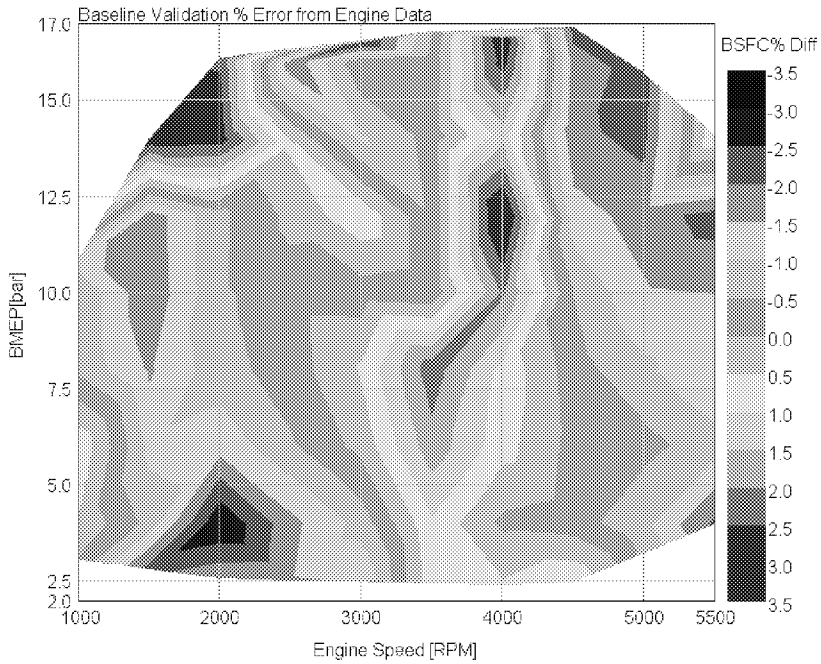


Figure A 5. BSFC Model Error

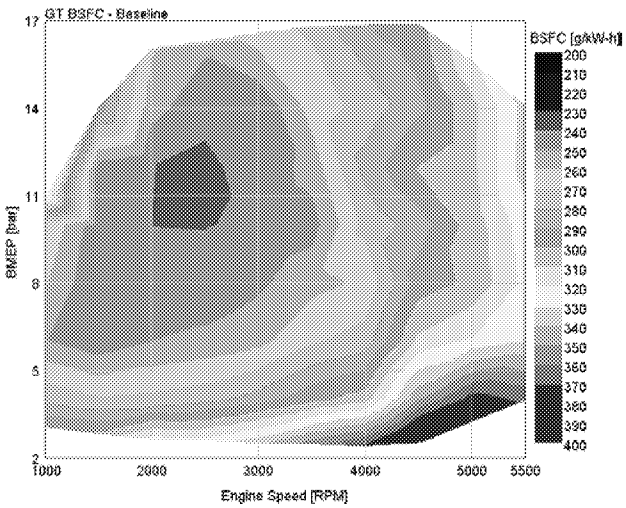


Figure A 6. Baseline Model BSFC

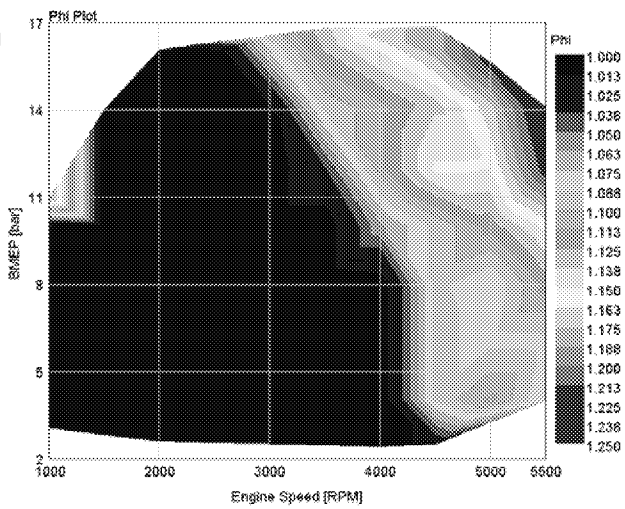


Figure A 7. Baseline Equivalence Ratio

1.2 Explore Variable Valve Lift (VVA/VVL)

- **Variable Valve Lift and Phasing**
  - Reduced pumping losses (reduced or eliminated throttling)
- **Additional Components include:**
  - Special cams and actuators to allow for variable valve lift
- **Variable Valve lift model modifications**
  - The engine throttle is removed and the load is controlled by changing the lift and duration of the intake valve
  - Valve lift for the 78 point test matrix shown in Figure A10 below
  - Low valve lift affects flow fields and might not be a realistic operating condition

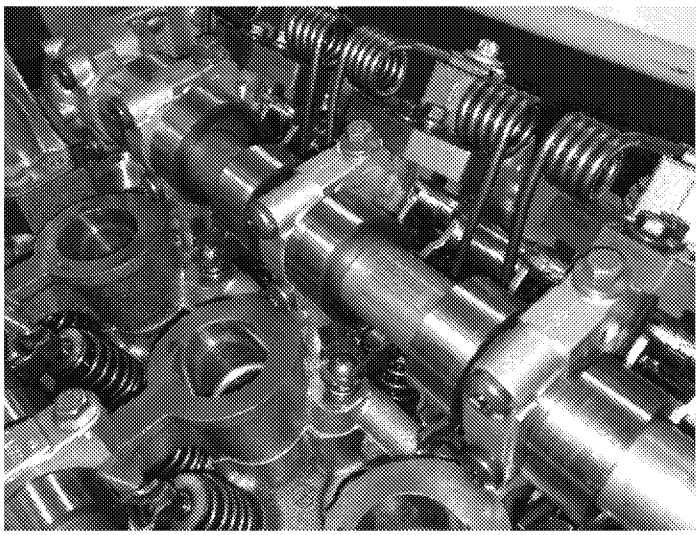


Figure A 8. VVL Actuators

- **Variable Valve lift Example**
  - Baseline Pumping loop, shown below in Figure A 9, shows the pumping work that is wasted under a "typical" throttled condition
  - Improved Pumping work from VVL, shown below in Figure A10

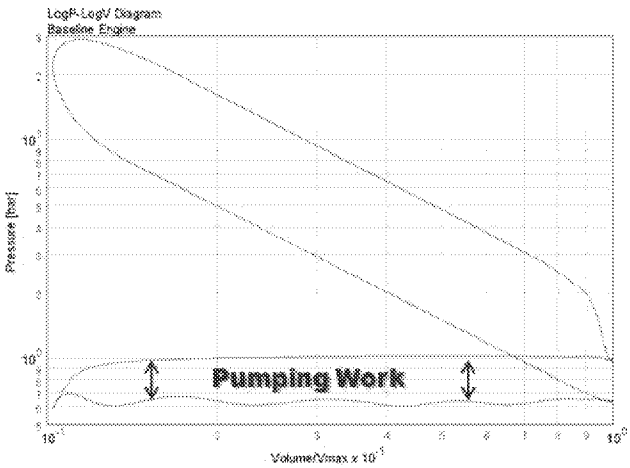


Figure A 9. Pumping Work

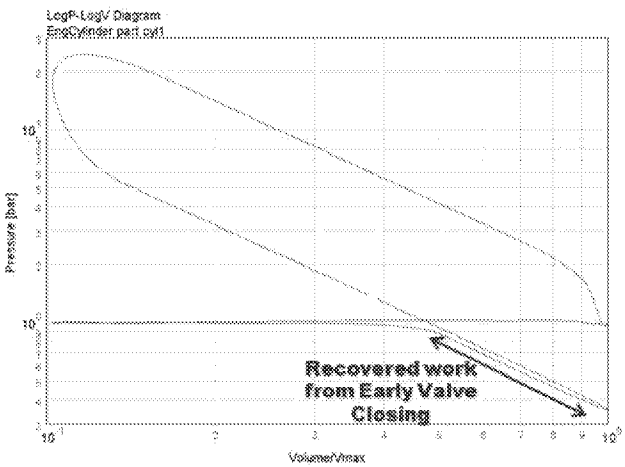


Figure A 10. Energy Recovery

Variable valve lift allows for improvement in efficiency during part load or "normally" throttled conditions. By closing the intake valve early and allowing the cylinders to pull a vacuum on the downward stroke, some of the energy is recovered as the piston comes back up.

This is more evident at higher engine speeds, and the benefit phases out as load increases. Special cam actuators are required to allow for variable lift and phasing as shown in the figures above. As the valve lift and duration are shortened, the in-cylinder charge motion may be affected negatively and cause unstable combustion at the low lift, or low load conditions. If the engine has two intake valves per cylinder, a potential solution might be to vary the lift on one valve much more than the other to keep the velocity high through at least one of the intake ports during low load operation. For the purposes of this model, charge motion was assumed not to be affected.

The variable valve lift model is a modified version of the baseline 3.5L V6. The throttle was removed and the load was controlled by the intake valve lift. Intake valve duration was a mathematical function of the lift that attempted to emulate a realistic VVL system. In addition to the variable valve lift, the intake and exhaust cams have independent phasing capability. To optimize fuel efficiency, more than 1400 intake and exhaust timing combinations were run for the 78 point test matrix. Shown to the right in Figure A 11, is the final intake and exhaust valve timing for the 78 speed/load conditions. Variable valve lift allows for improvement in BSFC at throttled conditions. The benefit is more evident at higher engine speeds, and it phases out as load increases. Shown below are the BSFC and BSFC improvement over the baseline engine contour maps.

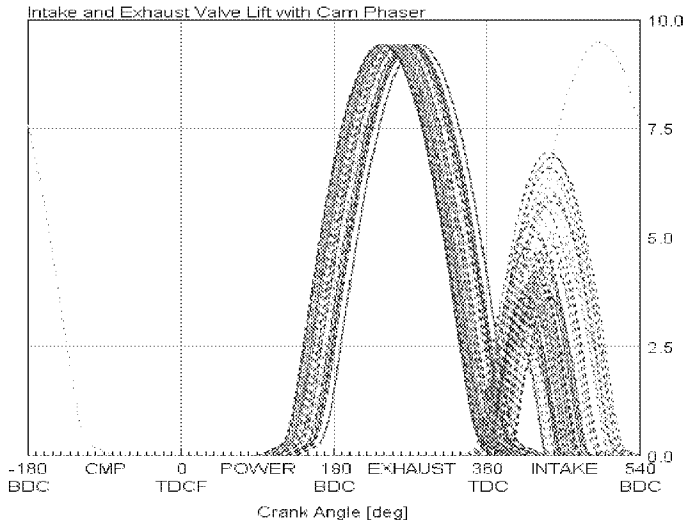
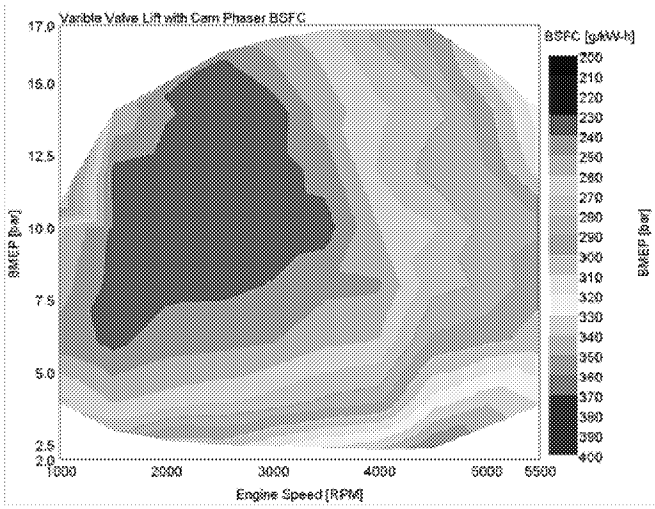


Figure A 11. 3.5L V6 VVL Cam Phasing



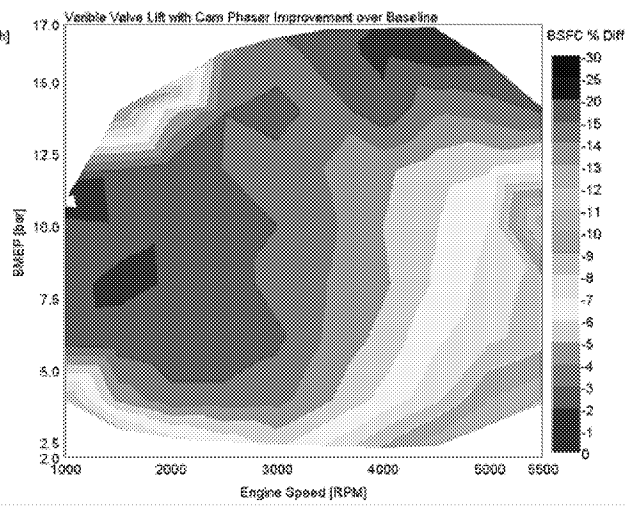


Figure A 12. Variable Valve Lift BSFC **Figure A 13. BSFC Improvement over Baseline**

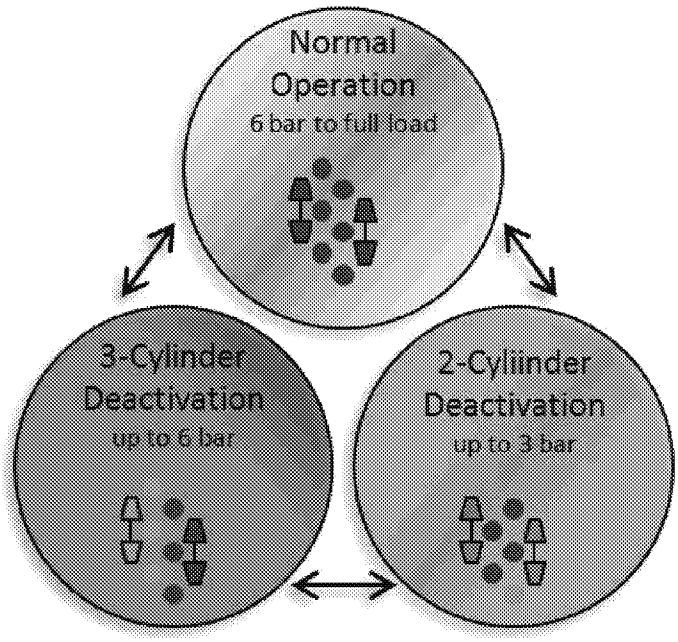


Figure A 14. Cylinder Deactivation Method

1.3 Explore Cylinder Deactivation

- **Two and Three Cylinder Deactivation**
  - Reduced pumping losses (less throttling)
  - Reduced energy loss from deactivated valves
  - Applicable for loads up to 6 bar BMEP
- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation
  - Active Engine mounts/dampers

Engines that have six cylinders have demonstrated operation with two and three cylinder deactivation, such as Honda's Variable Cylinder Management (VCM). The engine at idle conditions will operate on all six cylinders to minimize vibration, but between idle and three bar BMEP, three cylinders are deactivated by cutting fuel injection and valve lift. To ensure adequate throttle response, compressor outlet pressures were maintained. The model was run up to the maximum load that three-cylinder combustion would allow, nine bar BMEP. (see Figure A 15) Then the operating areas that were less efficient than the baseline six-cylinder were removed. (see Figure A 16)

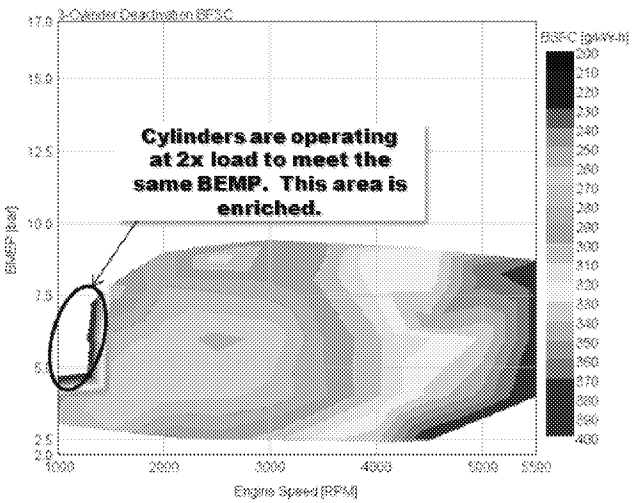


Figure A 15. Full load Three-Cylinder

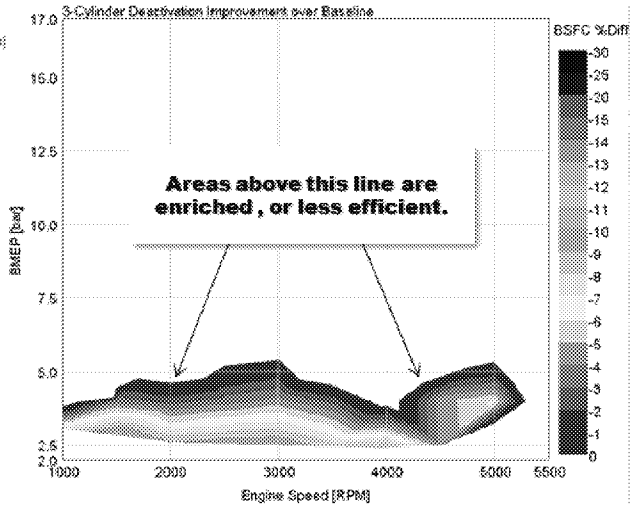


Figure A 16. Potential Operating Range

Because this engine has one turbocharger per bank of cylinders, when 3 cylinders are deactivated, one full bank is shut down. This approach allows normal turbocharger operation on the functioning cylinder bank as shown below in Figure A 17.

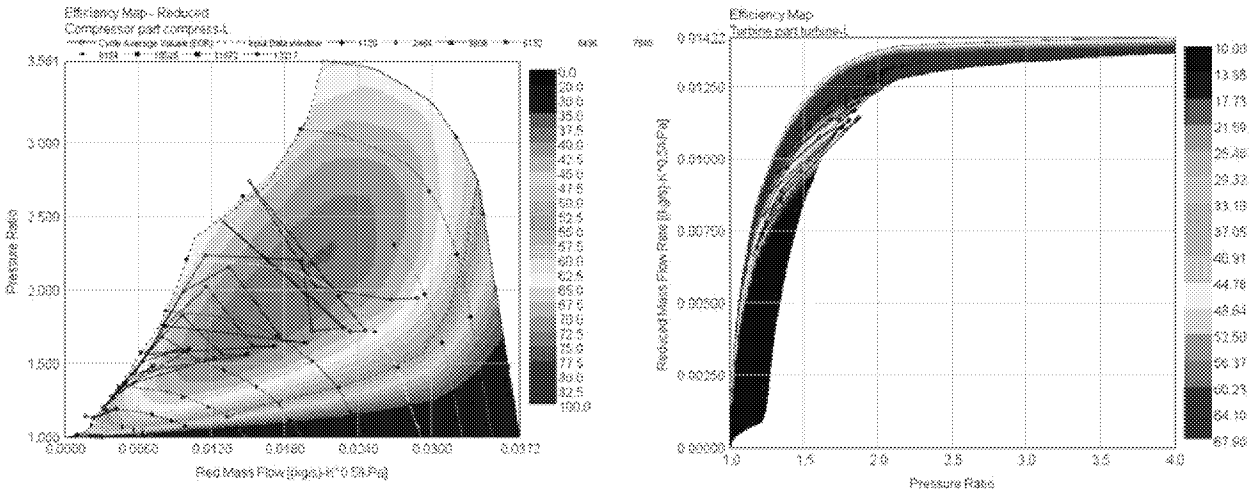


Figure A 17. Turbo Operation in Three-Cylinder Mode (Compressor on left, turbine on right.)

As load increases above three bar BMEP, an additional cylinder will be reactivated allowing four active cylinders to reach engine loads of up to six bar BMEP. In addition, to ensure original throttle response, compressor outlet pressures were maintained at the baseline levels. The model was run up to the maximum load the four-cylinder combustion would allow which was 13 bar BMEP (see Figure A 18). The areas of 4-cylinder operation that were less efficient than the baseline six-cylinder operation were removed. (see Figure A 19)

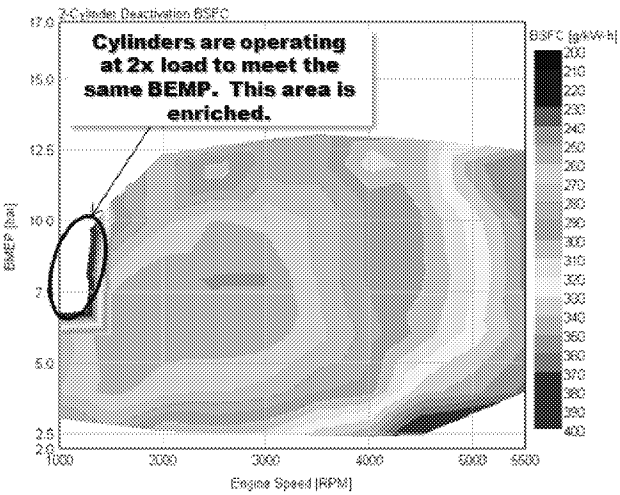


Figure A 18. Full load 4-Cylinder

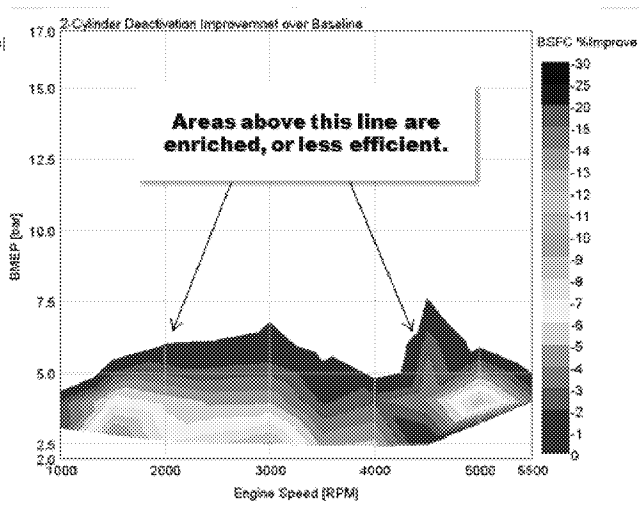


Figure A 19. Potential 4-Cyl. Operating Range

The four-cylinder combustion mode deactivates one cylinder per bank and cuts the mass flow to each turbo by one third. The overall operating points on the turbo maps are shifted to the left, which pushes some of the high engine load points into compressor surge. This is not a problem in four cylinder operation, since the engine will not operate at these high load points in four-cylinder combustion mode due to lower efficiency.

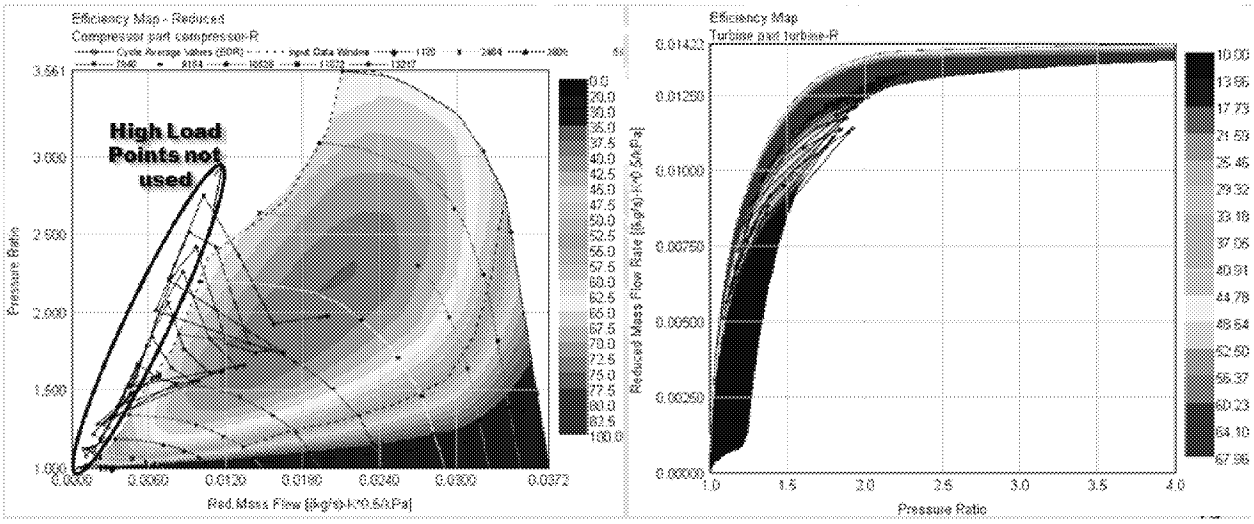


Figure A 20. Turbo Operation in 4-Cylinder Mode. Compressor map (left), Turbine map (right)

The engine efficiencies were compared for the three-cylinder, four-cylinder, and six-cylinder combustion modes and a composite operating range of best efficiencies was compiled. Figures A 21 - A 23 below, shows the engine operating ranges, BSFC, and percent BSFC improvement over the baseline engine.

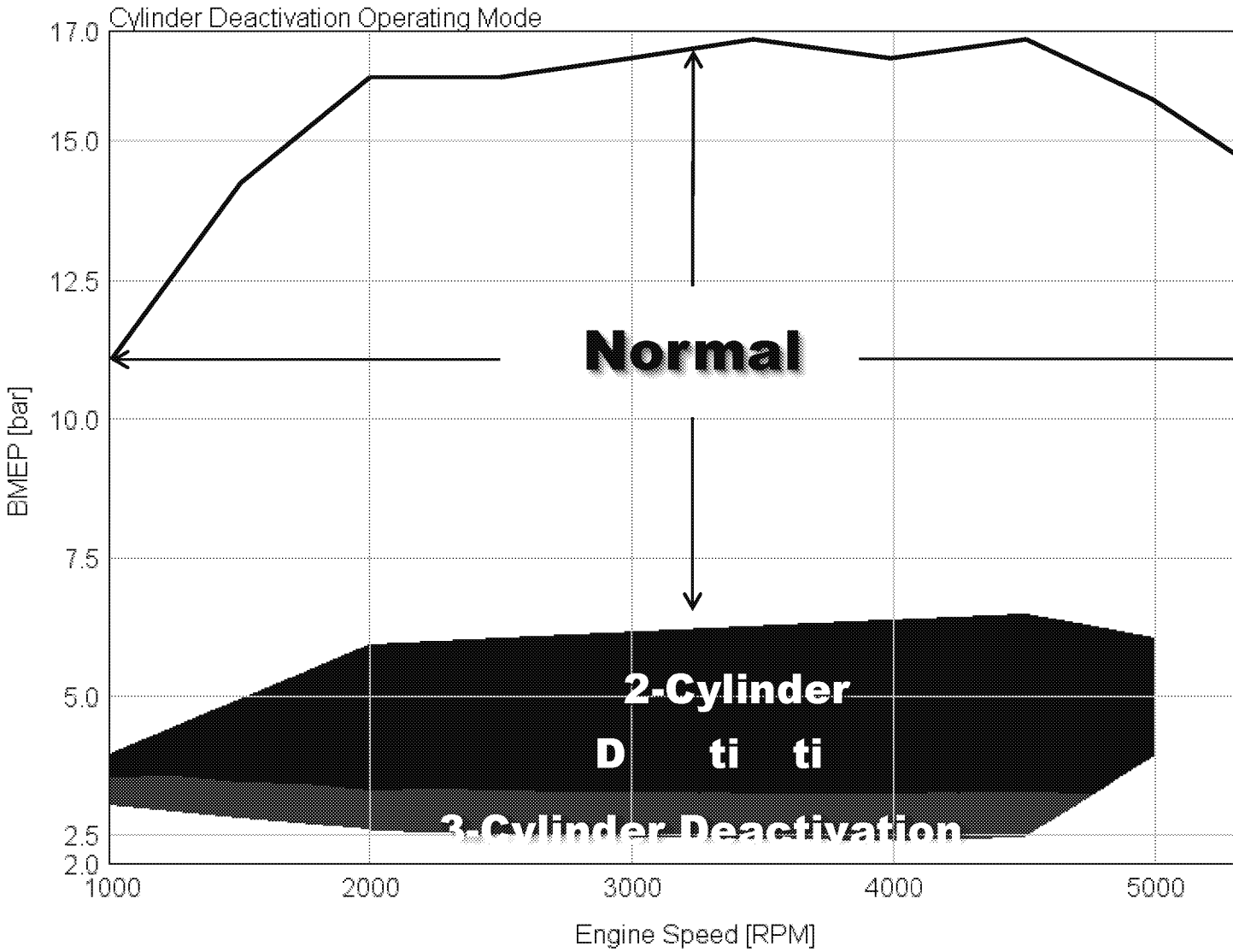


Figure A 21. Composite Engine Operating Range

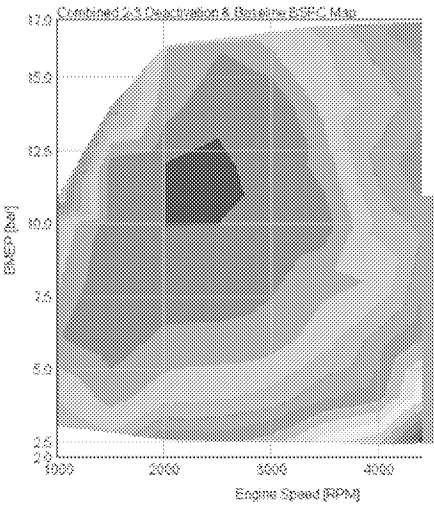


Figure A 22. Combined BSFC Map

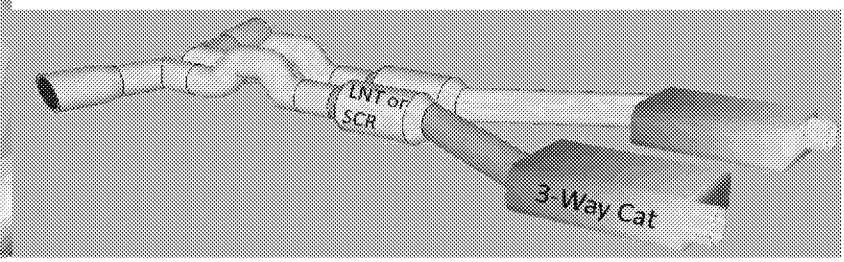


Figure A23. BSFC Improvement over Baseline

1.4 Lean Burn GDI

- Lean Burn Benefits
  - Reduced pumping losses
  - Improved combustion efficiency
  - Improved working fluid
  - Reduced heat transfer
- **Additional Components include:**
  - Piezo Fuel Injectors
  - NOx Sensor
  - NOx Trap
  - Exhaust Gas Temperature Sensor

Lean burn operation can improve engine efficiency by reducing throttling losses, increasing combustion efficiency due to excess oxygen and by improving gamma of the working fluid. In the stratified operating area, the majority of improvement comes from a pumping work improvement and reduced heat transfer due to cooler in-cylinder temperatures. In addition, the homogeneous lean area benefits some due to pumping work and greatly in the areas where the baseline engine utilized enrichment.

The improvement shown from the GT Power simulation show favorable improvements in its steady state operation, however, it does not show the fuel penalty for the regeneration of the LNT or account for the Urea needed in an SCR. In addition to these penalties, the location of the NOx aftertreatment would have to be located sufficiently far downstream to minimize the inlet

temperatures. This distance will help the durability of the aftertreatment, but another fuel penalty will be added at startup until the NOx aftertreatment is up to operating temperature. During this time, the engine will operate in stoichiometric mode to allow the three-way catalyst to operate. These fuel penalties can increase fuel comsumption on the drive cycle and potentially remove any of the benefits of lean operation.

To operate lean, additional components, such as a lean NOx traps or SCR systems, NOx sensors and Piezo fuel injectors for precise multiple injections will be needed. In order for this vehicle to be successful with current and future emission standards, a high NOx conversion efficiency will be required. For high LNT conversion efficiencies, relatively low space velocities are required; therefore a very large volume LNT will be required for conversion of NOx at high load, resulting in a costly LNT. For high SCR conversion efficiencies, high urea dosing rates will be required.

Some of the potential issues with operating in lean mode are degradation of the NOx aftertreatment at high load/temperature conditions and using US fuels with high sulfur content.

The pre-turbine temperature limit is 1223 K for the baseline engine and the maximum obtained during homogeneous operation was 1200 K. Ideally, the maximum temperature at NOx aftertreatment inlet would be less than 1050 K to avoid premature aging and less than 850 K for good conversion efficiency. A certain amount of heat loss will occur across the turbine and piping, but heat addition can take place at the catalyst. Since modeling of heat loss in the aftertreatment system was outside the scope of the project, the pre-turbine temperature limit was allowed to reach 1200 K and the lean operation limits were chosen based upon typical operating ranges from literature. [1, 2] It was assumed that a suitable location for the NOx aftertreatment that met inlet temperature requirements would be used for all vehicles.

High sulfur content will lead to sulfur poisoning and frequent desulfation of a LNT, which will lead to a shortened life of the aftertreatment system. There is the potential that future US gasoline fuel quality specifications will reduce sulfur content, and thus minimize the damage caused by sulfur in the fuel, but that is not presently the case.

This engine model configuration has three operating modes, stratified lean mixture, homogeneous lean mixture, and homogeneous stoichiometric to rich mixture. Shown below in Figure A 25, the engine operates at low speed/load, medium speed/load, and high load in stratified lean, homogeneous lean, and homogeneous stoichiometric modes respectively. Near full load, the engine operates rich, similar to a conventional gasoline engine.

Due to limited published engine data and inability to run stratified charge on our test engine, combustion phasing was assumed to be the same as the baseline operation. Stratified charge burn durations were chosen to be the same as the homogenous lean engine data collected on the test engine. Homogeneous lean and stoich combustion phasing/duration data was

collected from the test engine. It should be noted that efficiency is a strong function of combustion phasing and a weak function of burn duration.

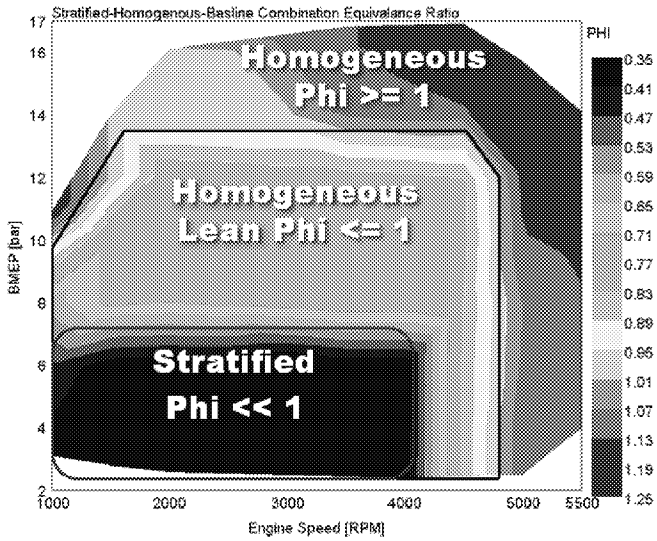


Figure A25. Engine Operating Modes

The engine efficiencies for the three combustion modes were combined and a composite engine operating map was generated. Figure A - A 27, show the composite engine BSFC, and percent BSFC improvement over the baseline engine.

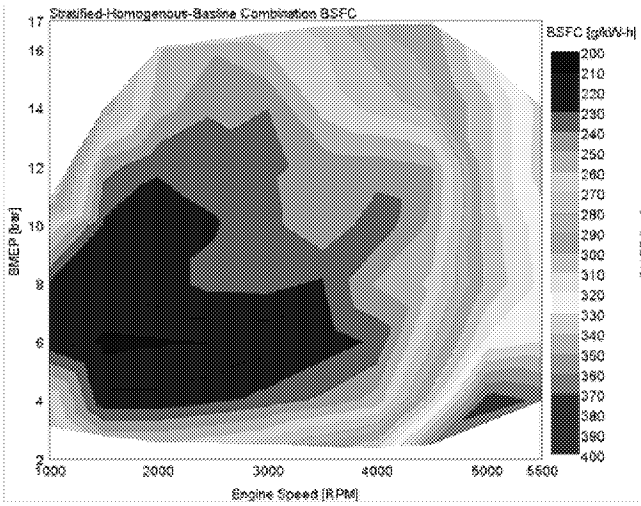


Figure A 26 Combined BSFC Map

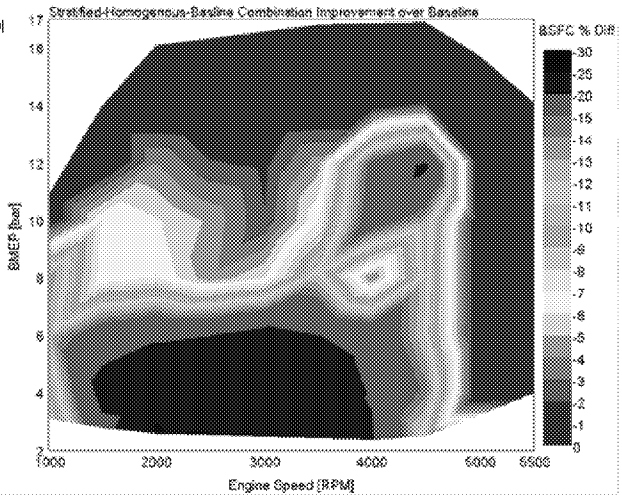


Figure A 27. BSFC Improvement over Baseline

1.5 Explore GDI with cooled EGR (HEDGE)

- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition

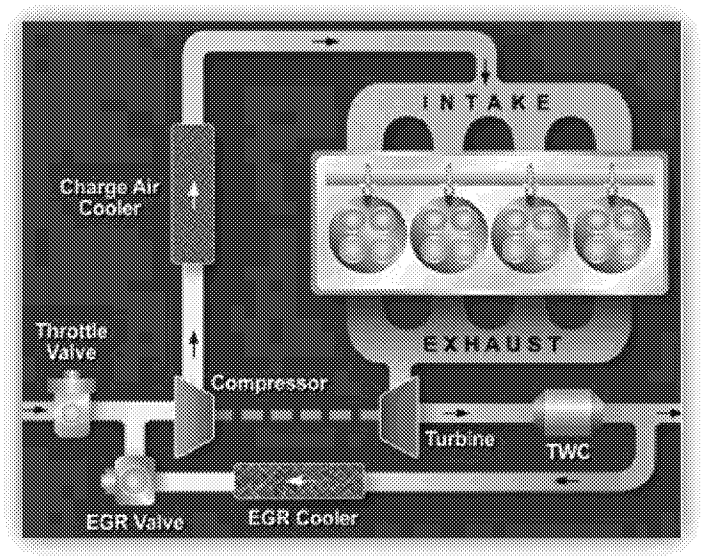


Figure A 28. Typical LPL-EGR Configuration

SwRI's High Efficiency Dilute Gasoline Engine (HEDGE) consortium has proven that engines with exhaust gas recirculation (EGR) show large benefits in efficiency and emissions. EGR engines require an EGR cooler and valve to recirculate the exhaust gasses, and a high energy ignition system to ignite the dilute mixture. [3]

A model based on the baseline engine model was developed to represent a low pressure loop exhaust gas recirculation (LPL-EGR) engine. EGR can improve efficiency in several ways. It enables full-map stoichiometric operation, improves the ratio of specific heats of the working fluid, lowers heat loss in-cylinder due to reduced combustion temperatures and reduces knock tendency which allows more favorable combustion phasing and/or an increase in compression ratio. All of these effects can be observed in the test cell and in GT Power.

Engine parameters, such as CA50, MFB 10-90, compression ratio, EGR rates, and cam timing were selected for this engine model based upon SwRI's experience in converting and calibrating EGR engines. [4,5,6,7] It is understood that while the values will not be exact, the values chosen are based upon the operating characteristics of the baseline engine and should be a close representation of an actual EGR conversion. The compression ratio was increased to 11.5:1, and trapped residuals were kept below 38 percent to ensure robust combustion. Appropriate EGR valves, coolers and controls were added to the model. Combustion phasing (CA50 and 10-90 burn duration) and EGR rates were adjusted to match SwRI experience with LPL-EGR engines and some limited data generated on the 3.5L EcoBoost test cell engine. The CA50 map was modified from the baseline to change any value that was less than or equal to 13 degrees after top dead center on the firing stroke (aTDCf) to a Maximum Brake Torque timing (MBT) value of 8 degrees aTDCf. The remaining area of the map advanced the timing to 50% of the angle between MBT and the baseline CA50 value. For example, if the base CA50 is 16 deg aTDCf and MBT is 8 deg, then (Base CA50 - MBT) x 50% + MBT = (16-8)x0.5+8 = 12 deg aTDCf. The 10-90 burn duration was uniformly lengthened by 10 percent due to the slower burning EGR mixture.

EGR flow rates were defined as follows: at low speed and light load, 12% EGR is used. At high speed light load, 15 % EGR is used. Under full load, EGR is 15% at low speed, increasing to 18% at high speed. Linear interpolation is used to determine the EGR rate for any point in the map.

Intake cam phasing was altered from baseline cam timing to an EGR optimized cam timing based upon SwRI's EGR experience. At low loads more cam overlap is used with normal to late intake valve closing. Mid loads used low overlap and later intake valve closing. High loads operated at best volumetric efficiency positions with normal to high overlap and normal intake valve closing.

Engine BSFC, and percent BSFC improvement over the baseline engine are shown below in Figures A 29- A 30.

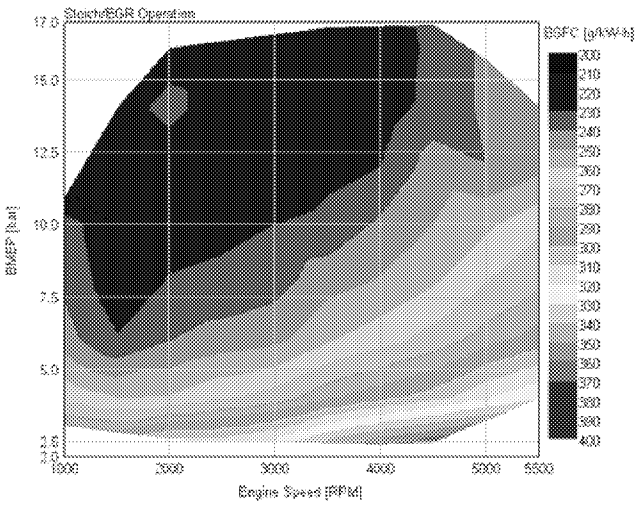


Figure A 8. Stoichiometric EGR BSFC Map

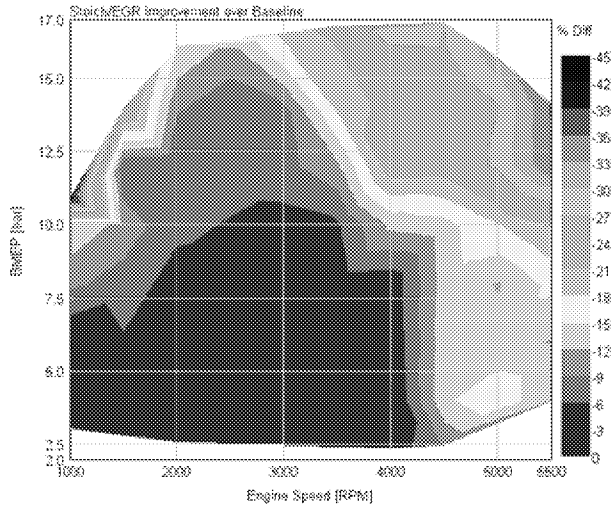


Figure A 30. BSFC Improvement over Baseline

1.6 EGR EGR Engine Down speeding with increased BMEP and PCP

- **Down speed Benefits**
  - Reduced pumping losses
- **Additional Components include:**
  - EGR Valve
  - EGR Cooler
  - High Energy Ignition
  - Improved cylinder pressure capability

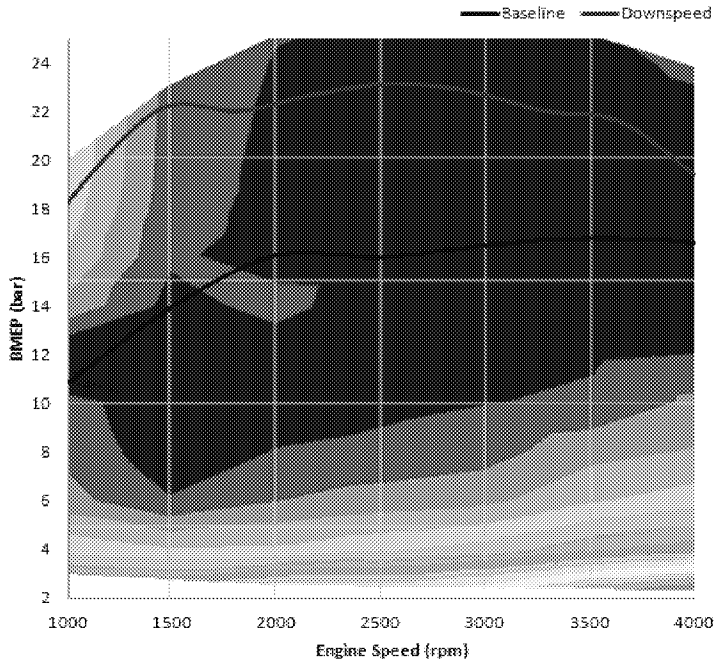


Figure A 31. BMEP Comparison of Standard and Down Speed Torque Curves

A model based on the LPL-EGR engine model was developed to down speed the engine from 5500 rpm to 4000 rpm while maintaining the same peak power. To accomplish this, the BMEP requirement of the engine becomes greater as demonstrated by the red line in Figure A 31 above. The model was allowed to run to even higher loads, (areas above red line) but the final torque curve and fuel map was limited to keep the power levels the same as the baseline and to keep the maximum cylinder pressures below 105 bar.

1.7 Explore FMEP Improvements

Reducing engine friction can be achieved in several ways, such as low viscosity oils, smaller or dynamic bearings, as well as smart controlled oil and water pumps. The modeling effort for this portion lumped together the friction items and reduced their value by 10 percent from the baseline model.

The baseline engine model with the reduced friction was run over the same 78 point test matrix and the BSFC and BSFC improvement over baseline can be seen in the plots below. As expected, the largest benefits occur at light load and higher engine speeds.

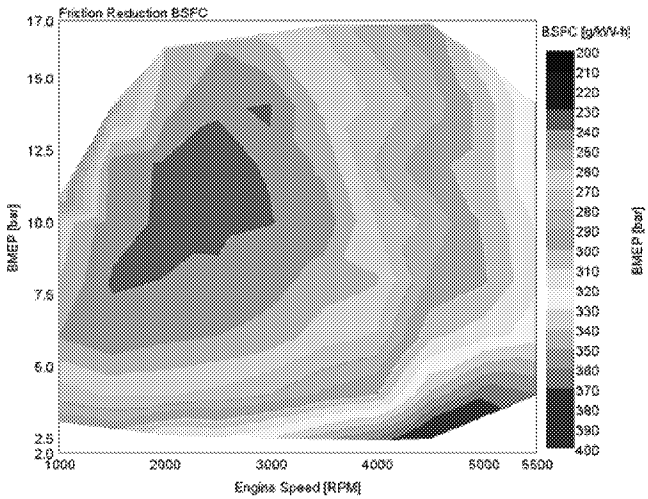


Figure A 32. Friction Reduction BSFC

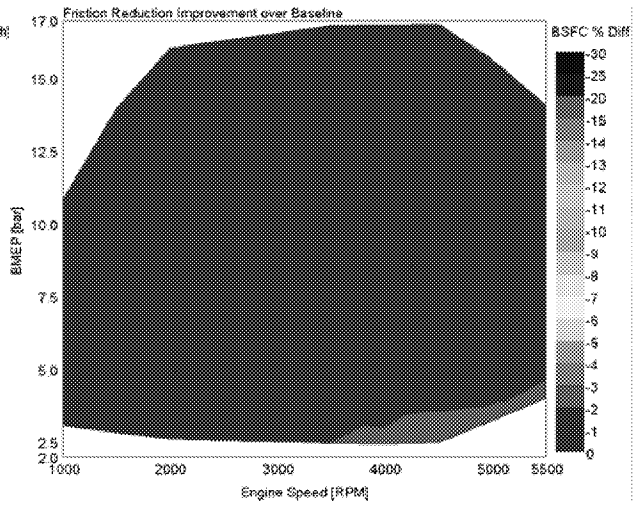


Figure A 33. BSFC Improvement over Baseline

1.8 Explore turbo efficiency improvement

Turbo Efficiency Improvement Benefits

- Reduced pumping losses
- Improved waste heat recovery

- **Additional Components include:**
  - Potentially more expensive turbo

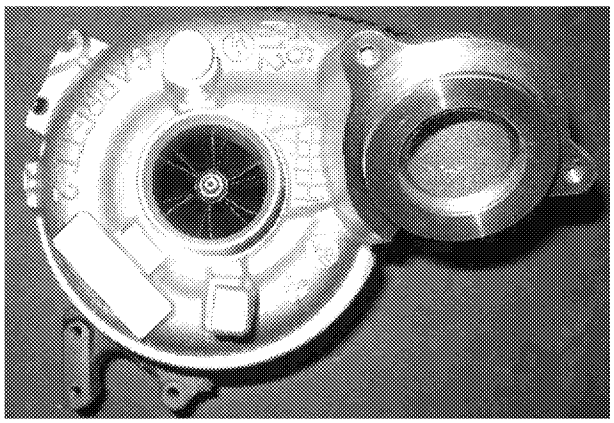


Figure A 34. Example turbocharger hardware

Improvements in turbo designs, bearings, and materials are leading to more efficient and robust turbochargers. An engine model based upon the baseline engine model was built to examine a five percent improvement in turbocharger compressor efficiency. In reality, a waste gated turbocharger, like the one on the 3.5L EcoBoost, operating with improved efficiency, would require additional waste gating to maintain the same engine power. To compensate for the five percent compressor efficiency increase, the turbine size was increased by six percent in the model such that the same amount of waste gating occurred. The baseline engine model with improved turbocharger efficiency was run over the same 78 point test matrix and the BSFC and BSFC improvement over baseline can be seen in the plots below in Figures A 35- A 36.

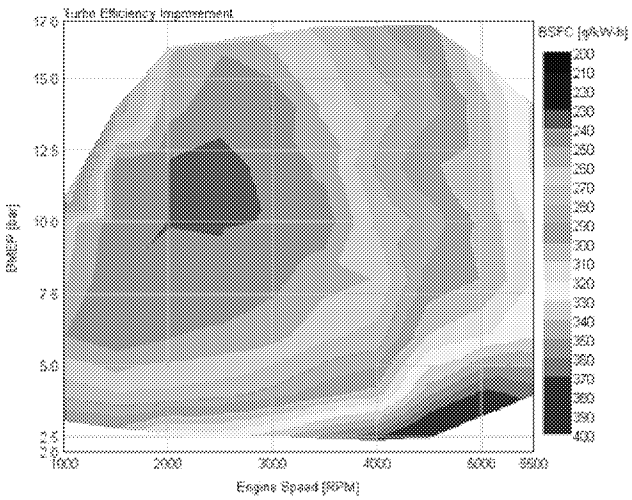


Figure A 35. Turbo Efficiency BSFC Map

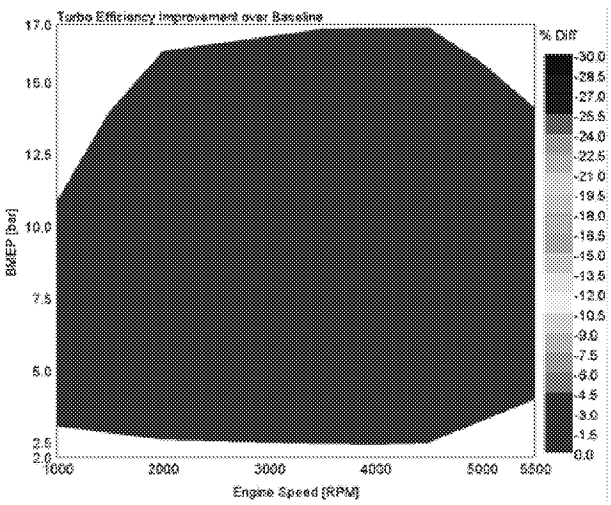


Figure A 36. BSFC Improvement over Baseline

2.1 Baseline V8 Validation

- **OEM V8**
  - 6.2L V8
  - 9.8:1 compression ratio
  - Naturally Aspirated
  - Single Overhead Cam w/Phaser
  - 2 valves per cylinder
  - Gasoline
  - 287/236 kW (<10K/>10K GVWR)
  - 550/538 Nm (<10K/>10K GVWR)

A model of a 6.2L V8 was built with the help and input parameters from an engine OEM. To validate the engine model, 82 part and full load test points were run on an instrumented engine at the OEM facilities and supplied to Southwest Research Institute. Similar to the 3.5L, the model inputs are shown below:

1. **50% Mass Fraction Burned**
2. **10-90 Burn Duration**
3. **Valve Flow Coefficients**
4. **FMEP**
5. **Cam Phaser Position**
6. **Air/Fuel Ratio**

The GT Power model was then run over the same 82-point test matrix and validated by the following operating parameters:

1. **Pre/Post Throttle pressures and temperatures**
2. **Air and Fuel Flow**
3. **BSFC**
4. **BMEP, IMEP, PMEP**

With the "matched" operating conditions, the 82 operating points were run again to confirm that the BSFC calculated by GT-POWER was within +/- 3% of the experimental data. Shown in Figure A 37 below is the comparison between the engine data and model reported BSFC. Also shown in Figures A 38- A 39 are the full BSFC and equivalence ratio contour.

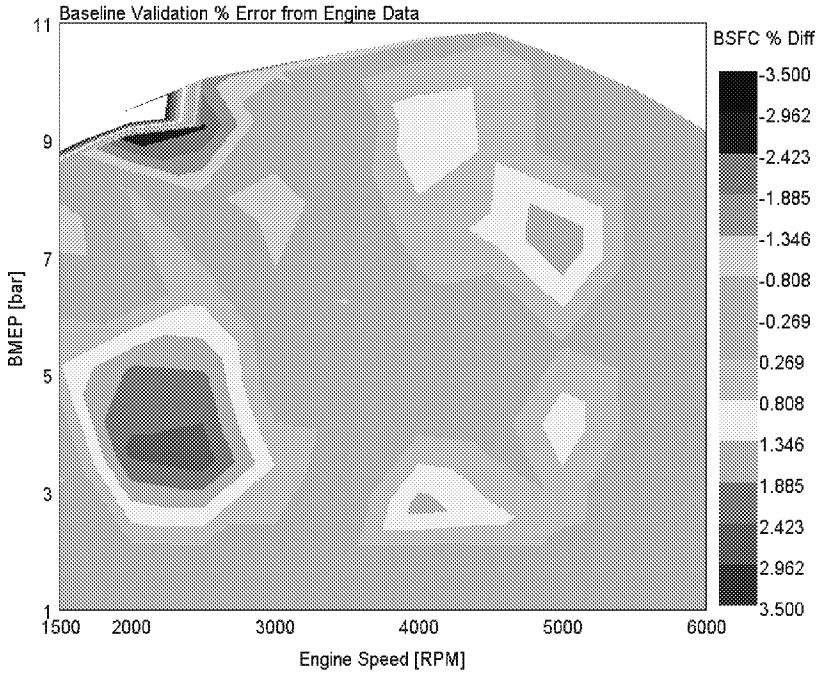


Figure A 37. BSFC Model Error

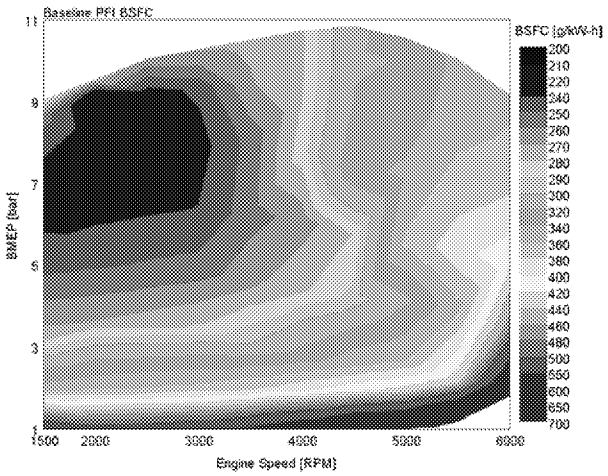


Figure A 38. Baseline Model BSFC Map

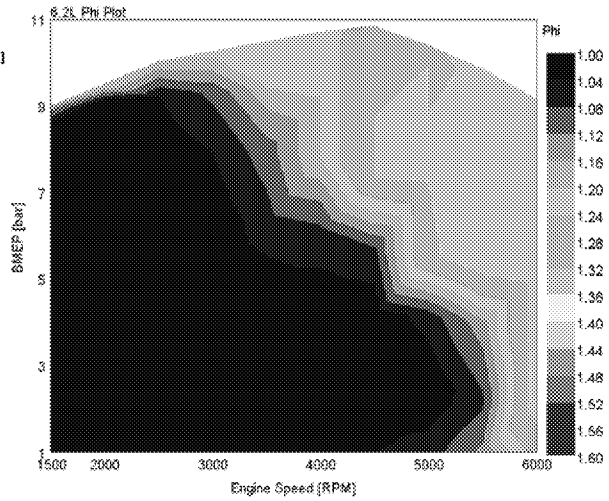


Figure A 39. Baseline Equivalence Ratio

2.2 Stoichiometric

- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output is available (but not used in this project)
  - Allows higher compression ratio
- **Additional Components include:**
  - High pressure pump
  - High pressure injectors
  - High pressure fuel lines
  - High voltage electronics

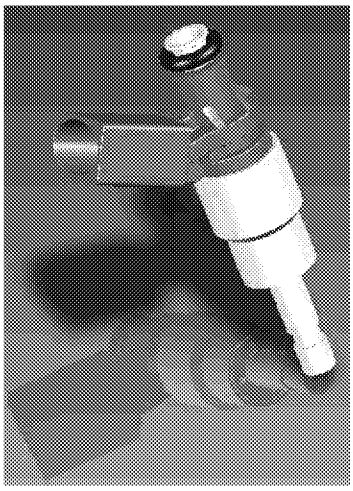


Figure A 40. Gasoline Direct Injector

Gasoline direct injection is typically found on boosted engines with increased power density or lean burn engines that need precise fuel control. In the case of this naturally aspirated V8 engine, a higher compression ratio and improved combustion phasing might be possible, offset with a penalty of degraded combustion efficiency and increased parasitic power losses for the high pressure fuel pump. The baseline GT power model was modified to represent a GDI engine. Port fuel injectors (PFI) were replaced with GDI injectors, compression ratio was increased by 1.5 points, combustion efficiency was reduced by two percent. There has been continual improvement in GDI fuel systems, (i.e. injector relocation from side to central) to improve combustion efficiency. Direct comparisons of PFI and GDI show a 10-90 % increase in CO emissions throughout the engine operating range, indicating a reduction in combustion efficiency with GDI. [8] For this study, a conservative average of combustion efficiency reduction was taken across the operating range. GDI fuel pump loads were calculated based upon engine conditions and the required fuel flow and typical pressures. This power was directly removed from the crankshaft in the GT Power model.

The baseline engine model with gasoline direct injection was run over the same 82 point test matrix and the BSFC and BSFC improvement over baseline can be seen below in Figures A 41 - A 42.

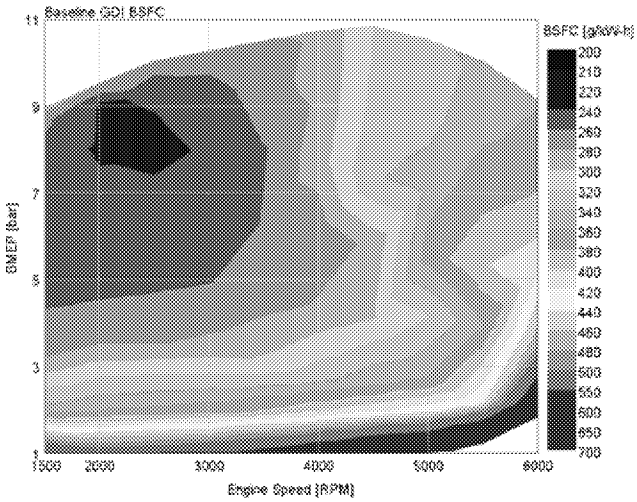


Figure A 41. GDI BSFC Map

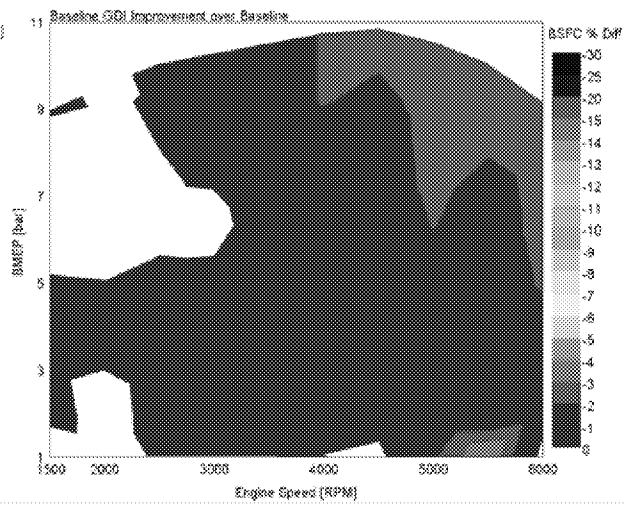


Figure A 42. BSFC Improvement over Baseline

2.3 Lean Burn GDI w/SCR

- **GDI conversion**
  - Allows for in-cylinder charge cooling
  - Better Fuel control
  - Higher power output
  - Reduced pumping losses
  - Improved combustion efficiency
- **Additional Components include:**
  - High pressure pump
  - High pressure injectors
  - High pressure fuel lines
  - Higher voltage electronics
  - NOx Trap or SCR Catalyst
  - NOx Sensor
  - Urea/Injector/mixer
  - Exhaust Gas Temperature Sensor

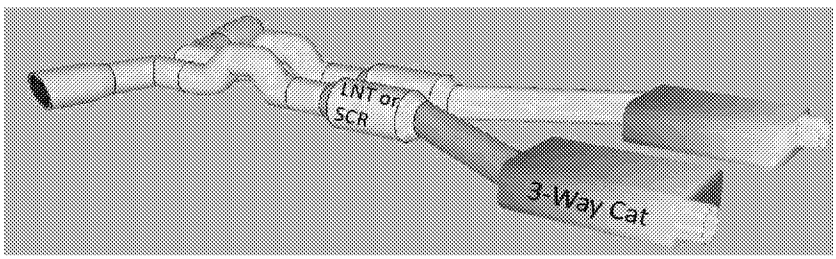


Figure A 43. Lean Aftertreatment

Lean burn operation can improve engine efficiency by reducing throttling losses, increasing combustion efficiency due to excess oxygen and by improving gamma of the working fluid. In the stratified operating area, the majority of improvement comes from a pumping work

improvement and reduced heat transfer due to cooler in-cylinder temperatures. In addition, the homogeneous lean area benefits some due to pumping work and greatly in the areas where the baseline engine utilized enrichment.

The improvement shown from the GT Power simulation show favorable improvements in its steady state operation, however, it does not show the fuel penalty for the regeneration of the LNT or account for the Urea needed in an SCR. In addition to these penalties, the location of the NOx aftertreatment would have to be located sufficiently far downstream to minimize the inlet temperatures. This distance will help the durability of the aftertreatment, but another fuel penalty will be added at startup until the NOx aftertreatment is up to operating temperature. During this time, the engine will operate in stoichiometric mode to allow the three-way catalyst to operate. These fuel penalties can increase fuel comsumption on the drive cycle and potentially remove any of the benefits of lean operation.

To operate lean, additional components, such as a lean NOx traps or SCR systems, NOx sensors and Piezo fuel injectors for precise multiple injections will be needed. In order for this vehicle to be successful with current and future emission standards, a high NOx conversion efficiency will be required. For high LNT conversion efficiencies, relatively low space velocities are required, therefore a very large volume LNT will be required for conversion of NOx at high load, resulting in a costly LNT. For high SCR conversion efficiencies, high urea dosing rates will be required.

Some of the potential issues with operating in lean mode are degradation of the NOx aftertreatment at high load/temperature conditions and using US fuels with high sulfur content. The exhaust temperature limit is 1175 K for the baseline engine and the maximum obtained during homogeneous operation was 1175 K. Ideally, the maximum temperature at NOx aftertreatment inlet would be less than 1050 K to avoid premature aging and less than 850 K for good conversion efficiency. A certain amount of heat loss will occur across the turbine and piping, but heat addition can take place at the catalyst. Since modeling of heat loss in the aftertreatment system was outside the scope of the project, the pre-turbine temperature limit was allowed to reach 1200 K and the lean operation limits were chosen based upon typical operating ranges from literature. [1, 2] It was assumed that a suitable location for the NOx aftertreatment that met inlet temperature requirements would be used for all vehicles. High sulfur content will lead to sulfur poisoning and frequent desulfation of a LNT, which will lead to a shortened life of the aftertreatment system. There is the potential that future US gasoline fuel quality specifications will reduce sulfur content, and thus minimize the damage caused by sulfur in the fuel, but that is not presently the case.

This engine model configuration has three operating modes, stratified lean mixture, homogeneous lean mixture, and homogeneous stoichiometric to rich mixture. Shown below in Figure A 43, the engine operates at low speed/load, medium speed/load, and high load in

stratified lean, homogeneous lean, and homogeneous stoichiometric modes respectively. Near full load, the engine operates rich, similar to a conventional gasoline engine.

Due to limited published engine data and inability to run stratified charge on our test engine, combustion phasing was assumed to be the same as the baseline operation. Stratified charge burn durations were chosen to be the same as the homogenous lean engine data collected on the test engine. Homogeneous lean and stoich combustion phasing/duration data was collected from the test engine. It should be noted that efficiency is a strong function of combustion phasing and a weak function of burn duration.

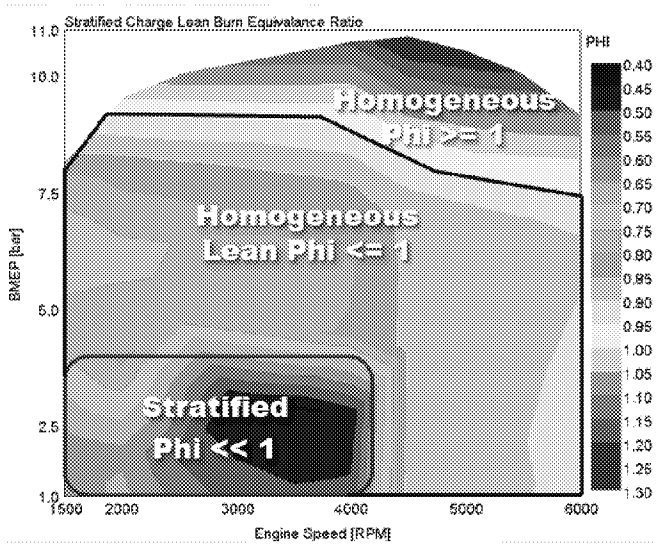


Figure A 44. Engine Operating Modes for lean GDI

The engine efficiencies for the three combustion modes were combined, and a composite engine operating map was generated for the same 82 operating points. Figures A 45 and A 46 below show the composite engine BSFC, and percent BSFC improvement over the baseline engine.

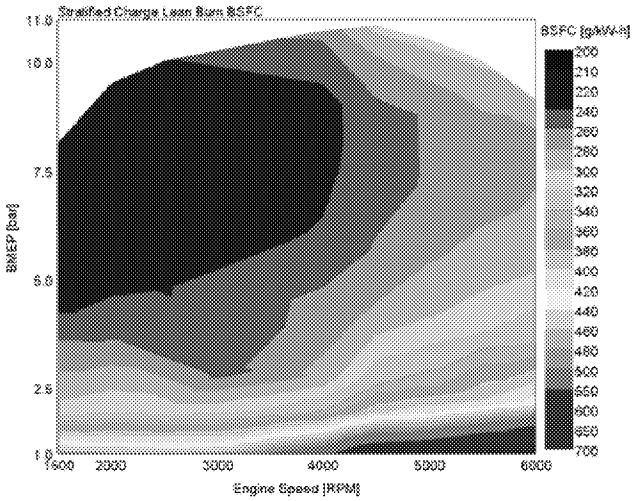


Figure A 45. Combined Lean Burn BSFC

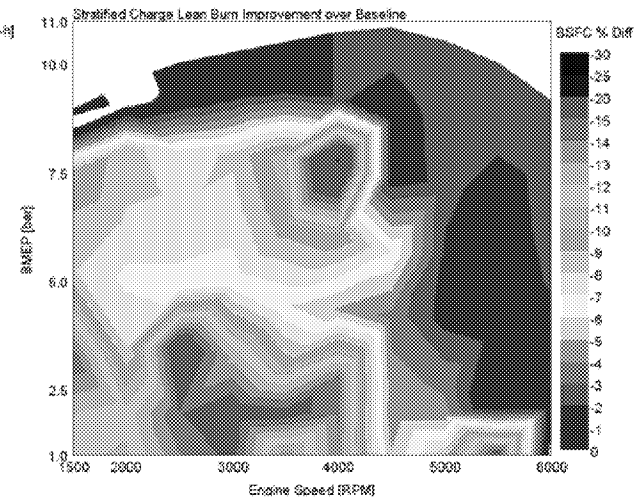


Figure A 46. BSFC Improvement over Baseline

2.4 Variable Valve Lift

- **Variable Valve Lift (VVL) and Phasing**
  - Reduced pumping losses (reduced or eliminated throttling)
- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation

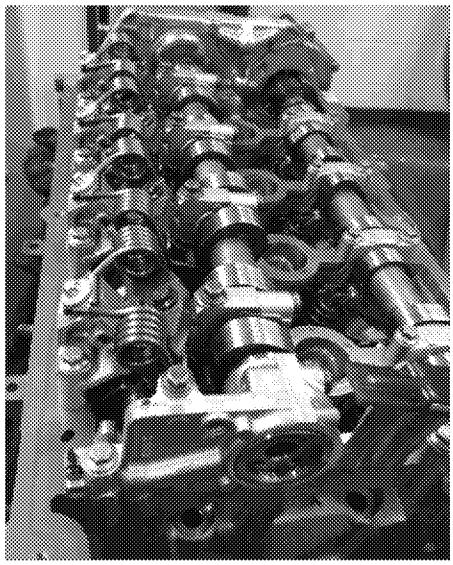


Figure A 47. VVL arrangement

Variable valve lift (VVL) allows for improvement in efficiency during part load or "normally" throttled conditions. By closing the intake valve early and allowing the cylinders to pull a vacuum on the downward stroke, some of the energy is recovered as the piston comes back up. The benefit is more evident at higher engine speeds, and it phases out as load increases. Special cam actuators are required to allow for variable lift and phasing as shown in Figure 50 above. As the valve lift and duration are shortened, the in-cylinder charge motion may be affected negatively and cause unstable combustion at the low lift, or low load conditions. If the engine has two intake valves per cylinder, a potential solution for might be to vary the lift on one valve much more than the other to keep the velocity high through at least one of the intake ports during low load operation. For the purposes of this model, given the fact that this engine only has one intake valve, charge motion was assumed not to be affected.

The variable valve lift model is a modified version of the baseline 6.2L V8. The throttle was removed and the load was controlled by the intake valve lift. Intake valve duration was a mathematical function of the lift that attempted to emulate a realistic VVL system. In addition to the variable valve lift, the intake and exhaust cams are now have independent phasing capability. To optimize fuel efficiency, more than 1300 intake and exhaust timing combinations were run for the 82 point test matrix. Shown below in Figure A 48, is the final intake and exhaust valve timing for the 82 speed/load conditions.

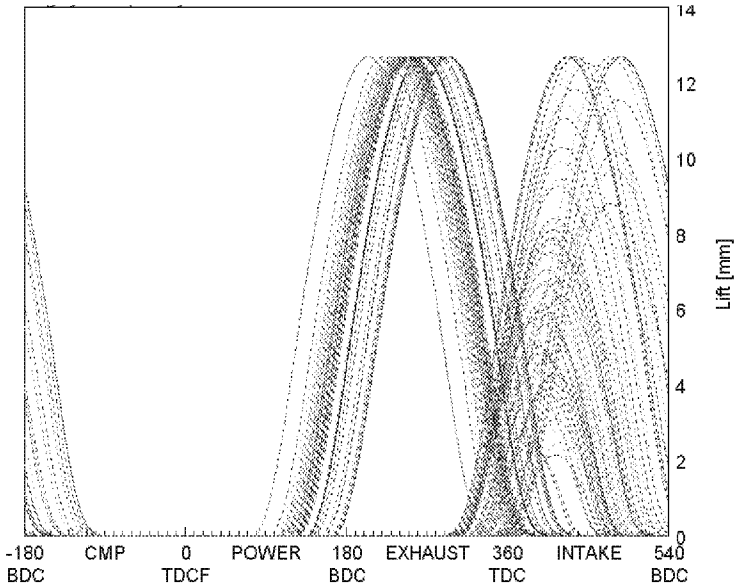


Figure A 48. 6.2L V8 Cam Phasing

Variable valve lift allows for improvement in BSFC at throttled conditions which is more evident at higher engine speeds, but the benefit phases out as load increases. Shown below in Figures A 49- A 50, are the BSFC and BSFC improvement over the baseline engine contour maps.

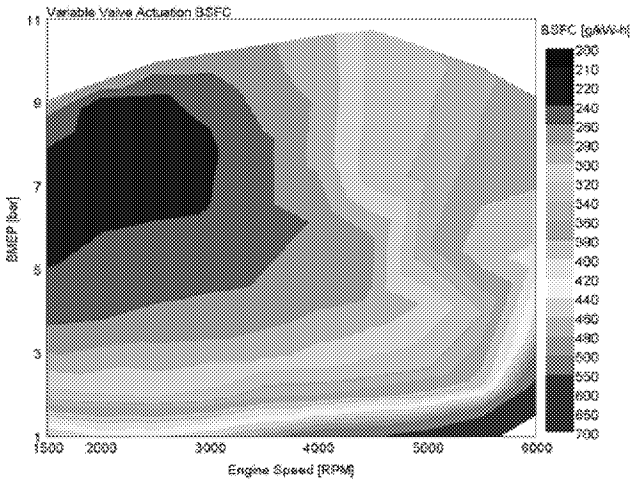


Figure A 49. Variable Valve Lift BSFC Map

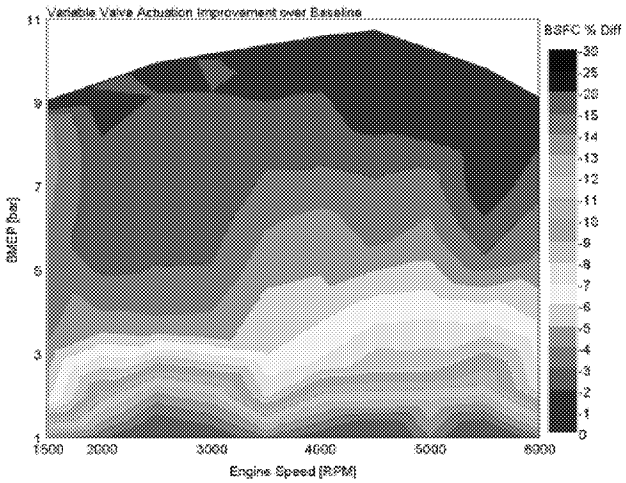


Figure A 50. BSFC Improvement over Baseline

2.5 Cylinder Deactivation

- **Four Cylinder Deactivation. GM Active Fuel Management (pushrod engines) and Audi cylinder on demand (OHC engines)**
  - Eliminates pumping losses in deactivated cylinders
  - Deactivation of every second cylinder by firing order (1 5 4 8 6 3 7 2)
  - Reduced pumping losses in active cylinders (less throttling)
  - Reduced energy loss from deactivated valves
  - Possible at loads up to 6 bar BMEP

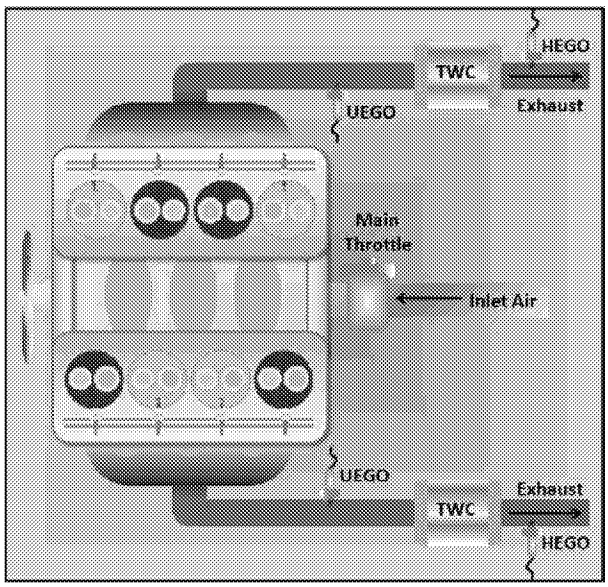


Figure A 51. Cylinder Deactivation

- **Additional Components include:**
  - Special cams and actuators to allow for valve deactivation
  - Active Engine mounts/dampers
  - Special exhaust to handle 2nd and 4th order

Engines that have eight cylinders have demonstrated operation with four cylinder deactivation such as General Motors Active Fuel Management and Audi Cylinder on Demand. The engine at idle conditions will operate on all eight cylinders to minimize vibration, but between idle and approximately five bar BMEP, four cylinders will cut fuel injection and valve actuation. The model was run up to the maximum load the four-cylinder would allow, five bar BMEP (see Figure A 52) and the areas that were less efficient than the baseline eight-cylinder were removed. (see Figure A 53) Loads above five bar BMEP will transition back to eight-cylinder operation.

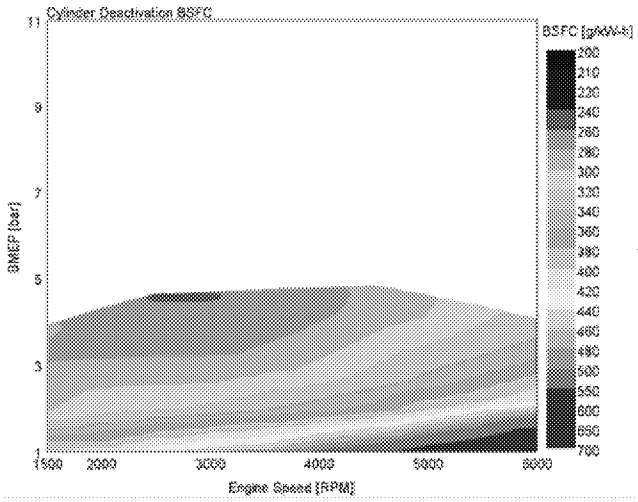


Figure A 52. Cylinder Deactivation BSFC Map

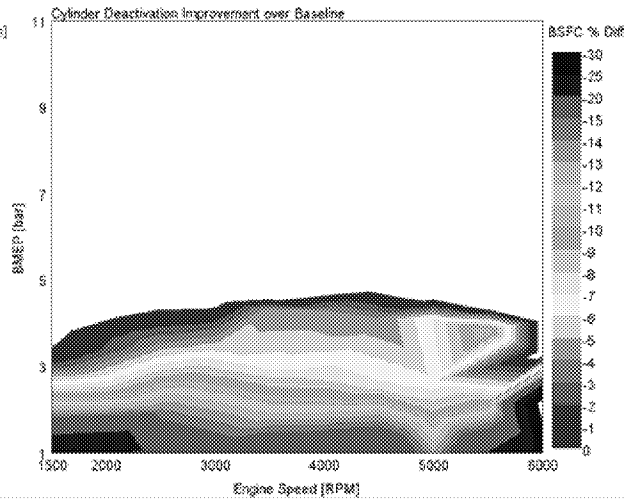


Figure A 53. BSFC Improvement over Baseline

2.6 GDI with EGR

- **EGR Benefits**
  - Reduced pumping losses
  - Improved working fluid
  - Improved knock tolerance
    - Improved combustion phasing
    - Increased compression ratio
  - Reduce heat transfer
  - Eliminate enrichment for catalyst protection
- **Additional Components include:**
  - EGR Valves
  - EGR Cooler
  - High Energy Ignition

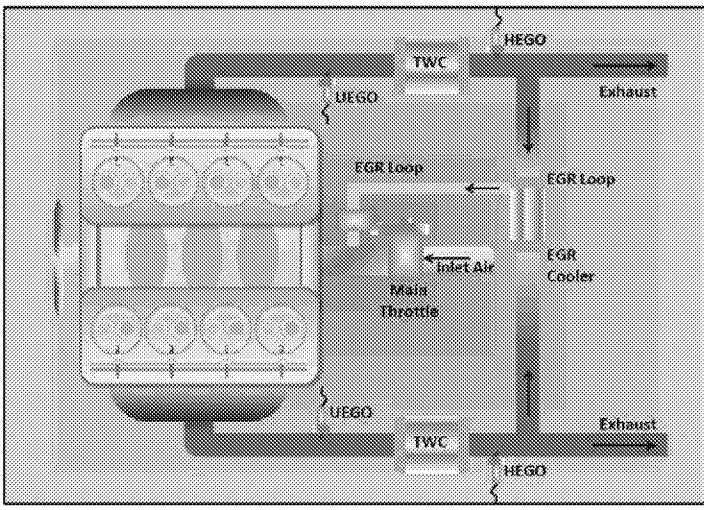


Figure A 54. EGR System for naturally aspirated V-8

SwRI's High Efficiency Dilute Gasoline Engine (HEDGE) consortium has proven that engines with exhaust gas recirculation (EGR) show large benefits in efficiency and emissions.

EGR engines require an EGR cooler and valve to recirculate the exhaust gasses, and a high energy ignition system to ignite the dilute mixture.

A model based on the baseline engine model was developed to represent a low pressure loop exhaust gas recirculation (LPL-EGR) engine. EGR can improve efficiency in several ways. It enables full-map stoichiometric operation, improves the ratio of specific heats of the working fluid, lowers heat loss in-cylinder due to reduced combustion temperatures and reduces knock tendency which allows more favorable combustion phasing and/or an increase in compression ratio. All of these effects can be observed in the test cell and in GT Power.

Engine parameters, such as CA50, MFB 10-90, compression ratio, EGR rates, and cam timing were selected for this engine model based upon SwRI's experience in converting and calibrating EGR engines. [4,5,6,7] It is understood that the values will not be exact, however, the values chosen are based upon the operating characteristics of the baseline engine and should be a close representation of an actual EGR conversion. The compression ratio was increased to 11.5:1, and trapped residuals were kept below 38 percent to ensure robust combustion. Appropriate EGR valves, coolers and controls were added to the model. Combustion phasing (CA50 and 10-90 burn duration) and EGR rates were adjusted to match SwRI experience with LPL-EGR. The CA50 map was modified from the baseline to change any value that was less than or equal to 13 degrees aTDCf to a MBT value of 8 degrees aTDCf. The remaining area of the map advanced the timing to 50% of the angle between MBT and the baseline CA50 value. For example, if the base CA50 is 16 deg aTDCf and MBT is 8 deg, then (Base CA50 - MBT) x 50% + MBT = (16-8)x0.5+8 = 12 deg aTDCf. The 10-90 burn duration was uniformly lengthened by 10 percent due to the slower burning EGR mixture.

EGR flow rates were defined as follows: at low speed and light load, 12% EGR is used. At high speed light load, 15 % EGR is used. Under full load, EGR is 15% at low speed, increasing to 18% at high speed. Linear interpolation is used to determine the EGR rate for any point in the map.

Intake cam phasing was altered from baseline cam timing to an EGR optimized cam timing based upon SwRI's EGR experience. At low loads more cam overlap is used with normal to late intake valve closing. Mid loads used low overlap and later intake valve closing. High loads operated at best volumetric efficiency positions with normal to high overlap and normal intake valve closing.

Figures A 55- A 56 below, show the engine BSFC, and percent BSFC improvement over the baseline engine.

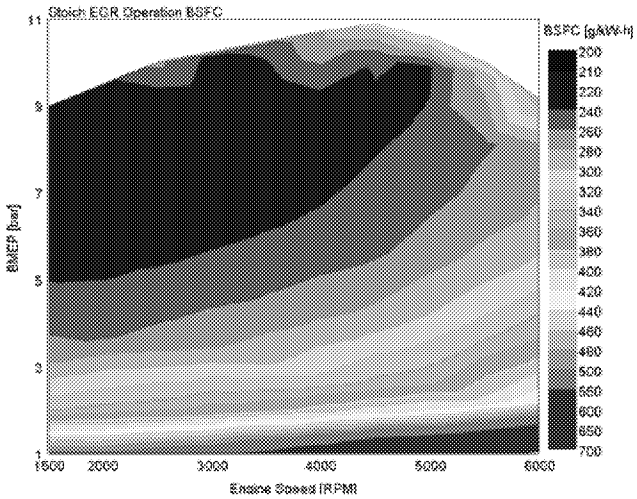


Figure A 55. Stoichiometric EGR BSFC Map

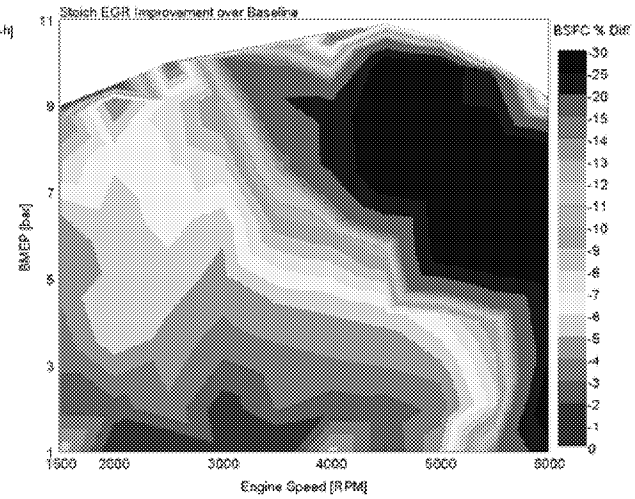


Figure A 56. BSFC Improvement over Baseline

2.7 FMEP Improvements

Reducing engine friction can be achieved in several ways, including low viscosity oils, smaller or dynamic bearings, as well as smart controlled oil and water pumps. The modeling effort for this portion lumped together the friction items and reduced their value by 10 percent from the baseline model.

The baseline engine model with the reduced friction was run over the same 82 point test matrix and the BSFC and BSFC improvement over baseline can be seen in the plots below.

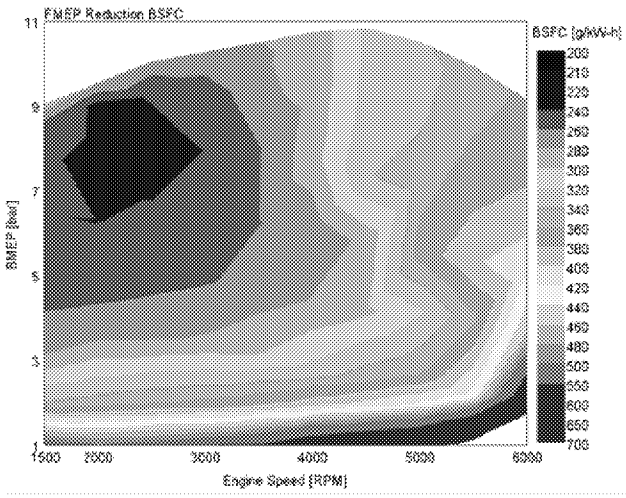


Figure A 57. Friction Reduction BSFC Map

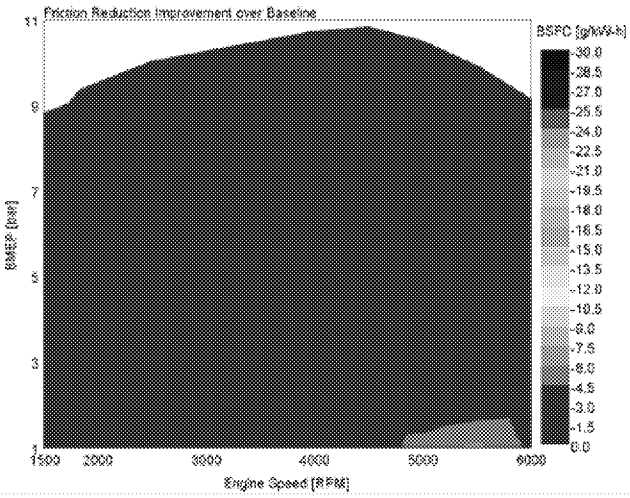


Figure A 58. BSFC Improvement over Baseline

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7. Raphael Gukelberger, Terrence Alger, Jess Gingrich, Barrett Mangold, (2012), The Effects of Operating Parameters on Ignition System Energy Consumption, SAE Paper 2014-01-1233
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APPENDIX B

DIESEL ENGINE TECHNOLOGIES

Part 2: Diesel Engine Technologies

Objective: Simulate Future Diesel Engine Technologies to demonstrate Fuel Economy Improvement Potential in Class 2b through 7 vehicles utilizing:

- **14.6L turbocharged diesel engine**
- **6.7L VG turbocharged Medium Duty 300 bhp diesel engine**
- **6.7L VG turbocharged Pick Up 385 bhp diesel engine**

1. 15L turbocharged diesel engine evaluation plan:

1.1. **Baseline Validation**
1.2. **Reduced Exhaust Backpressure**
1.3. **Reduced Inlet System Restriction**
1.4. **Optimized Mechanical Turbocompound (APT)**
1.5. **Optimized Electrical Turbocompound (APT)**
1.6. **No EGR**
1.7. **Turbocompound Removed (No APT)**
1.8. **No EGR or APT**
1.9. **Asymmetric Turbocharger and EGR circuit**
1.10. **Down Speeding with Increased BMEP**
1.11. **Downsizing with Constant BMEP**
1.12. **Downsizing with Constant Torque**
1.13. **Explore FMEP Improvements**
1.14. **Explore Turbo Efficiency Improvement**
1.15. **Variable Valvetrain Actuation**

2. 6.7L VG turbocharged Medium Duty 300 bhp diesel engine evaluation plan

2.1. **Baseline Validation**
2.2. **Reduced Exhaust Backpressure**
2.3. **No EGR**
2.4. **Explore Turbo Efficiency Improvement**
2.5. **FMEP Improvements**

3. 6.7L VG turbocharged Pick Up 385 bhp diesel engine evaluation plan

3.1. **Baseline Validation**
3.2. **Reduced Exhaust Backpressure**
3.3. **No EGR**
3.4. **Explore Turbo Efficiency Improvement**
3.5. **4.5L Version (4 cyl), Constant BMEP**
3.6. **FMEP Improvements**

1.1 DD15Baseline Validation

- **Basic engine specification**
  - 14.6L inline 6 cylinder
  - Single Fixed Geometry Turbo
  - Auxiliary Power Turbine (Turbocompound) with geared link to engine
  - 4 valves per cylinder
  - Diesel
  - 376 kW @1800 rpm
  - 2200 Nm @ 1240-1400 rpm

GT Power model was built using the geometry of a DD15 engine previously benchmarked at SwRI and run in a test cell. The engine had been fully instrumented, including temperatures, pressures, speed, torque and high-speed cylinder pressure measurements and had been operated over a full test matrix that covered the entire engine operating range. Engine data from the test cell, shown below, was used as model input data.

- **Combustion data – from analysis of high-speed cylinder pressure data**
  - **50% Mass Fraction Burned**
  - **10-90 Burn Duration**
- **Valve Flow Coefficients**
- **FMEP**
- **Air/Fuel Ratio**
- **EGR Rates**

The GT Power model was then run over a speed range of 1000 – 2100 rpm at 10, 20, 40, 60, 80 & 100% load (see figure B1a), and validated by the following operating parameters:

- **BMEP, IMEP, PMEP**
- **BSFC**
- **Air and Fuel Flow**
- **Pre/Post compressor pressures and temperatures**
- **Pre/Post Turbine pressures and temperatures**
- **EGR Rates**

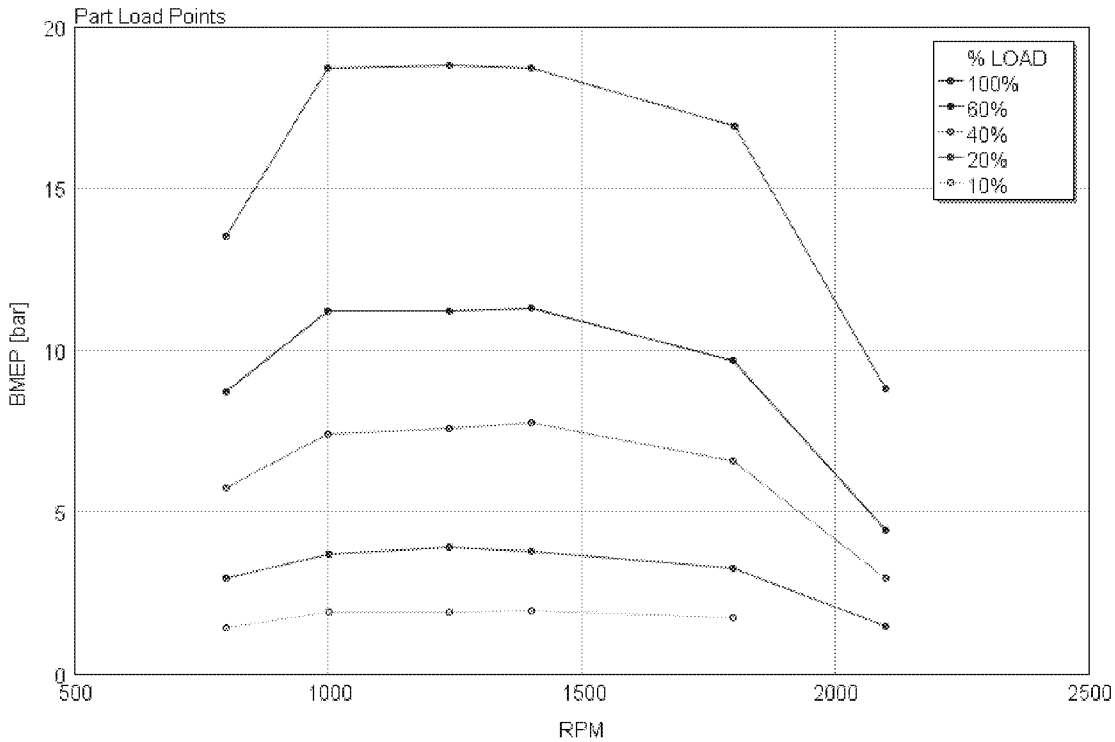

Figure B1a. DD15 GT baseline operating points

The GT model was setup using combustion data derived from the measured high-speed cylinder pressure data. A typical correlation between measured (Test) data and the GT simulated data are shown in the figure below.

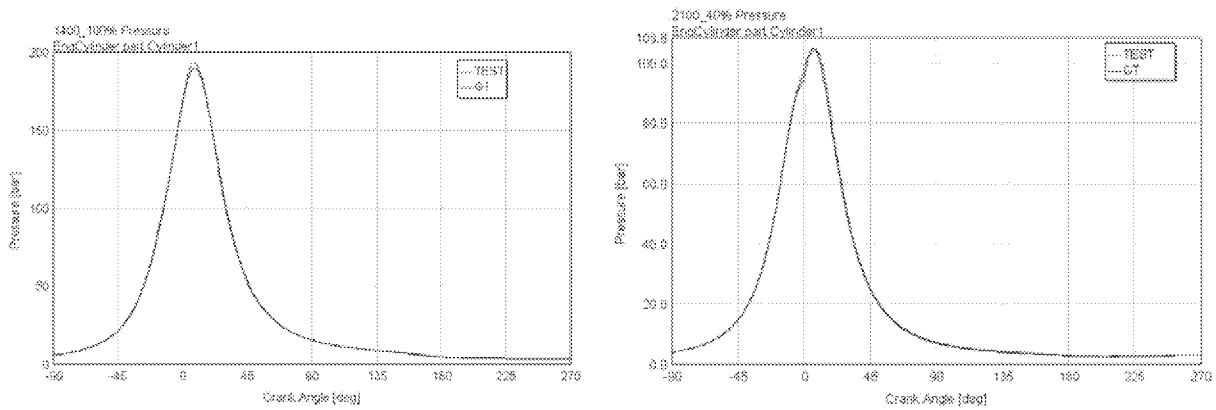

Figure B1b. DD15 GT Cylinder pressure correlation

The geometry was constructed from measurements of the real hardware and port flow data and valve lift was from flow-rig tests. The actual turbo maps for both the main turbo (twin entry) & the APT were not available, so existing maps from a similarly sized engine were used and scaled so that that the measured inlet & outlet conditions were matched to test data.

A review of published data indicated that a match of +/- 3-5% should be achievable with a correctly setup GT model. Two examples of papers relating to models for similar medium duty engines are:

- "Creation and Validation of a High Accuracy, Real-Time-Capable Mean-Value GT-Power Model" by Tim Prochnau, International Truck & Engine Corporation. Presented at the 11th GT-Suite Users' Conference, November 13, 2007
- "Transient engine modeling at John Deere using GT-Power" by John Deere. Presented at GT-Suite North American Conference 2009

Further papers showing the modelling, accuracy and application of GT Power models can be found at https://www.gtisoft.com/knowledgebase .

With the "matched" operating conditions, the operating points were run again to confirm that the simulated BSFC was within +/- 3% of the experimental results. Shown below is the comparison between the engine data and model reported BSFC. Also shown is the full range of matched data. The accuracy of the model was also evaluated by comparing simulated and experimental pumping mean effective pressure (PMEP), air flow, EGR rate, peak cylinder pressure, as well as turbocharger pressures and temperatures. See Figure B1d for comparison plots of these parameters.

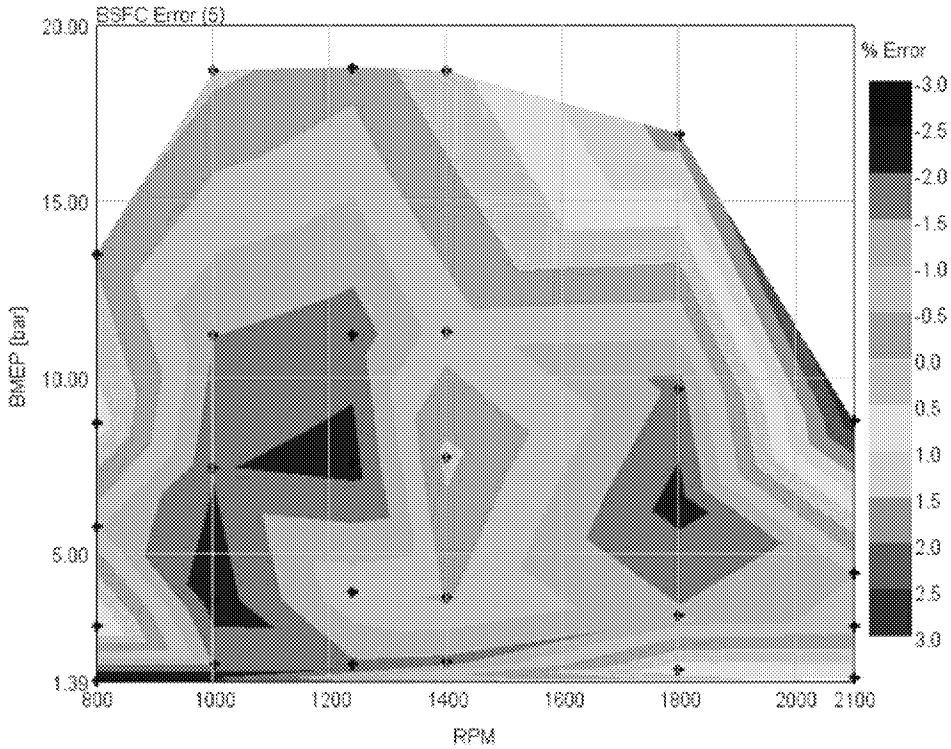

Figure B1c. BSFC Model Error

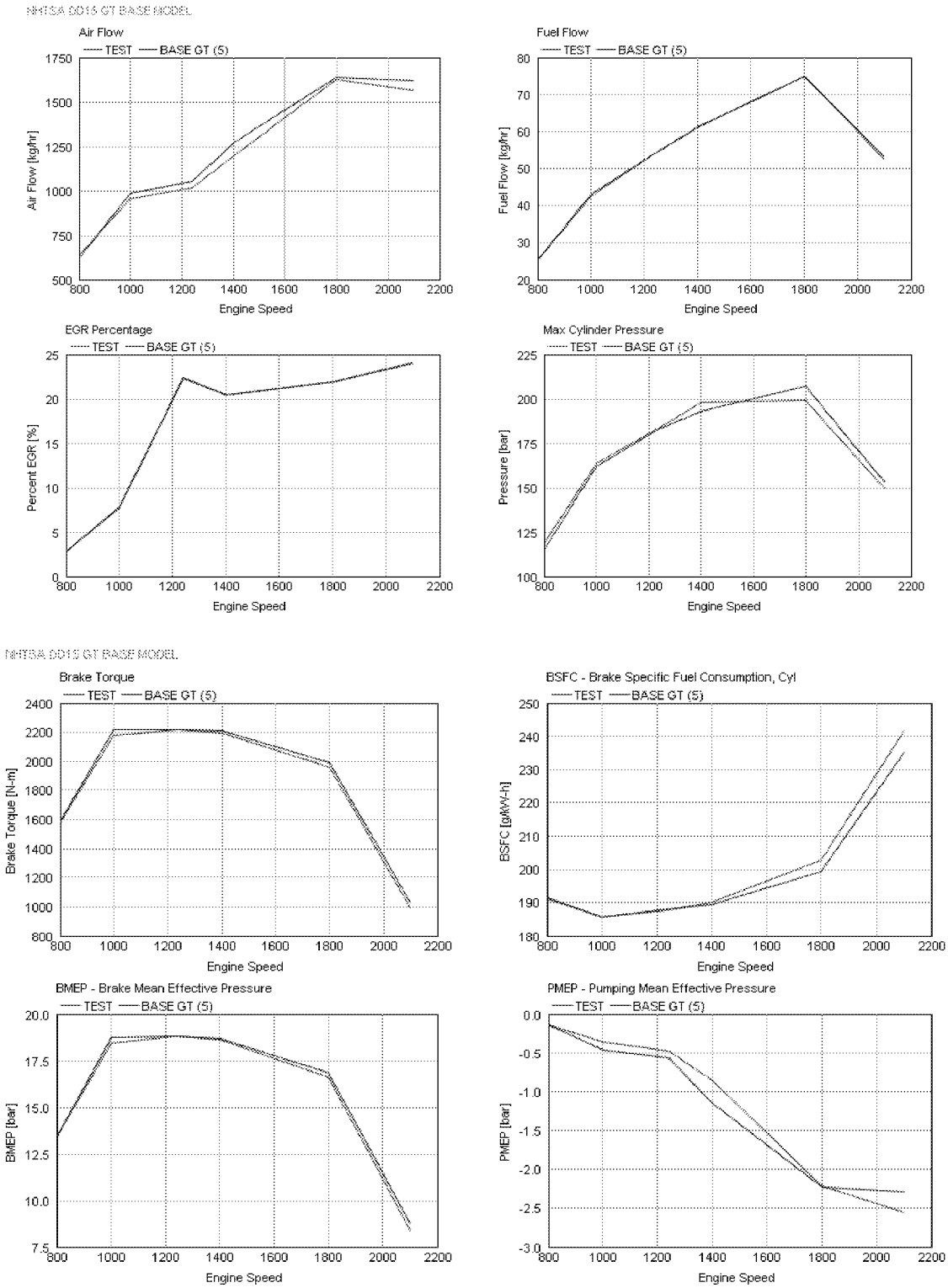

Figure B1d. (Part 1) Baseline Model Data Correlation at Full Load

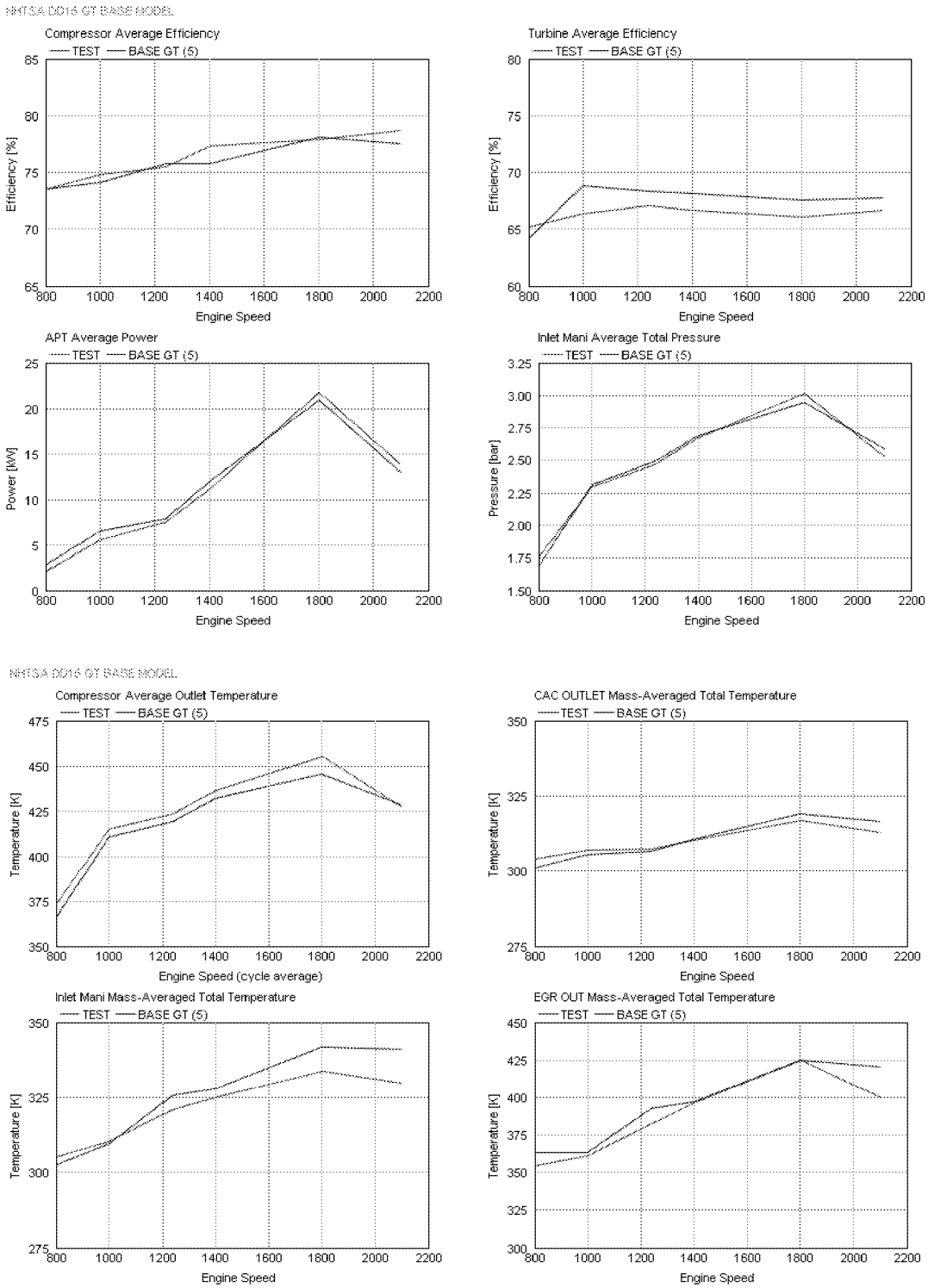

Figure B1d. (Part 2) Baseline Model Data Correlation at Full Load

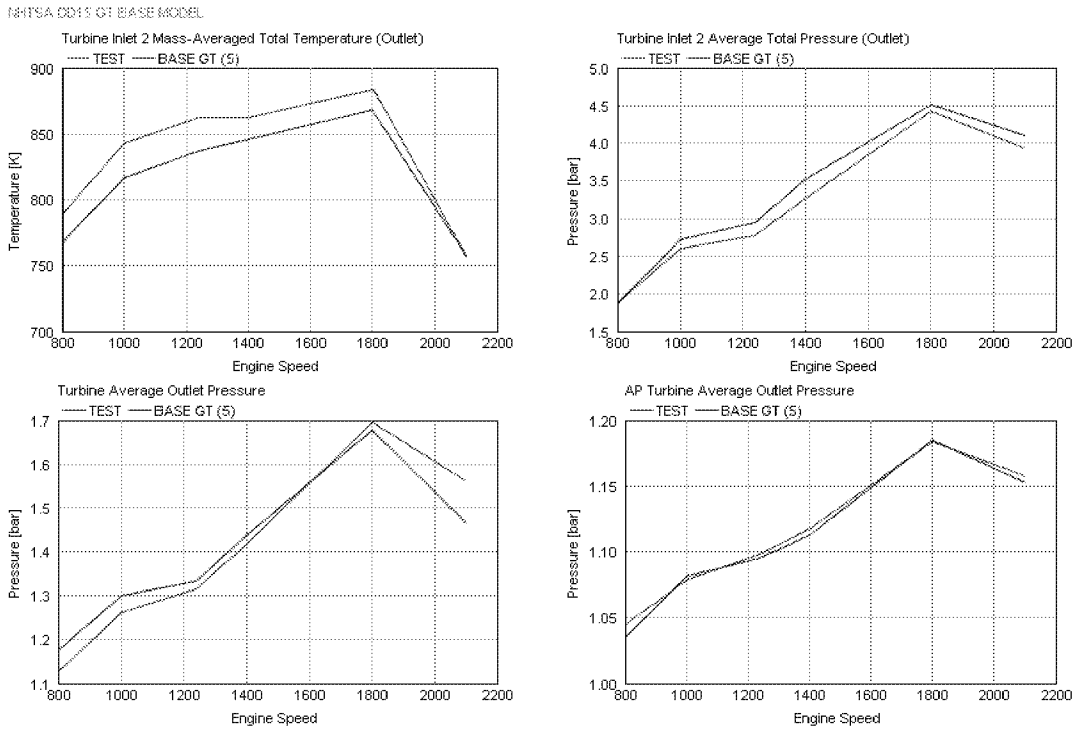

Figure B1d. (Part 3) Baseline Model Data Correlation at Full Load

1.2 Reduced Exhaust Restriction

The aim of running the model with reduced exhaust restriction is to simulate the effect of improved flow after-treatment systems for emissions control and the resulting reduction in pumping losses. The baseline GT model was originally setup without modeling the emissions control hardware, but the effective backpressure seen in the exhaust at the APT exit is simulated by the use of a simple orifice. To model the reduced exhaust backpressure the orifice is resized to achieve the desired target backpressure at the rated condition. In this case, the backpressure has been reduced by 45%, from 18.5 to 10 kPa. The effect on the engine BSFC is shown in figure B2a. Assuming that the after-treatment effectiveness is retained, there will be no effect on either engine-out or tailpipe emissions of criteria pollutants.

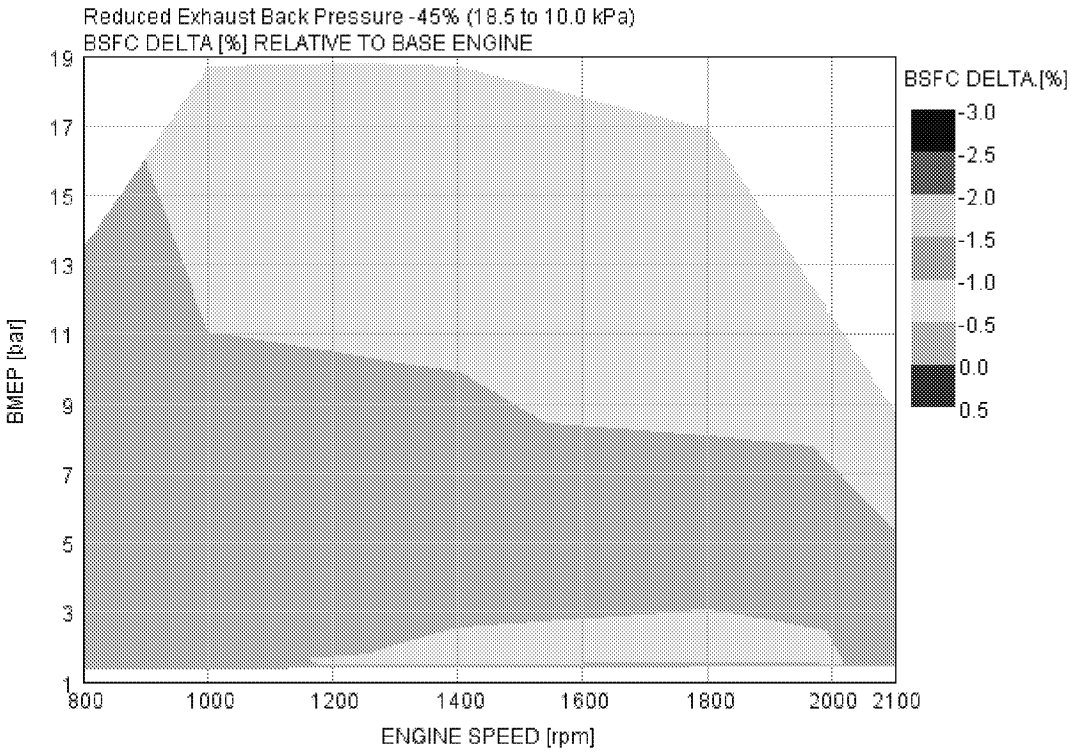

Figure B2a. Reduced Exhaust backpressure BSFC Improvement

1.3 Reduced Inlet System Restriction

The two areas of the inlet system considered in this section where the inlet filter and the charge air cooler (CAC). The filters effective restriction was reduced by 50% and the CAC restriction was virtually eliminated by opening up the GT model orifice that controlled the restrictions. Despite the dramatic sounding changes, the overall effect was minimal with < 0.5% BSFC improvement across the range. This technology as modeled has no effect on EGR rates, and is therefore not predicted to have measureable effects on engine-out or tailpipe criteria emissions.

1.4 Optimized Mechanical Turbocompound (APT)

The base engine model incorporates an axial power turbine (APT) that recovers exhaust energy after it has passed through the main engine turbo, and is connected to the engine crankshaft via a gearbox & fluid clutch. The setup is shown in figure B4a. The system is setup to deliver maximum power at engine rated power, so for this study the turbine was re-sized to improve the power delivery at part load drive cycle speeds, even at the expense of maximum power. Additionally the gear ratio between the APT and the crankshaft was modified to improve the overall performance. The remainder of the engine system, including the main turbo was left unmodified. By changing the APT setup the effective backpressure seen by the main turbo changed, leading to it potentially operating in a different point on its map. The backpressure seen by the APT was maintained as per the baseline model by controlling the exhaust orifice.

As shown in figure B4b, the revised APT improved BSFC across the majority of the operating map by 1-2%, but at the expense of the higher speed section. In reality the engine rarely operates in this zone, so it has little effect on the drive cycle fuel consumption. This technology as modeled has no effect on EGR rates, and is therefore not predicted to have measureable effects on engine-out or tailpipe criteria emissions.

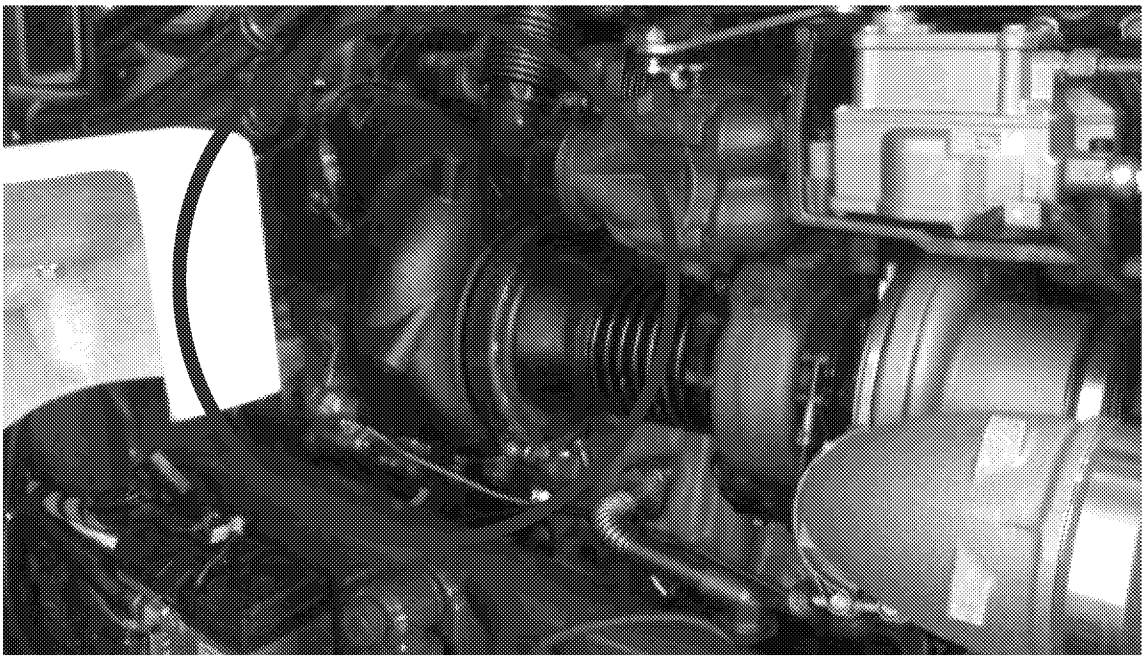

Figure B4a. DD15 Axial Power Turbine portion of the turbocompound system

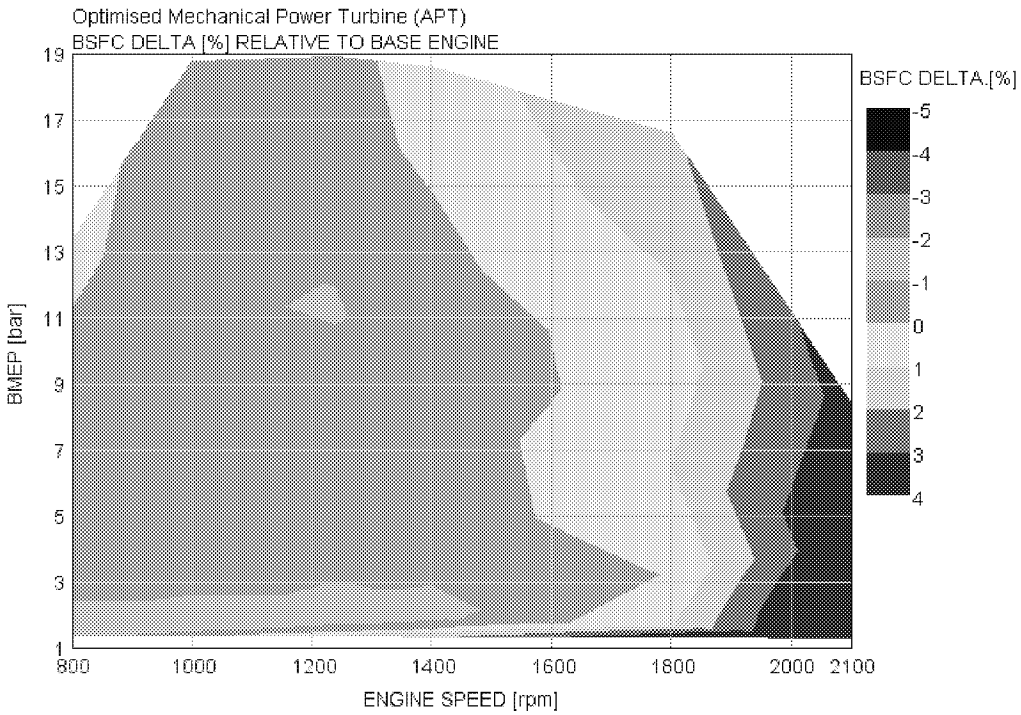

Figure B4b. BSFC improvement from Optimized Mechanical Axial Power Turbine

1.5 Optimized Electrical Turbocompound (APT)

For the electrical APT model the energy recovered is stored in an electrical form. On a vehicle this energy can be used to power electrical accessories – fans, pumps, lighting and entertainment system. In this analysis, the stored energy was used to drive a motor attached to the crankshaft, through a gearbox. An electrical generator efficiency map was used for the storage process, shown in figure B5a, and a motor efficiency of 90% is assumed for the power motor. The resulting effect on BSFC is shown in figure B5b. In reality, the energy could be stored and used only at critical or pre-determined conditions, but the results show the effect of the energy produced at the given speed/load point. As for the mechanical system, the APT is re-sized to give improvements at cruise speeds & loads, but in this case the penalty at higher speed & loads, where it does not operate so frequently on a typical drive cycle, is less significant. There will be no effect on engine-out or tailpipe criteria emissions from this technology.

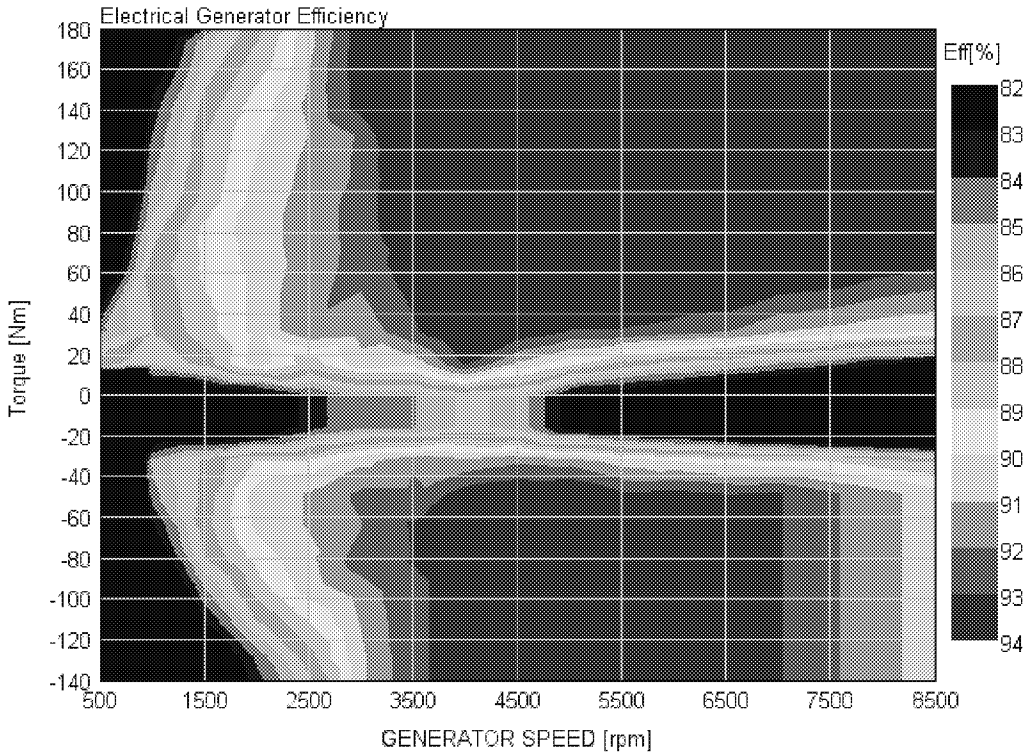

Figure B5a. DD15 Electrical generator efficiency map

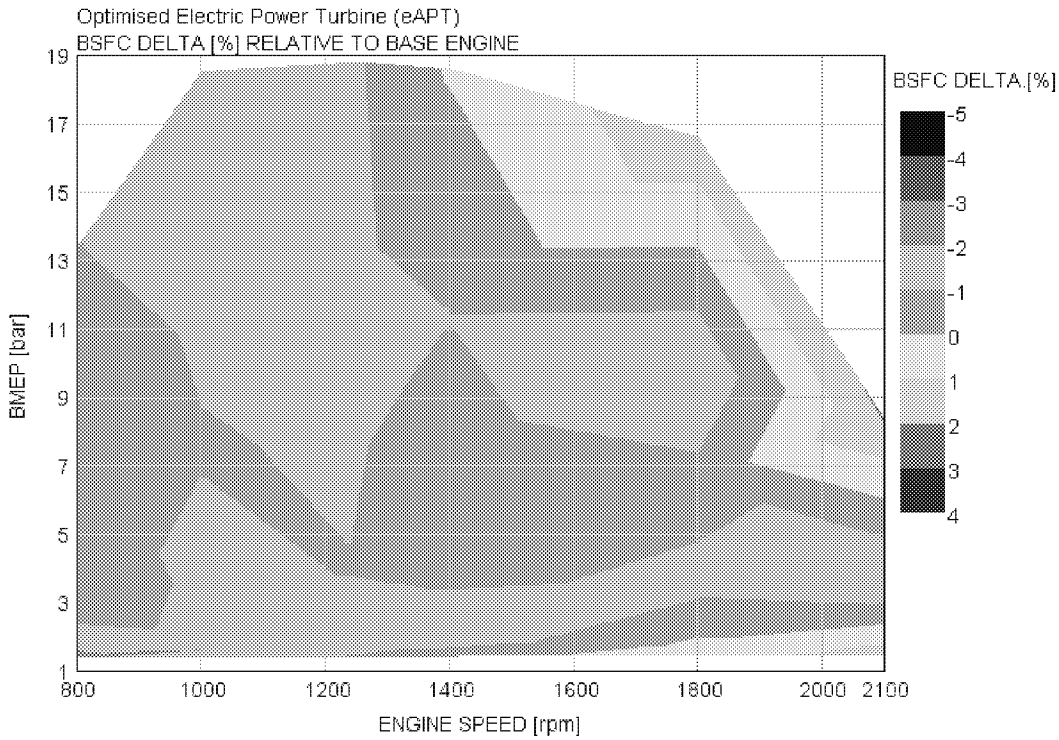

Figure B5b. BSFC improvement from Optimized Electrical Axial Power Turbine

1.6 No EGR

The base DD15 engine features a high-pressure EGR circuit, with 2 pre-turbine exhaust manifold feeds, 2 valves, an EGR cooler and venturi system, which dumps the EGR into the inlet system pre manifold but post heater & throttle valve. To assess the engine performance with no EGR demand, the entire EGR system set of system components was removed from the GT model, with the heater & throttle maintained. The engine was run with the same performance targets but an increased AFR limit (+2 ratios), and the combustion & injection parameters left as standard. In practice, eliminating EGR will shorten combustion duration, which should reduce fuel consumption slightly, so the results here are likely to slightly understate the benefit of EGR removal. This technology would involve very high engine-out NOx, and require a very efficient SCR system with a high urea consumption rate.

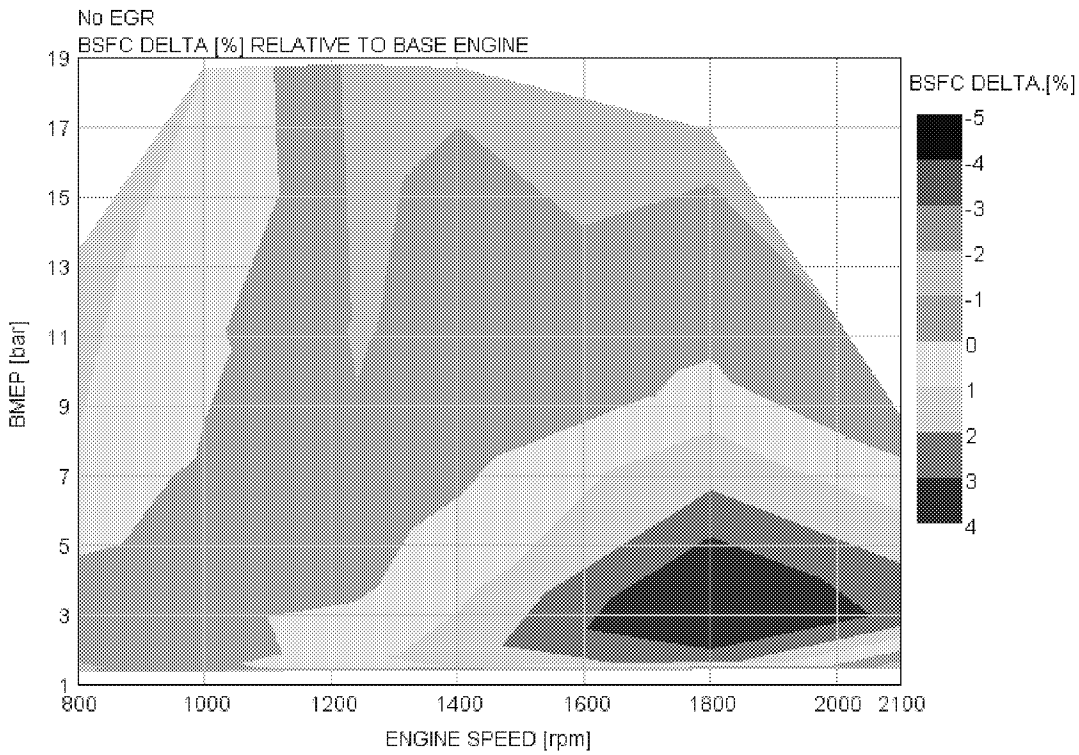

Figure B6a. BSFC improvement from EGR removal

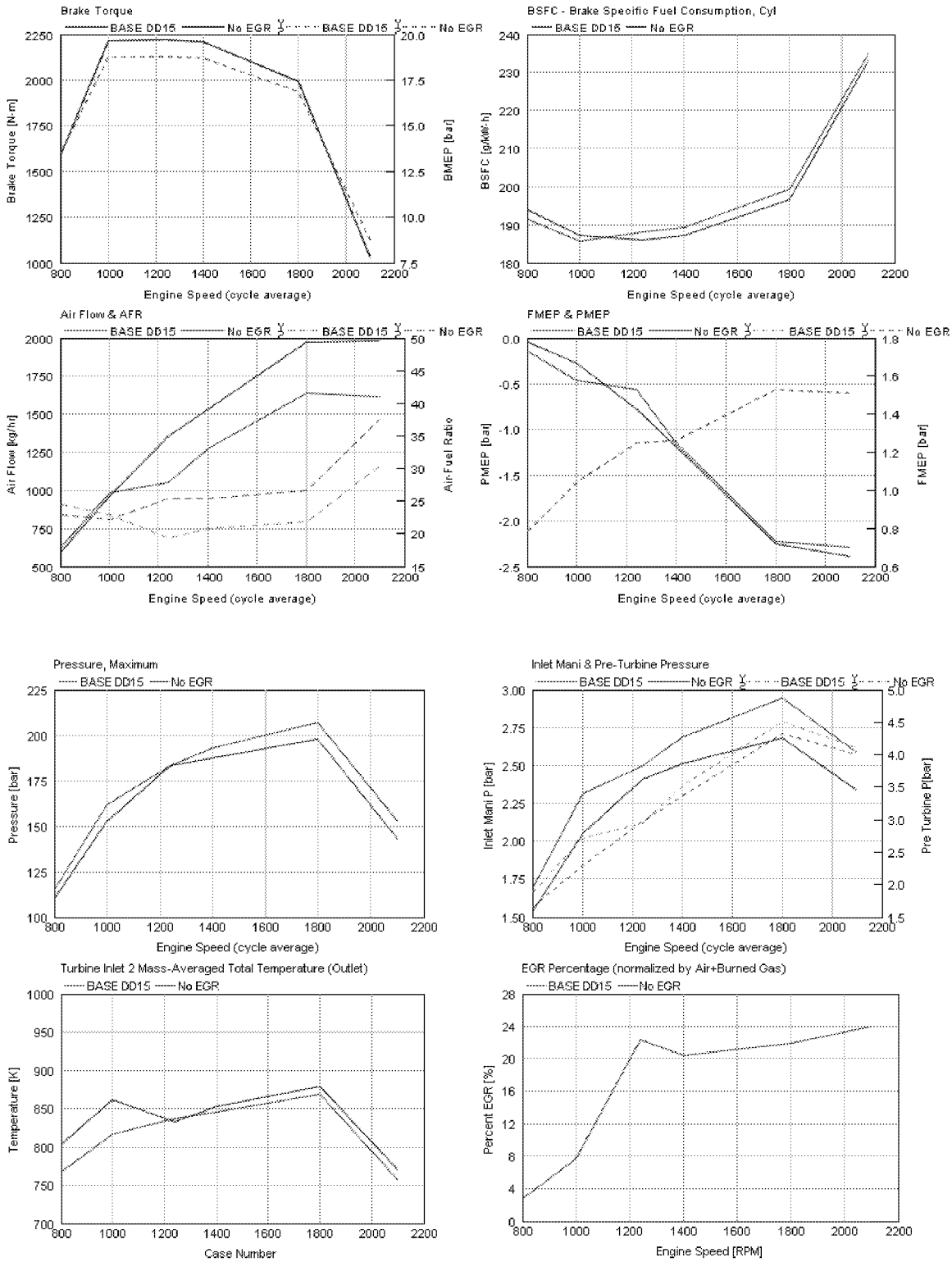

Figure B6b. Effect of EGR Removal on Engine Performance at Full Load

1.7 No Turbocompound (APT)

The base engine model incorporates an APT which recovers exhaust energy after it has passed through the main engine turbo, and is connected to the engine crankshaft via a gearbox & fluid coupling. In this model, the APT is removed from the engine and the back pressure seen by the main turbo was reset to match the baseline engine backpressure. The main turbo was not rescaled in this case as the contribution by the APT to the overall engine performance is relatively limited, particularly at part load. The latest generation of this engine has removed the APT (along with several other changes described in section 1.9) and claims improved BSFC. At lower engine speed, this configuration does not provide sufficient back pressure to drive EGR flow. As a result, this technology would involve very high engine-out NOx, and require a very efficient SCR system with a high urea consumption rate. Alternatives include the use of a variable geometry turbo (VGT). This would enable EGR flow, but would impose a BSFC penalty due to reduced turbo efficiency at speeds where this is required to drive EGR flow. VGT is by far the most common technology approach in the HD engine market today.

Note that in Figure B7b, the pumping work (PMEP) is reduced by about a half bar on the torque curve, which would normally result in lower fuel consumption. The fuel consumption on the torque curve is almost unchanged. The reason for this effect is that the power contribution from the APT has been removed. At full load, the lower PMEP cancels the power turbine contribution. At lighter loads, the benefit of reduced PMEP is greater than the penalty of reduced ATP contribution, so there is a net fuel consumption benefit at part loads.

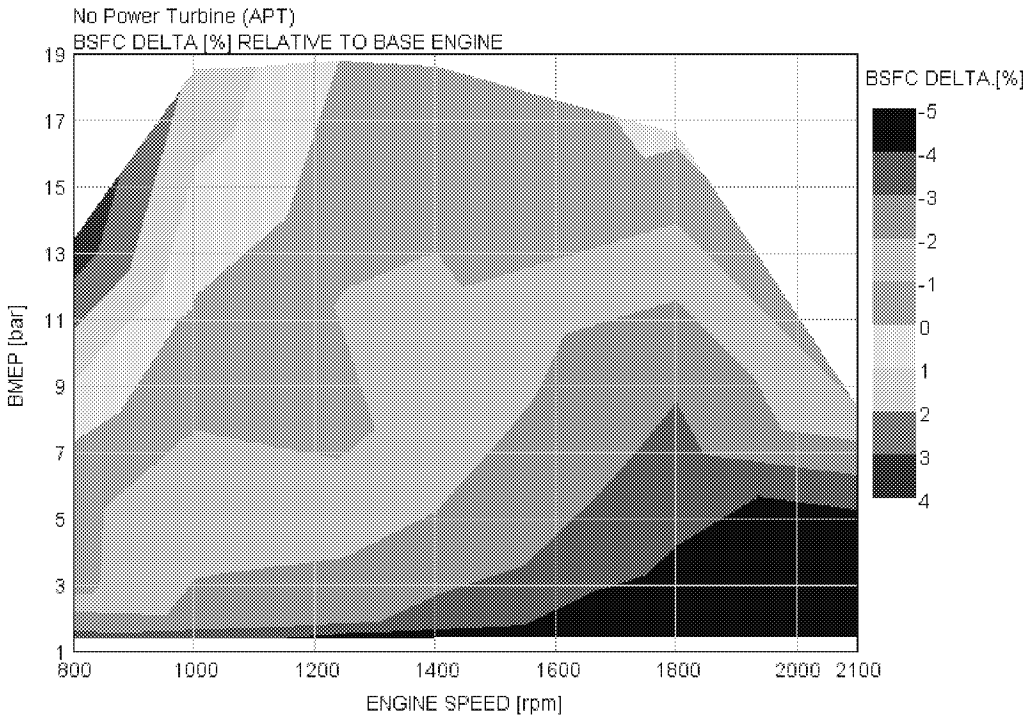

Figure B7a. BSFC improvement from removing turbocompound

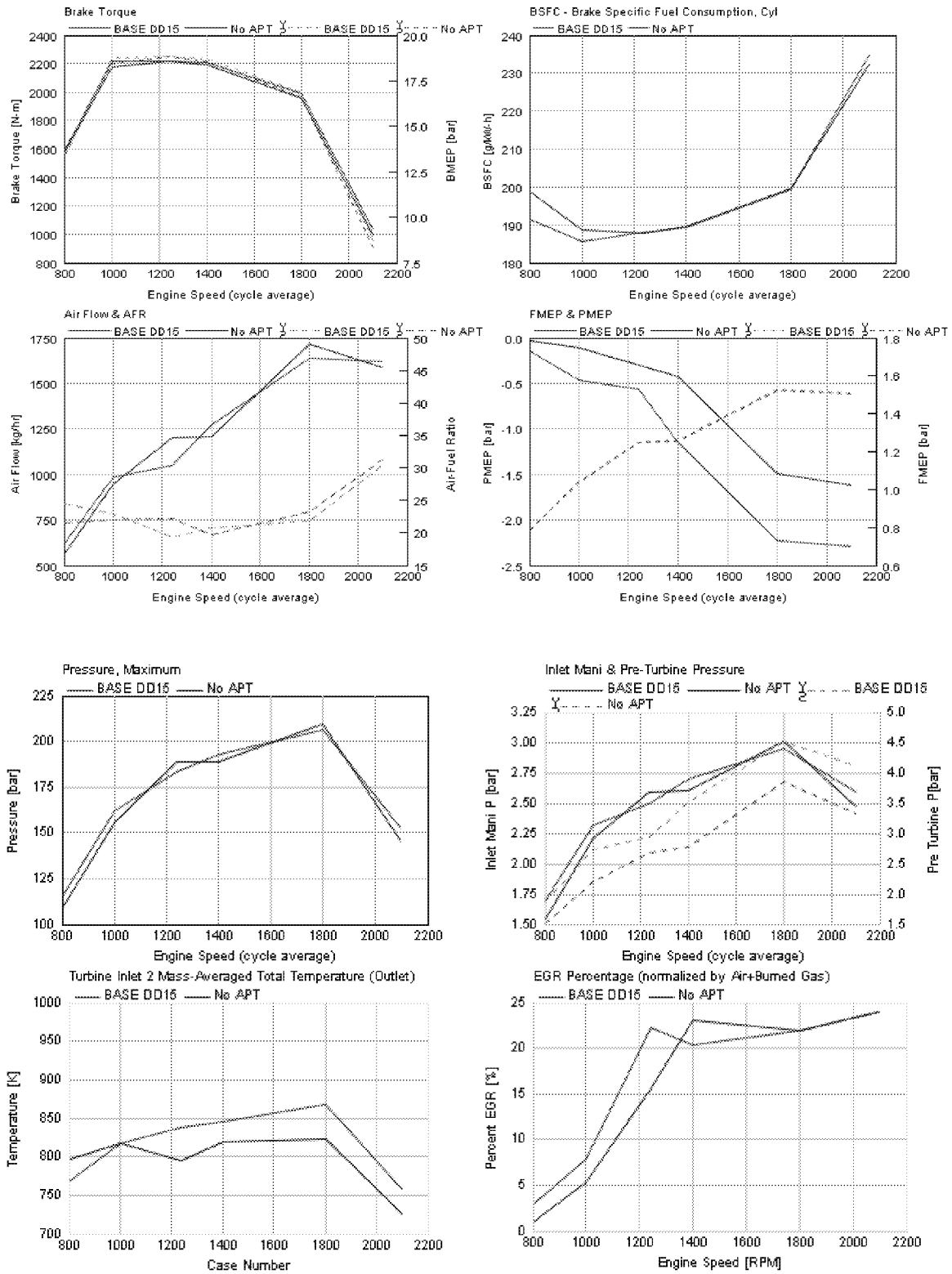

Figure B7b. Effect of Turbocompound Removal on Engine Performance at Full Load

1.8 No EGR or APT

This technology setup involved the removal of both the EGR system & APT as described in sections 1.6 & 1.7 above. This required the main turbo to be re-sized and the back pressure to be reset to achieve comparable performance with the base engine. Combustion & injection characteristics were left unchanged. This technology would involve very high engine-out NOx, and require a very efficient SCR system with a high urea consumption rate. In reality, eliminating EGR flow will shorten combustion duration, which has a positive effect on BSFC. We did not have sufficient data to model this effect accurately, but the net effect is that the fuel consumption reduction is probably slightly understated.

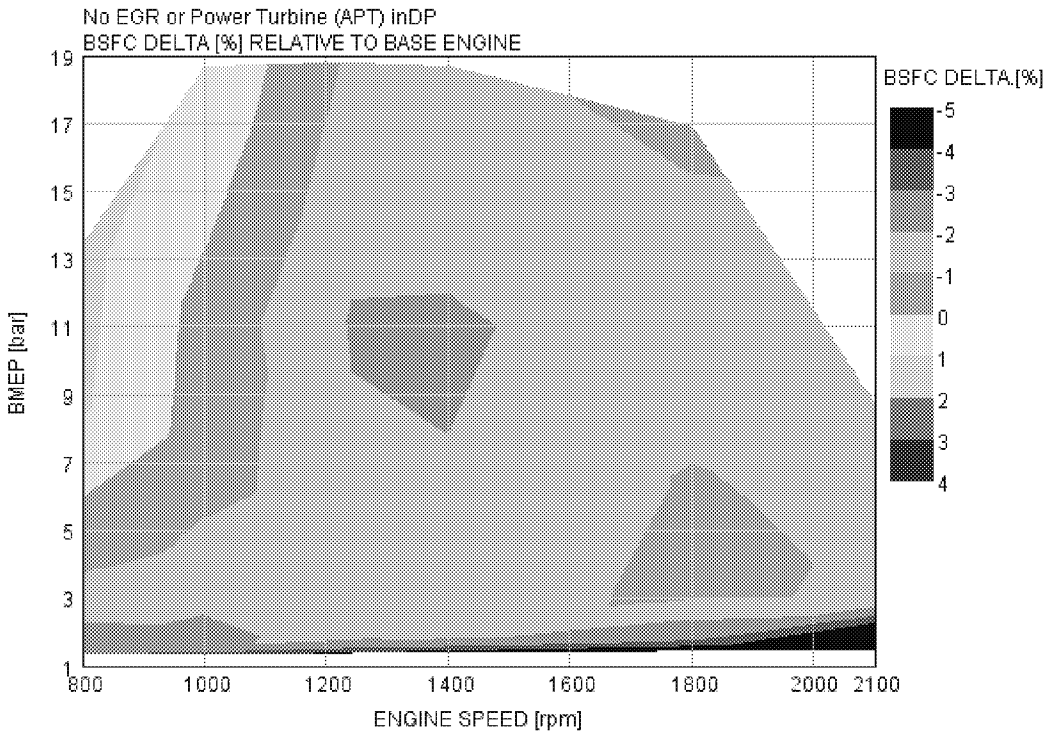

Figure B8a. BSFC improvement from EGR & APT removal

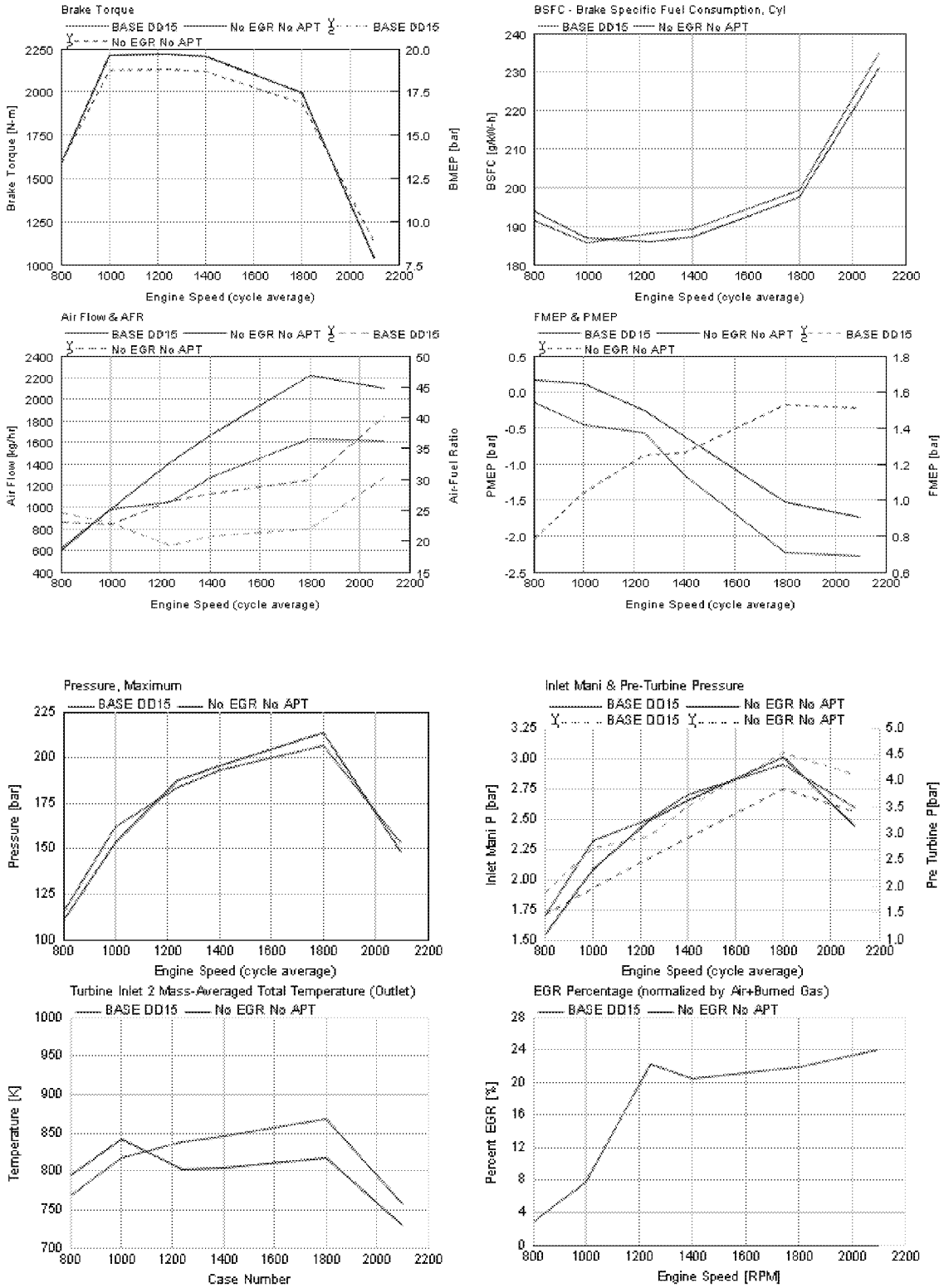

Figure B8b. Effect of EGR & APT Removal on Engine Performance at Full Load

1.9 Asymmetric Turbocharger and EGR Circuit

As described above in section 1.6, the base DD15 engine features 2 pre-turbine exhaust manifold feeds & 2 EGR valves, so effectively both the front & rear halves of the engine supply equal amounts of EGR. The latest generation of this engine has a revised EGR system that only takes EGR from one half of the engine. As the turbine is still twin entry, this leads to the requirement for an asymmetric turbine entry setup due to the differing flow rates from either side of the engine. The eventual ratio between the 2 entries was 37:63, and the EGR system was sized to achieve the same EGR rates are the baseline engine. Additionally, the APT has been removed. All other engine setups were left unchanged. The asymmetric turbo approach causes a fuel consumption penalty over most of the full load curve, especially near rated speed. The benefit of the power turbine is largest at maximum speed and load, so this result is to be expected. There is a modest improvement in BSFC in the cruise RPM range, especially at light loads, where the power turbine does not contribute. At high speed, light load, the benefit is large. At this condition, the power turbine hurts (from pumping work due to exhaust restriction) more than it helps.

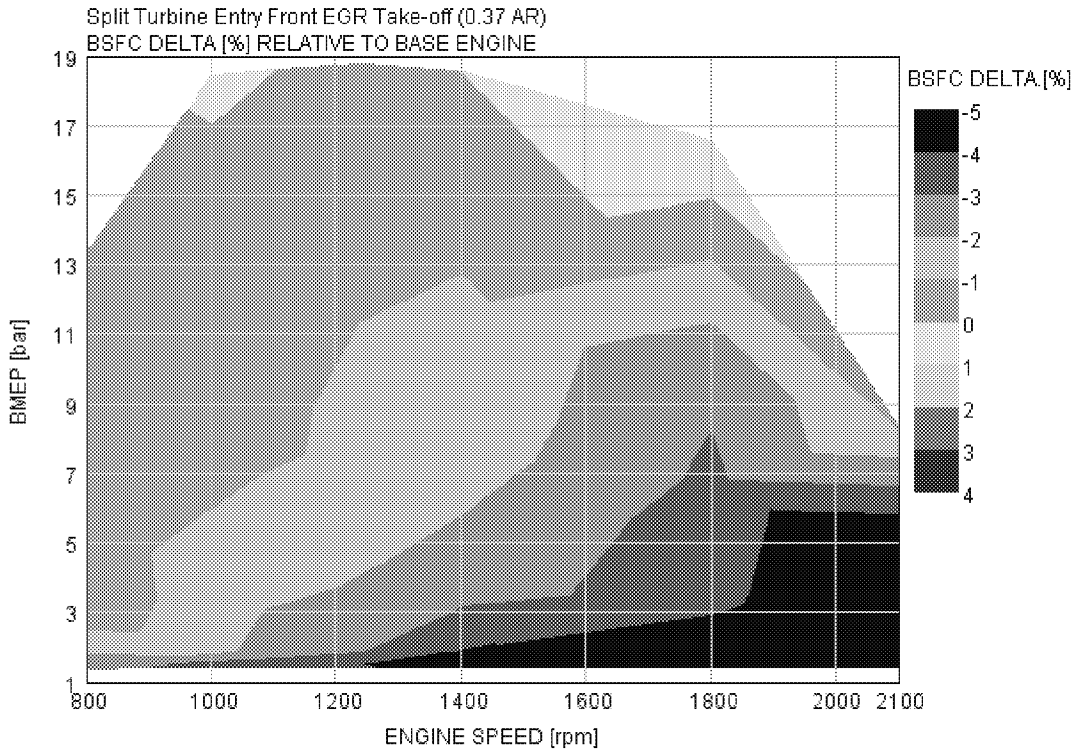

Figure B9a. BSFC improvement from Asymmetric Turbo and EGR Supply

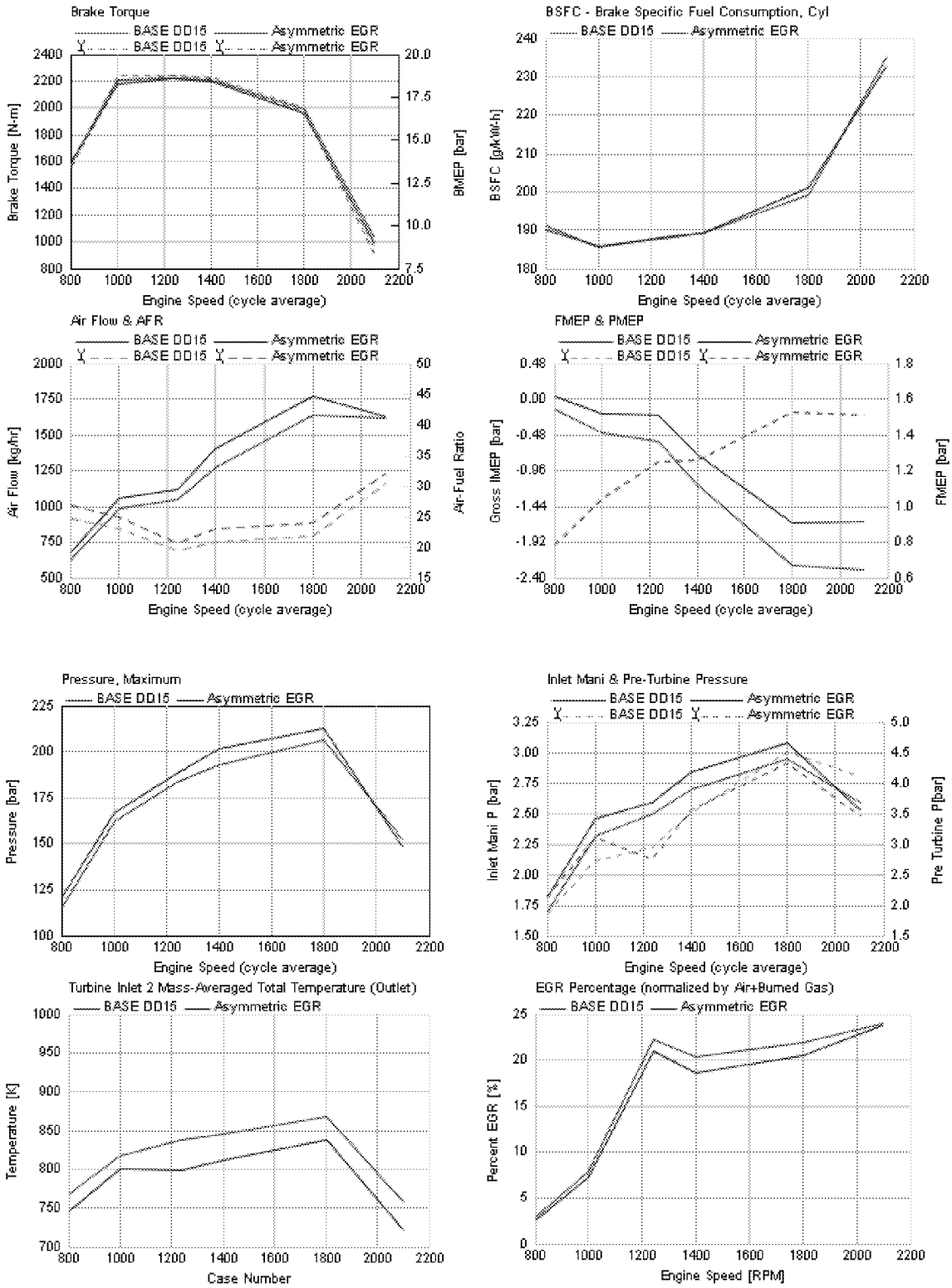

Figure B9b. Effect of Asymmetric Turbo and EGR Supply on Engine Performance at Full Load

1.10 Downspeeding with Increased BMEP

A common approach to improving the drive cycle fuel consumption is engine downspeeding. Typically, the peak torque engine speed is reduced and max torque available is increased. This allows the engine to run at a lower speed for a given vehicle speed. For this study, 2 downspeed cases were assessed, both reducing the peak torque speed to 1000-1200rpm (from 1200-1400rpm) with torque increases of 17 & 33% respectively. The higher torque levels were achieved by increasing injected fuel quantities and resizing the turbocharger and power turbine to match the new, higher power levels. Injection timing was retarded where required to keep cylinder pressure within the 207 bar limit. Compression ratio was left unchanged. In both downspeeding cases, the turbo systems where re-sized to achieve comparable minimum AFR (~19:1) and the same or slightly increased EGR (increased at 1000 rpm to retain NOx control at the lower peak torque speed). Vehicle cruising speeds were reduced from 1368 RPM @ 65 MPH for the baseline case, to 1209 RPM for Downspeed A, and 1051 RPM for Downspeed B.

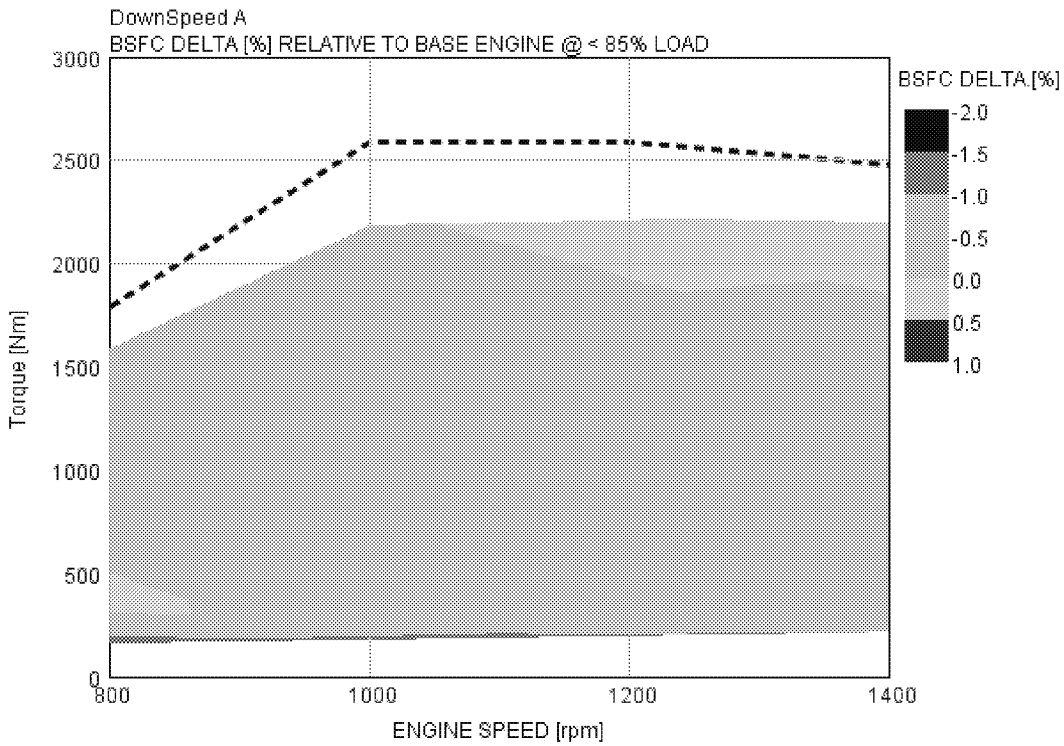

Figure B10a. DownSpeed 'A' BSFC improvement

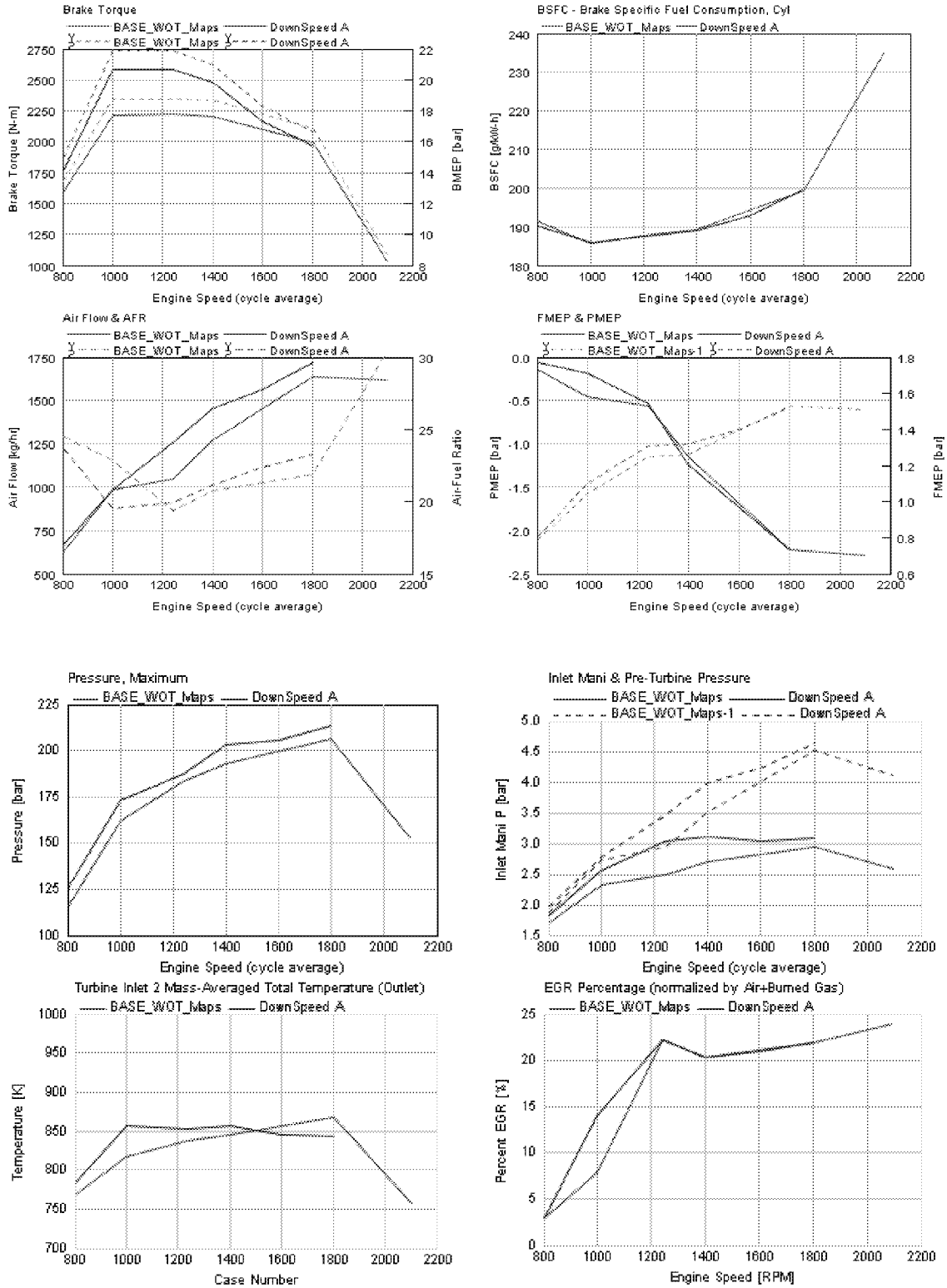

Figure B10b. Effect of DownSpeed 'A' on Engine Performance at Full Load

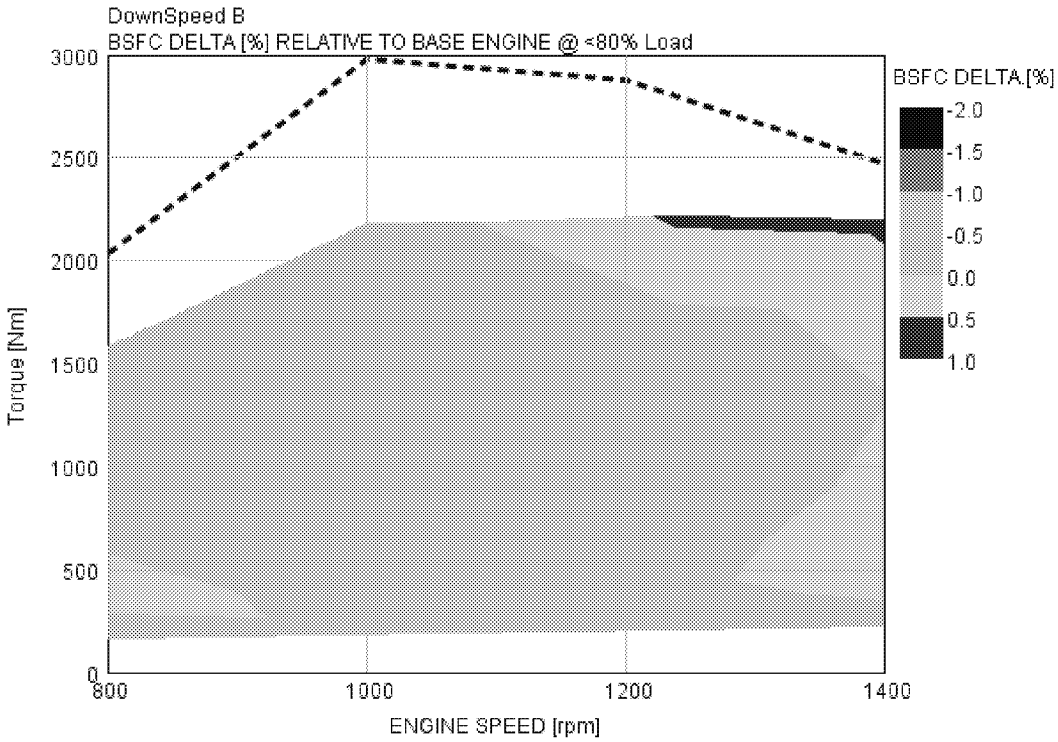

Figure B10c. DownSpeed 'B' BSFC improvement

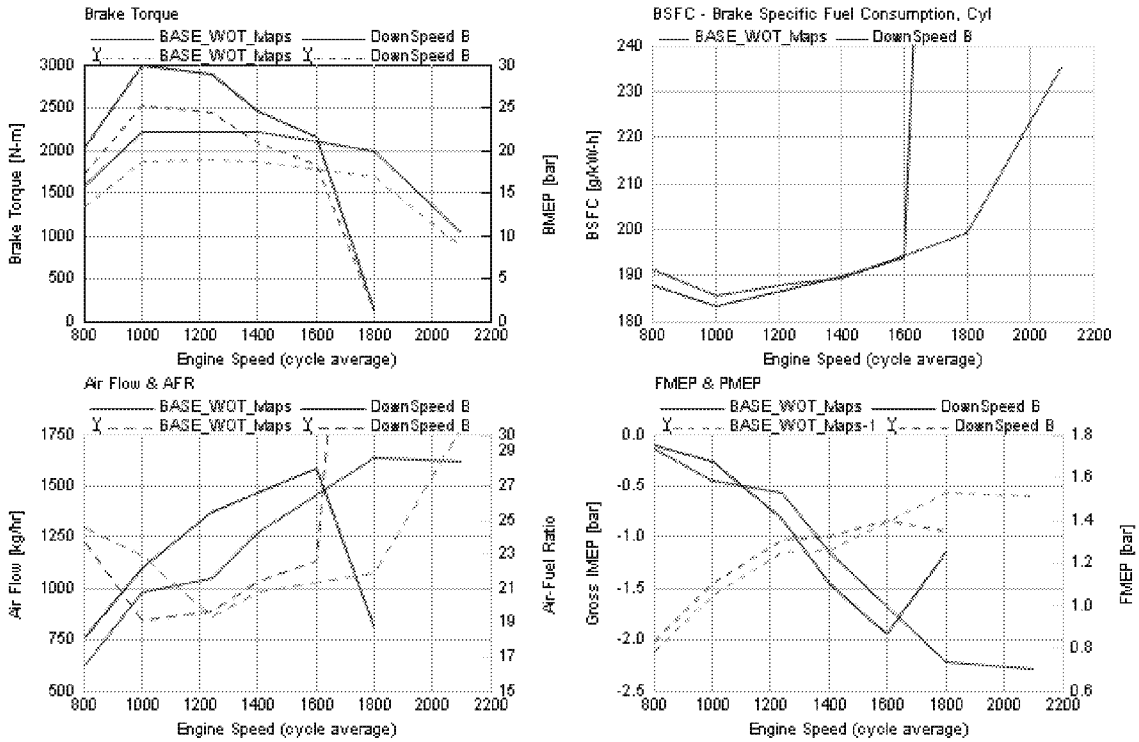

Figure B10d. (Part 1) Effect of DownSpeed 'B' on Engine Performance at Full Load

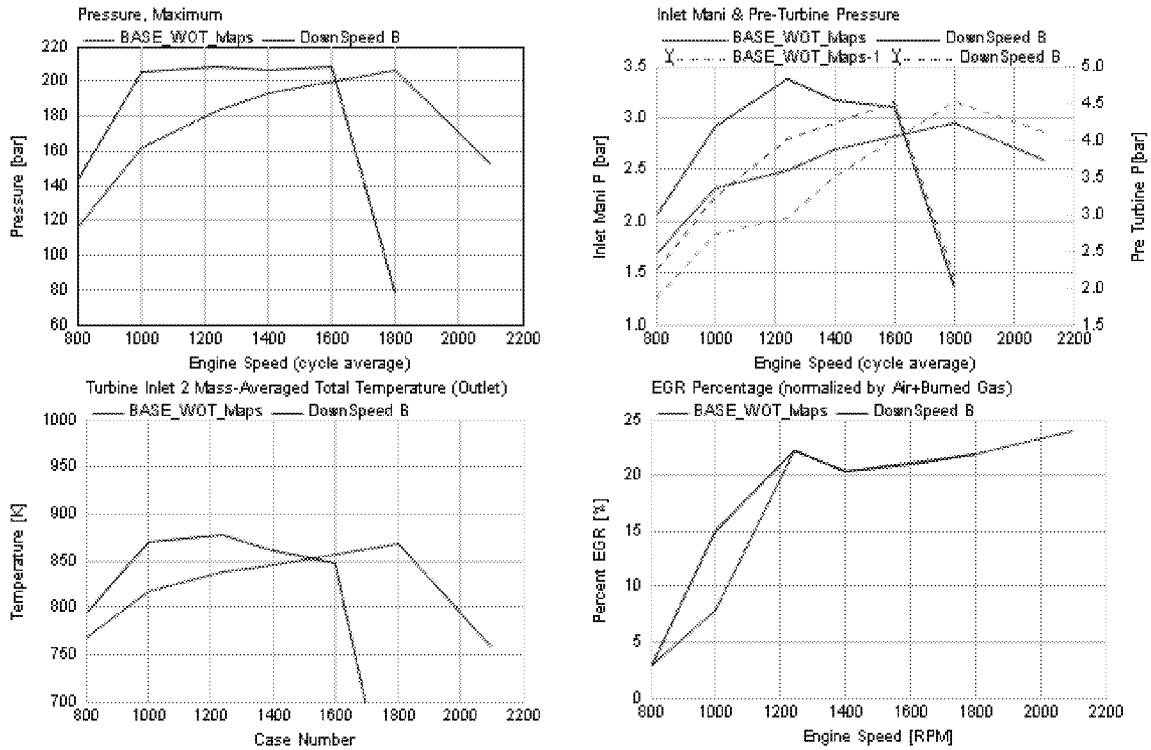

Figure B10d. (Part 2) Effect of DownSpeed 'B' on Engine Performance at Full Load

1.11 Downsizing with Constant BMEP

A 12.5L displacement version of the DD15 was constructed to assess the effect of downsizing. The approach taken was to remove 1 cylinder, so making it a 5-cylinder unit. This method was chosen because it was simpler to reconfigure the manifold layouts rather than re-size all the ports, valves & associated pipework. An ideal approach would be to model a smaller diesel engine, such as the Volvo D13 or the Detroit DD13. Unfortunately, this approach would require purchase and testing of an engine to provide input data for the model, building a new GT-POWER model, and calibrating it. This effort was beyond the scope of the project. In our experience, the performance differences between a 5 and 6-cylinder of comparable displacement will be small. With a 5-cylinder layout, the firing order has a number of options, which were assessed in conjunction with 2 exhaust manifold layout options of split or log type. The best setup, in terms of BSFC, was found to be a log style manifold with a firing order of 1-4-3-2-5.

The FMEP values are the same as for the base engine, so the friction torque or power at a given operating point is reduced by 5/6, due to the smaller displacement and cylinder count.

The engine was run at the same BMEP as the base engine, which results in a lower torque. The turbo was re-sized to achieve comparable Air Fuel Ratios as the base engine, and this has a slightly detrimental effect on PMEP. The start of injection (SOI) was adjusted to achieve the

same max cylinder pressure (207 bar) as the base engine. The APT was also maintained and re-sized. Given the requirement for same BMEP, the boost requirements should be broadly the same, which they are. EGR levels from the base engine where maintained to achieve NOx control.

The results show that the down sized engine is marginally better at part load conditions, but worse at higher loads and speeds due to the increased PMEP. This high load BSFC penalty can be assigned to the reduced performance of a turbocharger set up for downsized operation on a log manifold, compared to the more efficient dual entry turbo setup that is used on the baseline 6-cylinder engine. Plot B11a shows the BSFC delta on a like-for-like BMEP basis, while plot B11b show the fuel rate for both the baseline 6-cylinder engine & the downsized engine on a torque scale, to highlight the difference in torque.

In the vehicle simulation, the downsized engine performs better than Figure B11a would lead one to expect. This can be explained using the following logic. At any given point on the drive cycle, the vehicle imposes a certain power demand on the engine. Given the transmission gearing, that translates into a given torque and speed demand on the engine. If the engine is smaller, but still operates at the same speed and torque, the BMEP of the smaller engine will be higher. At lighter loads, BSFC improves rapidly as BMEP increases. Thus, for situations where the baseline engine would operate at a BMEP under approximately 10 bar, there will be a significant improvement in BSFC for the downsized engine, even if it is slightly less efficient at a given BMEP level.

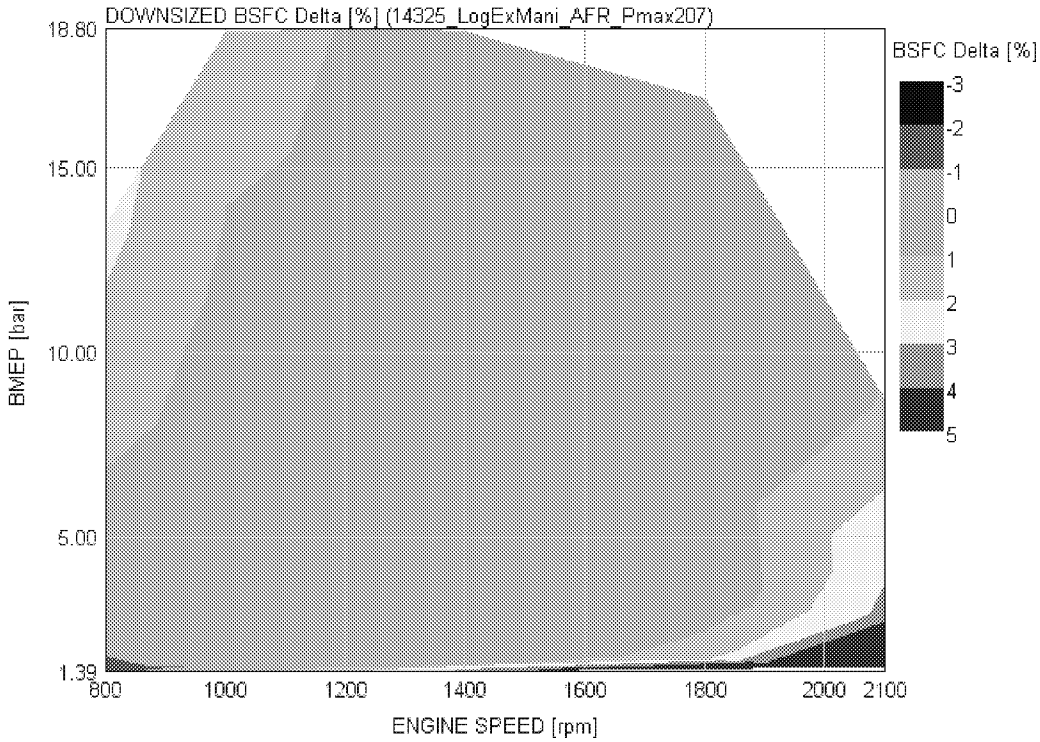

Figure B11a. BSFC improvement of Downsize Engine with Constant BMEP

Figure B11a indicates that over most of the operating range, the efficiency of the downsized engine is within +/- 1% of the 6-cylinder engine, when the two are compared at the same BMEP level. However, the vehicle does not care about BMEP, it cares only about speed and torque, so Figure B11b provides an alternative way of comparing the downsized and 6-cylinder engines. In this figure, BSFC is compared on an equal torque basis. Since the downsized engine has a lower torque curve, the comparison is only shown up to the maximum torque of the downsized variant. This figure shows that there is a BSFC penalty at low RPM and high torque, but the downsized version enjoys a significant BSFC advantage across most of the operating range, especially at light load.

Another way to compare the two engines is to look at the BSFC maps, which are shown in Figure B11c. These look similar at first glance (other than the lower maximum torque of the downsized engine), but a look at the light load portion of the maps (Figure B11d) shows significant advantages for the 5-cylinder.

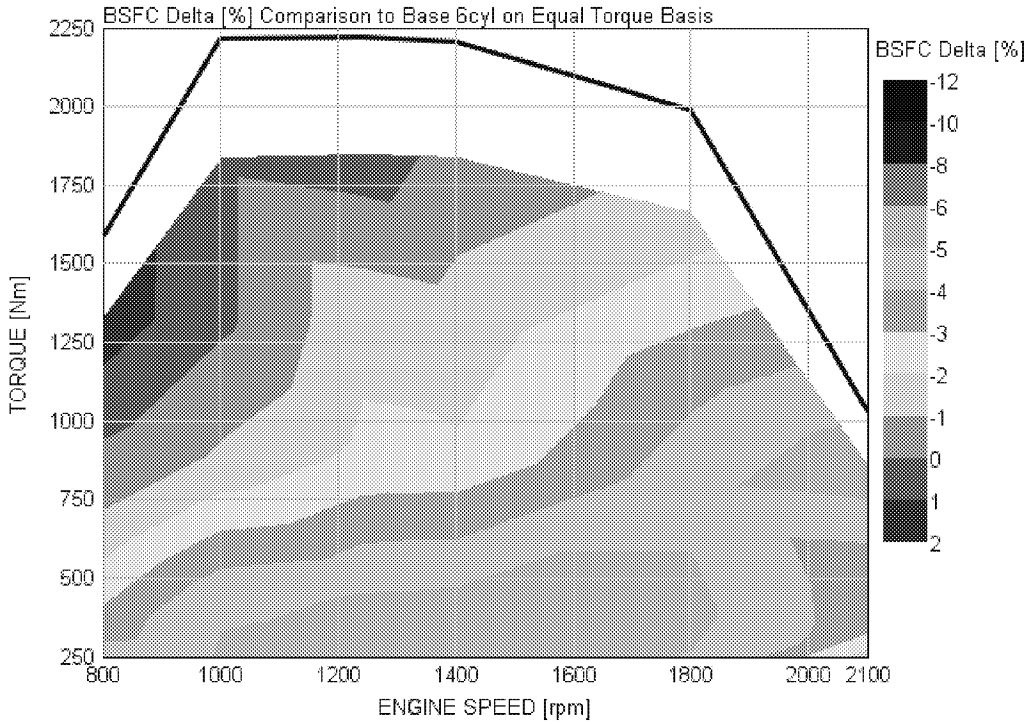

Figure B11b. BSFC improvement of Downsize Engine with Constant BMEP – Downsized Engine, with BSFC interpolated & compared at equivalent Base engine torques

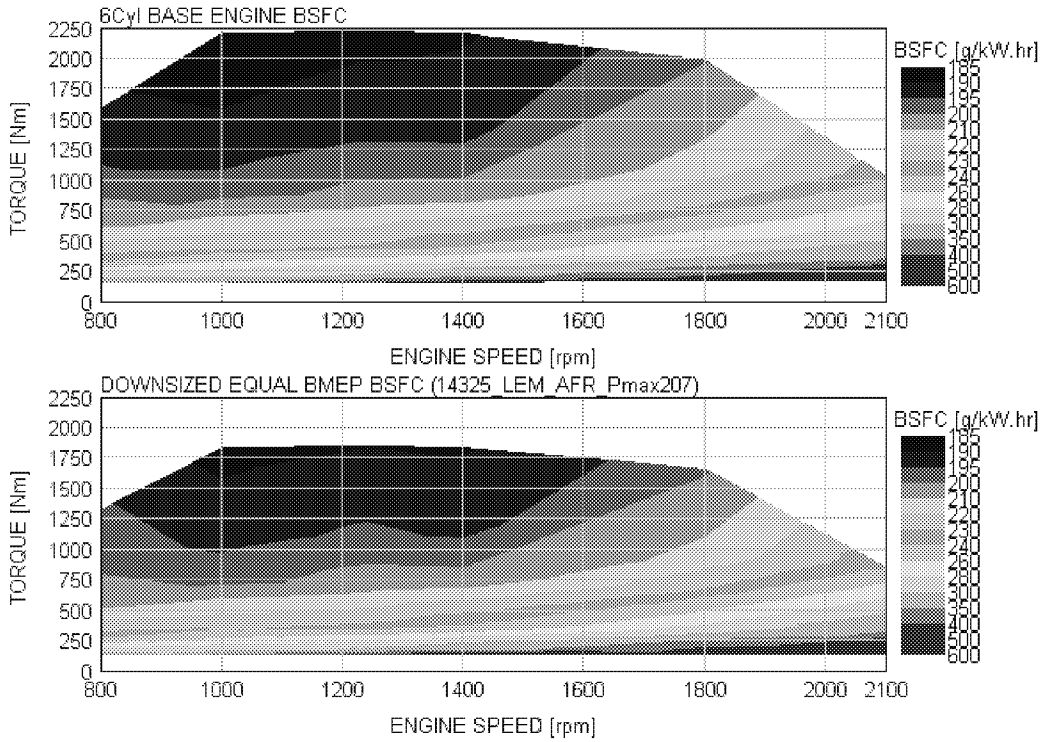

Figure B11c. Comparison of 6 Cyl vs. Downsized BSFC on a Torque basis

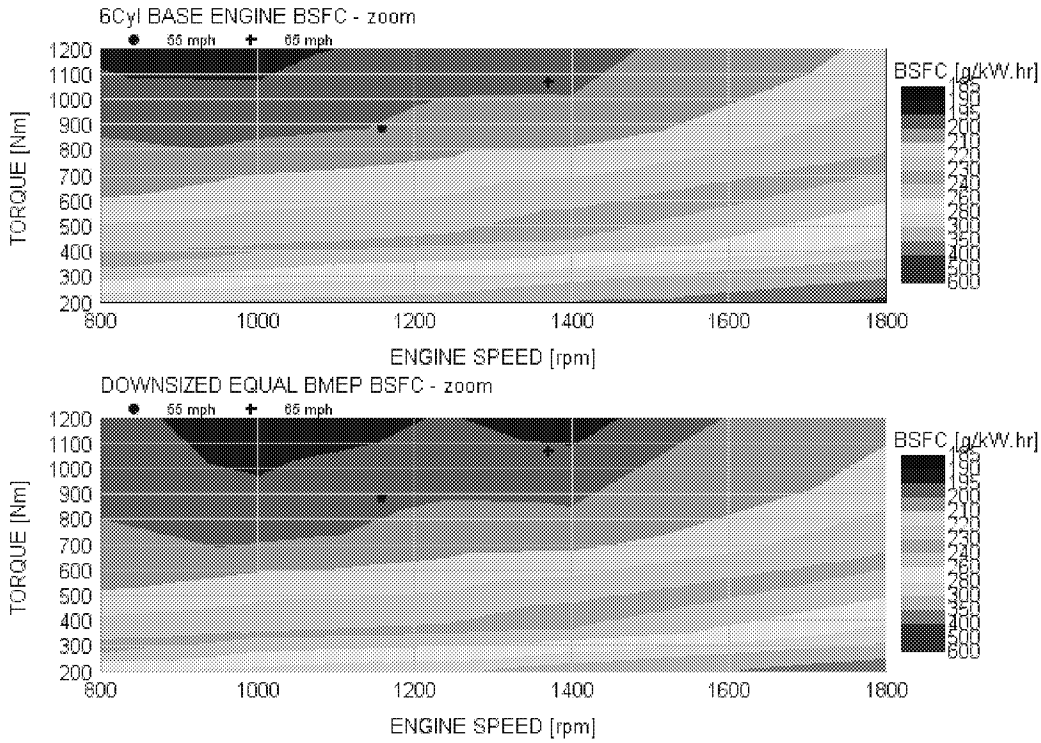

Figure B11d. Comparison of 6 Cyl vs. Downsized BSFC on a Torque basis – zoomed. Note the 55 and 65 MPH operating points marked on both plots. The downsized engine enjoys a BSFC advantage at both points.

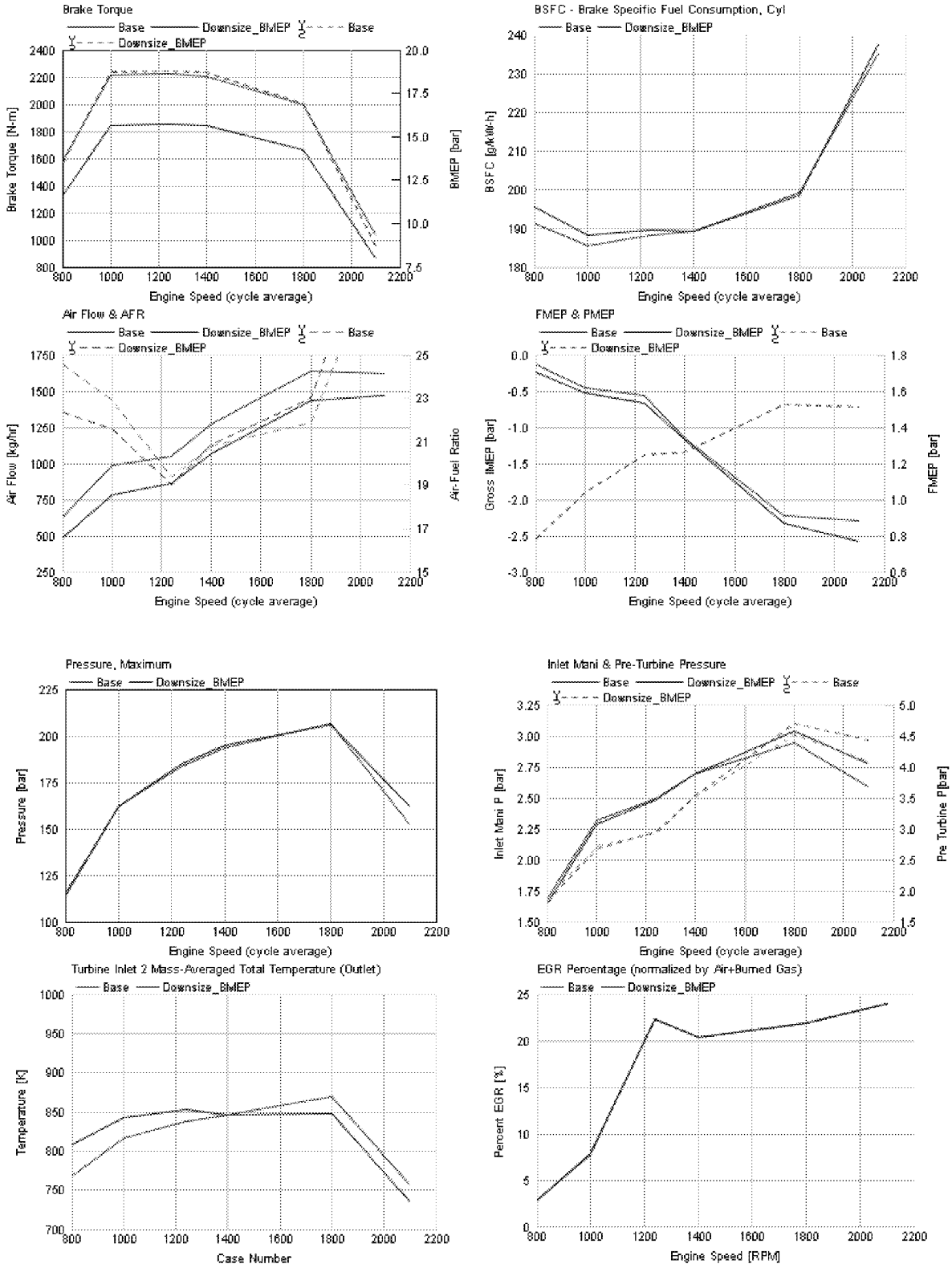

Figure B11e. Effect of Downsized Engine with Constant BMEP on Engine Performance at Full Load

1.12 Downsizing with Constant Torque

The engine model developed in section 1.11 was then run at the same torque levels as the base engine, which results in higher BMEP levels. Again, AFR & max cylinder pressure levels were maintained. Subsequently higher boost levels where required, PMEP is higher and FMEP is also higher as the engine is running at a higher BMEP on the speed-load lookup map.

The results show that the down sized engine is significantly better at part load conditions, but worse at higher loads and speeds due to the increased FMEP & PMEP. Plot B12a shows the BSFC delta on a like-for-like torque basis, while plot B12b show the fuel rate for both the baseline 6 cylinder engine & the downsized engine on a BMEP scale, to highlight the difference in BMEP.

It should be noted that the combustion model is setup so that a fixed set of Wiebe functions are used for a given speed & %load per cylinder condition: for example the 1400 rpm 10% load combustion data is the same for both models even though the value of 10% load per cylinder is 20% higher for the downsized model. At low load conditions the combustion duration can change by several degrees with a small change in load, so this approach introduces some uncertainty in light load fuel consumption values. Additionally, at full load the SOI is adjusted to maintain the 207 bar max cylinder pressure limit. This has the effect of making full load operation slightly less efficient for the downsized engine, compared to the baseline.

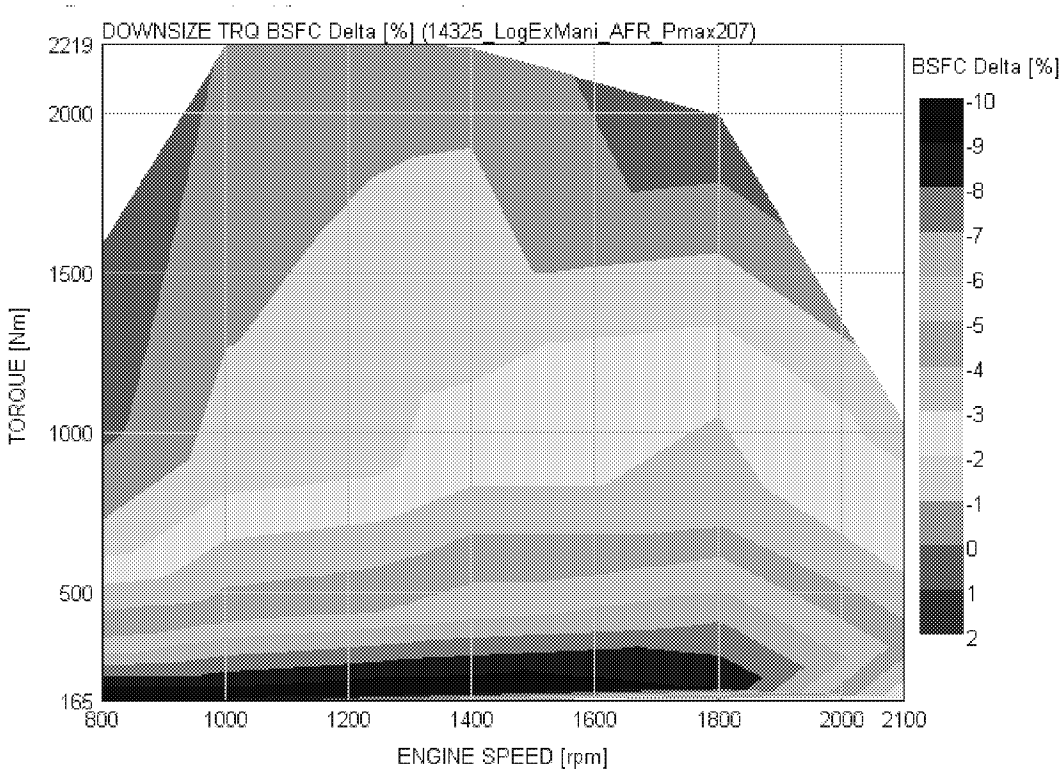

Figure B12a. BSFC improvement of Downsize Engine with Constant Torque

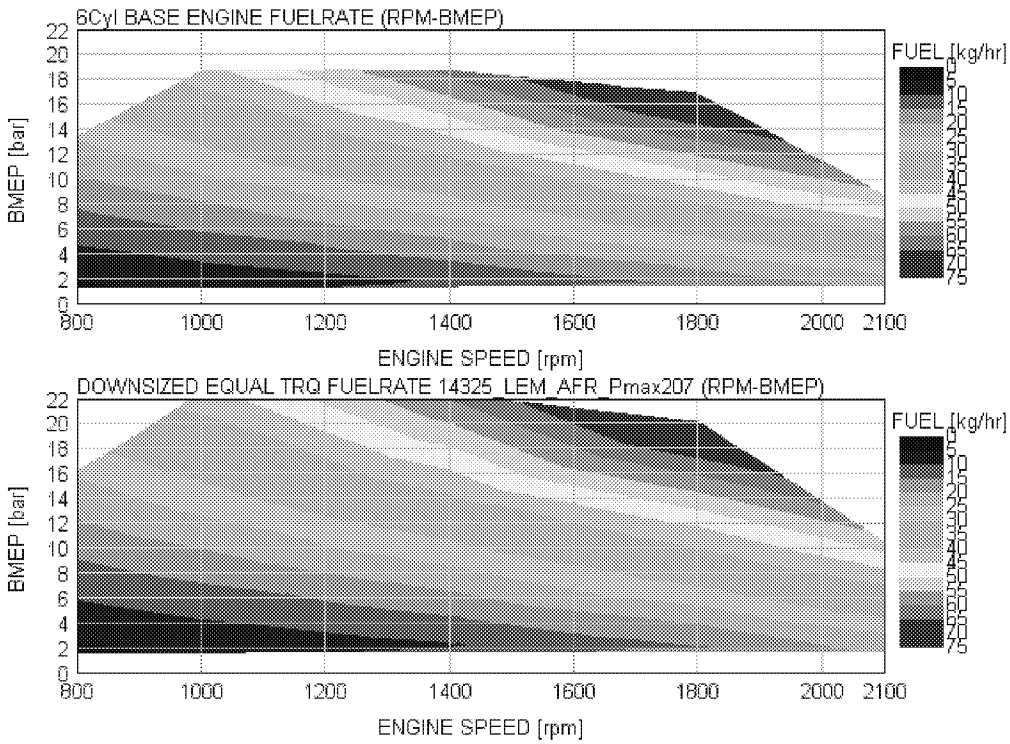

Figure B12b. Comparison of 6 Cyl vs. Downsized Fuel Rate on a BMEP basis

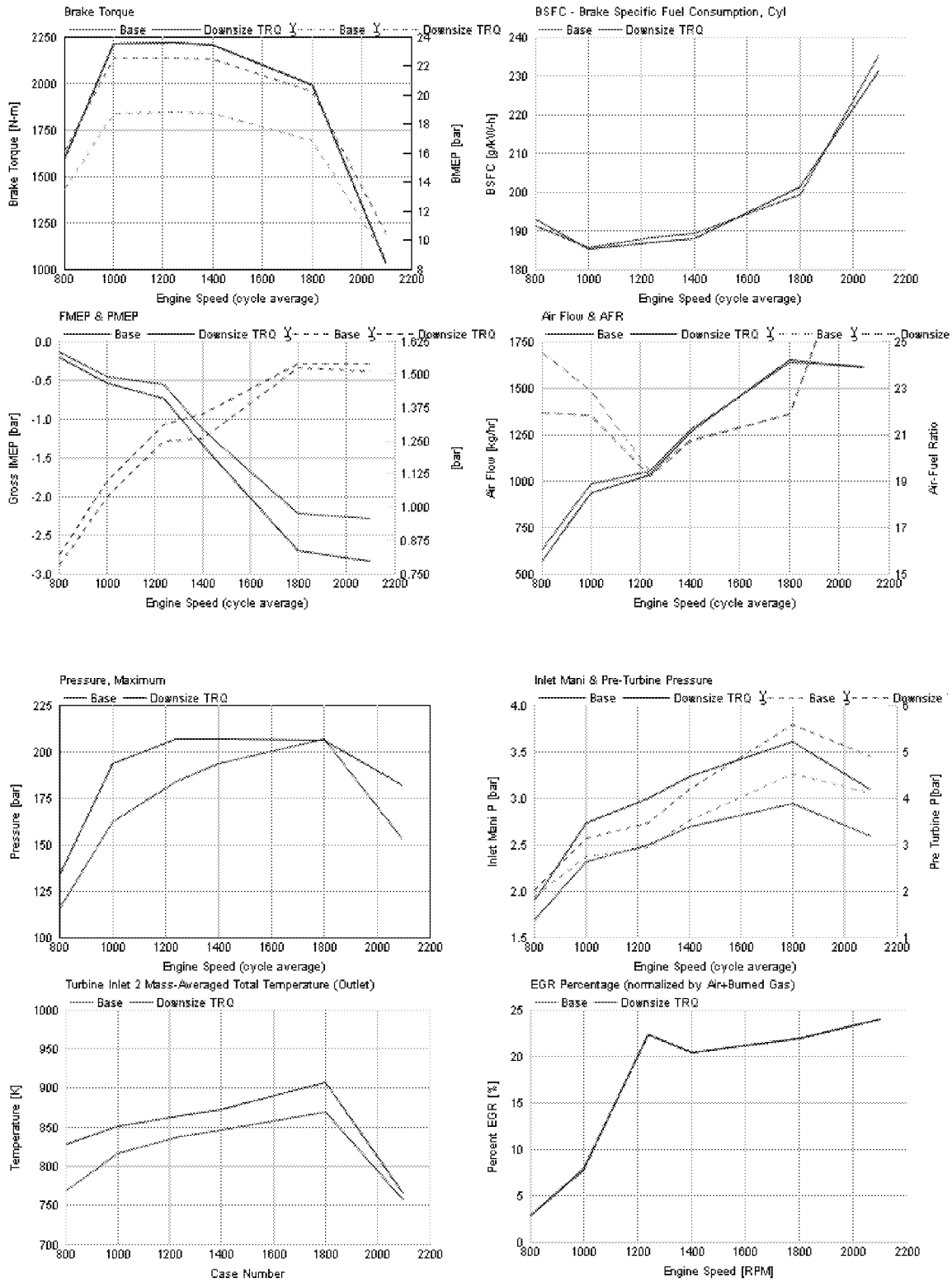

Figure B12c. Downsized Engine Full Load Performance with Constant Torque

1.13 Explore FMEP Improvements

The baseline engine model with a reduced friction map was run at the same conditions of as the baseline model. The friction (FMEP) was reduced on a speed-load relationship, with full load reductions of 10% and part load reduction of up to 35%. As expected, the largest benefits occur at light load and lower engine speeds.

Reducing engine friction can be achieved in several ways, such as low viscosity oils, smaller or dynamic bearings, ring/piston/liner interface improvements, a more efficient fuel pump, as well as smart controlled oil and water pumps. In this study, all the friction improvements where lumped together. Note that these would be a lot of development required to achieve the sort of friction reductions modeled here, and it is not certain that this size of benefit could be achieved without reliability/durability issues.

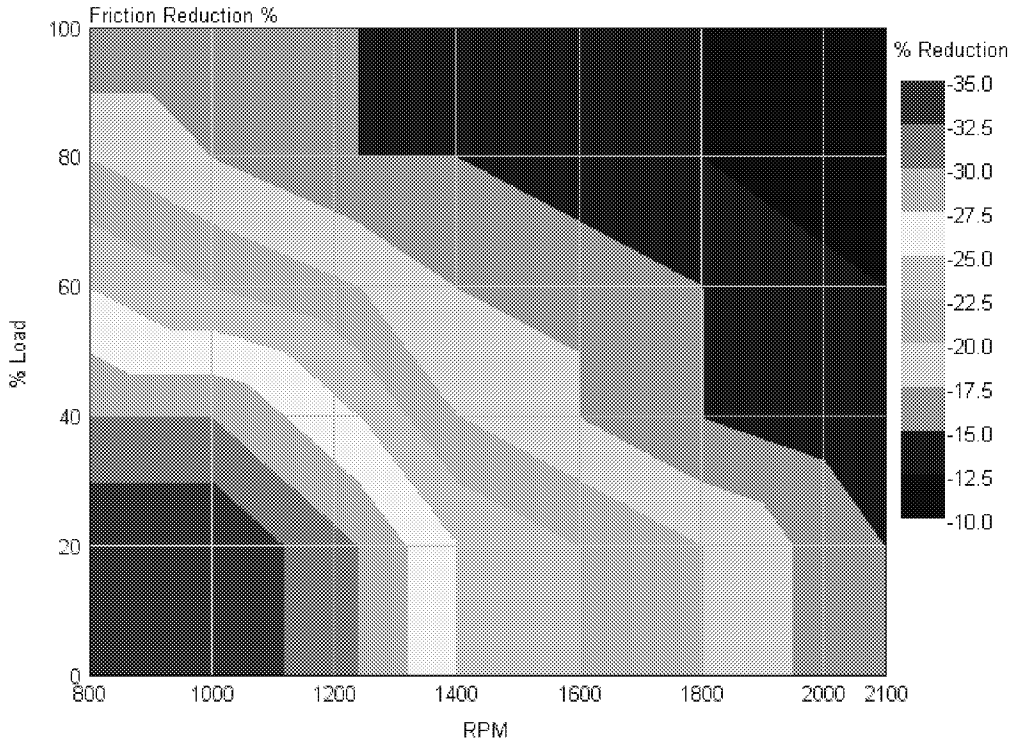

Figure B13a. Friction Reduction Assumptions

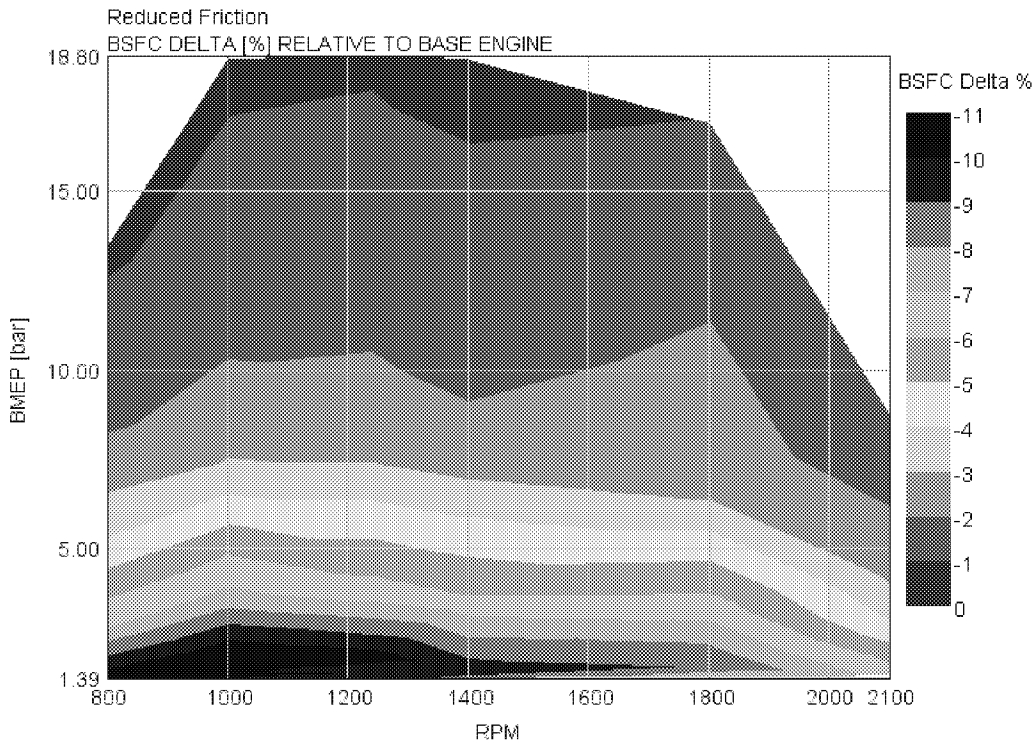

Figure B13b. Friction reduction BSFC Improvement over Baseline

1.14 Explore Turbo Efficiency Improvement

To simulate an improved efficiency turbo, the base engine model was run with a 5% efficiency increase on both the turbine & the compressor maps. If the overall turbocharger efficiency at a given operating point is 50%, this change would increase it by 5% to 52.5%.

Turbo efficiency improvement can be realized by improvements in turbo designs, bearings, and materials. Reduced pumping losses & improved waste heat energy recovery are typical benefits of improved turbo efficiency. For engines that use EGR and do not have turbocompound, there is limited scope for improving turbo efficiency. In these engines, which represent almost the entire market, improved turbocharger efficiency will result in a loss of EGR flow and thus a loss of NOx control. The results presented are run with no EGR demand on the engine and compared to a similar setup of the base engine.

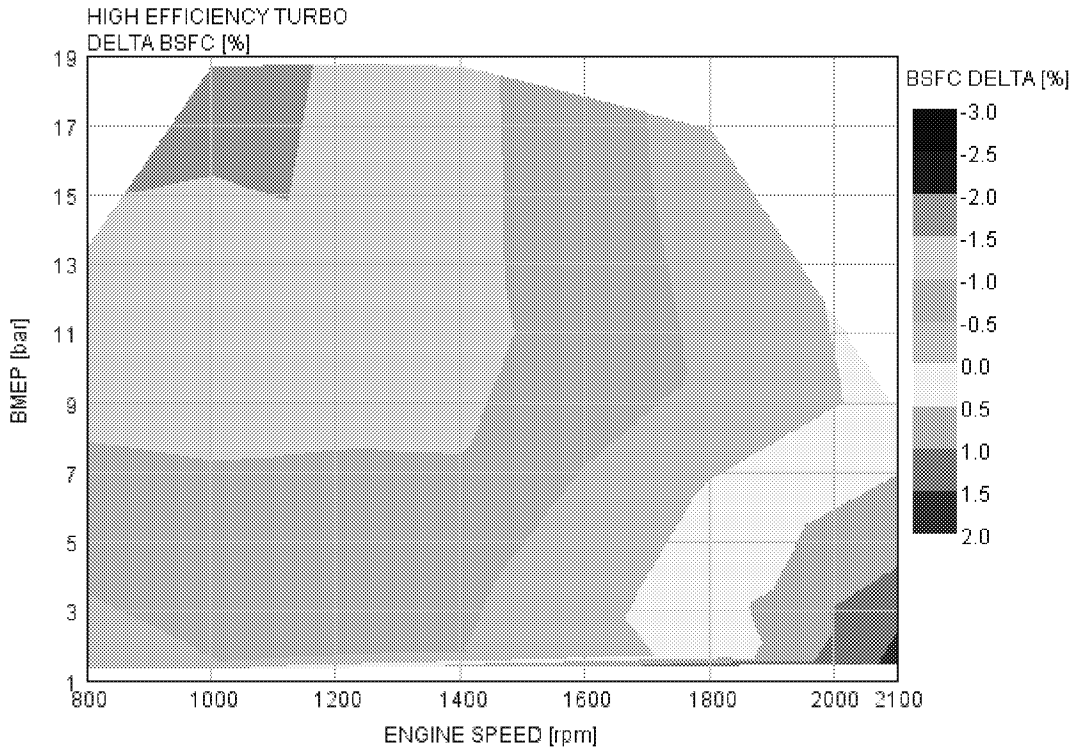

Figure B14a. BSFC improvement from High Efficiency Turbo

Note that the results above are compared to the base engine turbo setup with no EGR which has a 3-4% BSFC penalty at high speed & low load conditions, so the penalty seen in the graph above is actually an improvement compared the base engine (with EGR)

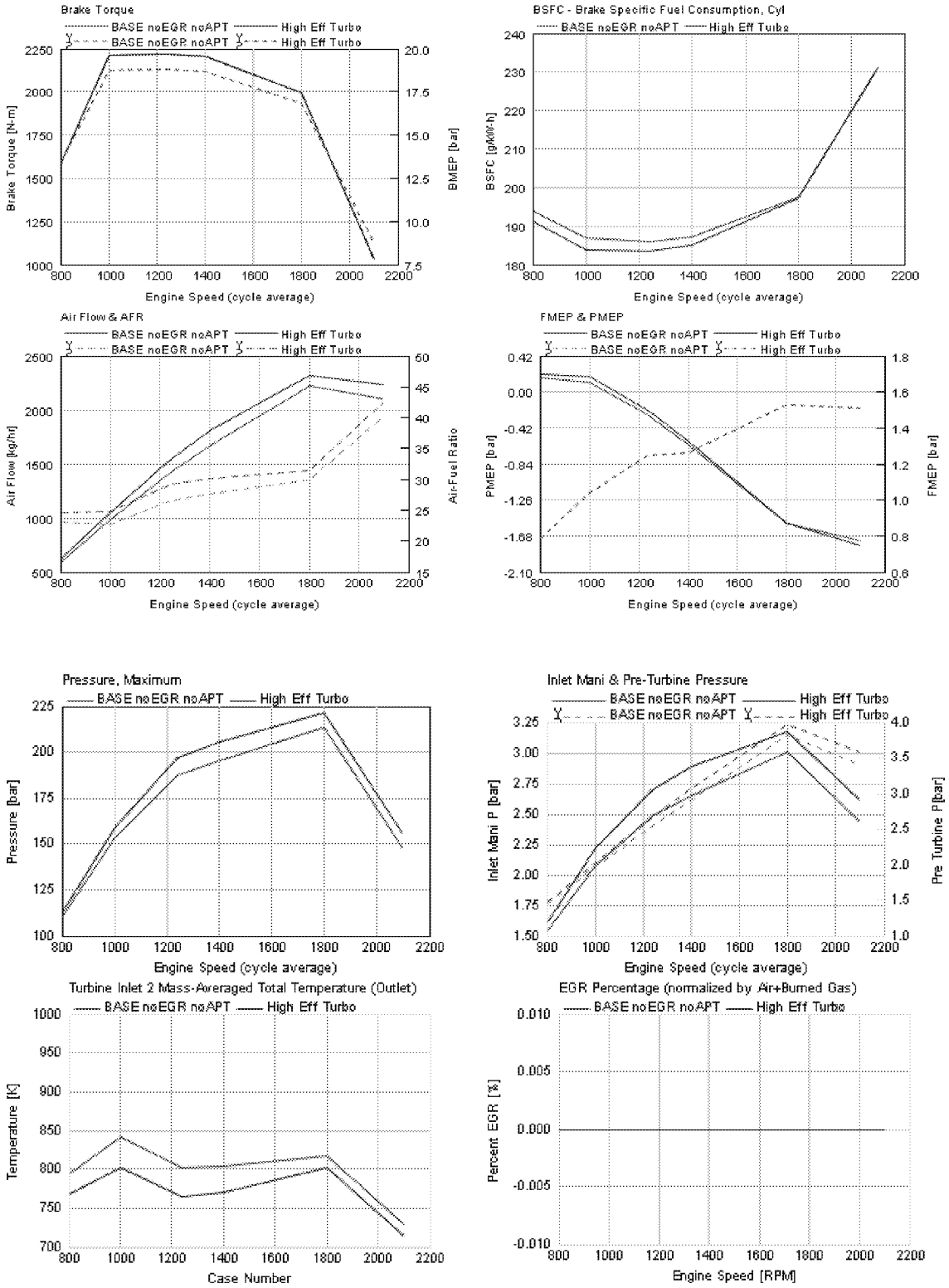

Figure B14b. Effect of High Efficiency Turbo on Full Load Engine Performance

1.15 Explore Variable Valvetrain Actuation Improvements

The application of variable valvetrain actuation (VVA) was investigated, with a full control system assumed, where both lift & duration and timing were adjustable. Previous experience and analysis of this type of technology on large diesel engines had shown that minimal performance gains were achievable. On the DD15 model, the mid speed & load range operating conditions were targeted for best gains on the drive cycles. The results indicated that a maximum of 1% BSFC improvement was achievable, at the conditions simulated. Given the complexity and cost of such a system it was decided not to perform a full speed & load mapping, which would have been very time consuming, and concentrate on other technologies. However, it is believed that VVA could be applied to the exhaust valvetrain to improve emissions equipment performance through exhaust gas temperature management.

2.1 ISB Medium Duty 300bhp Baseline Validation

- **Basic engine specification**
  - 6.7L inline 6 cylinder
  - Single Variable Geometry Turbo
  - 4 valves per cylinder
  - Diesel
  - 225 kW @ 2500 rpm
  - 900+ Nm @ 1300-2200 rpm

GT Power model was built using the geometry of an earlier generation (2007) ISB engine previously benchmarked at SwRI and run in a test cell. The main engine geometry – ports, manifolds, valve data etc. – was the same as the newer target engine (2011). Test high-speed data was used to give a guideline for the combustion but due to the different EGR system of the older engine, was not directly used. Further test data, but not high-speed, was taken from a vehicle running the 2011 specification engine at SwRI. A full speed/load range data set was taken, sufficient to calibrate the GT model.

The GT Power model was then run over a speed range of 1000 – 2500 rpm at 10, 20, 40, 60, 80 & 100% load and validated by the following operating parameters:

- **Torque, BMEP**
- **BSFC**
- **Air and Fuel Flow**
- **Pre/Post compressor pressures and temperatures**
- **Pre/Post Turbine pressures and temperatures**

Unfortunately, the VGT turbo & compressor maps where not available, so a VGT data set from a different engine was used and scaled to achieve the required performance, matching inlet & outlet conditions and airflow. The main issue with this approach was that the maps used did not have the correct performance range required, so the VGT turbine & compressor maps had to be scaled differently depending on speed & load conditions. This method is not ideal but did produce acceptable overall model correlation. This approach is acceptable, since all technology comparisons are done in a relative basis as opposed to providing absolute values of fuel consumption. When the different technologies were applied and a turbo re-size was necessary, the baseline scaling factors where globally multiplied (as opposed to on a speed-load basis).

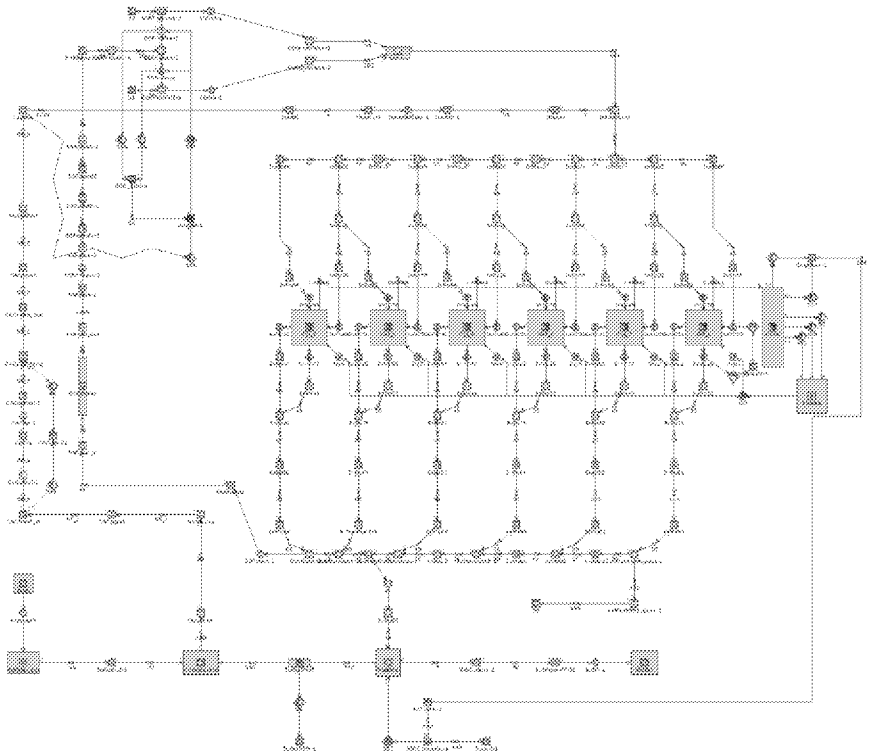

Figure B2.1a GT Model

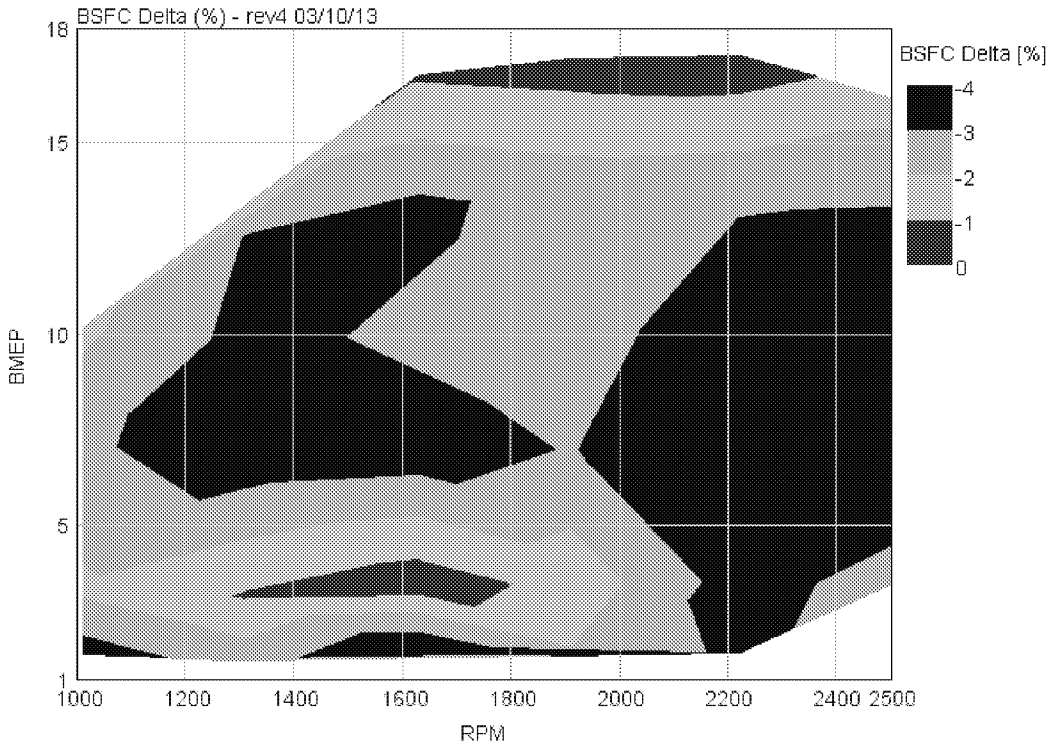

Figure B2.1b Baseline Model BSFC error

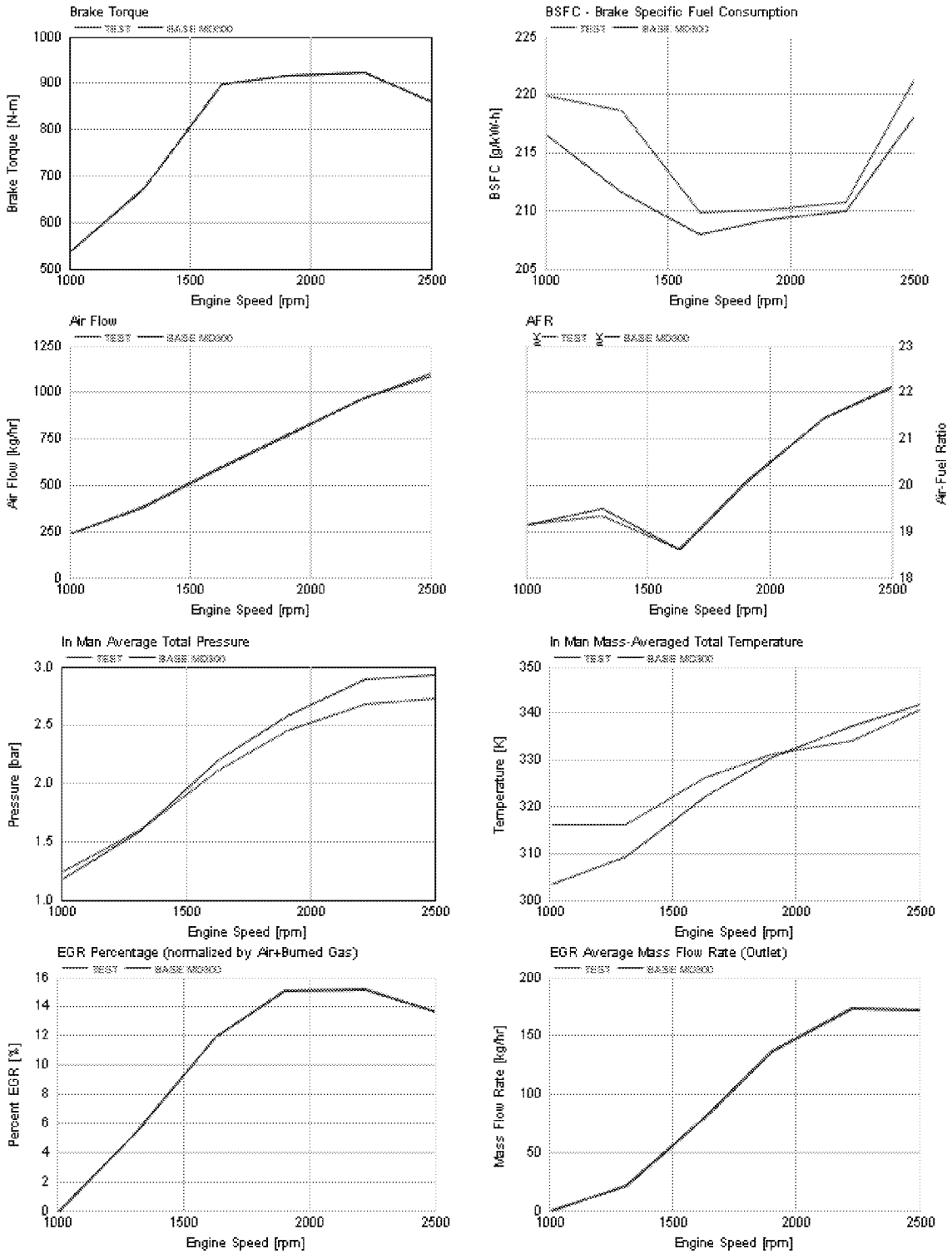

Figure B2.1c (Part 1) Baseline Model Data Correlation at Full Load

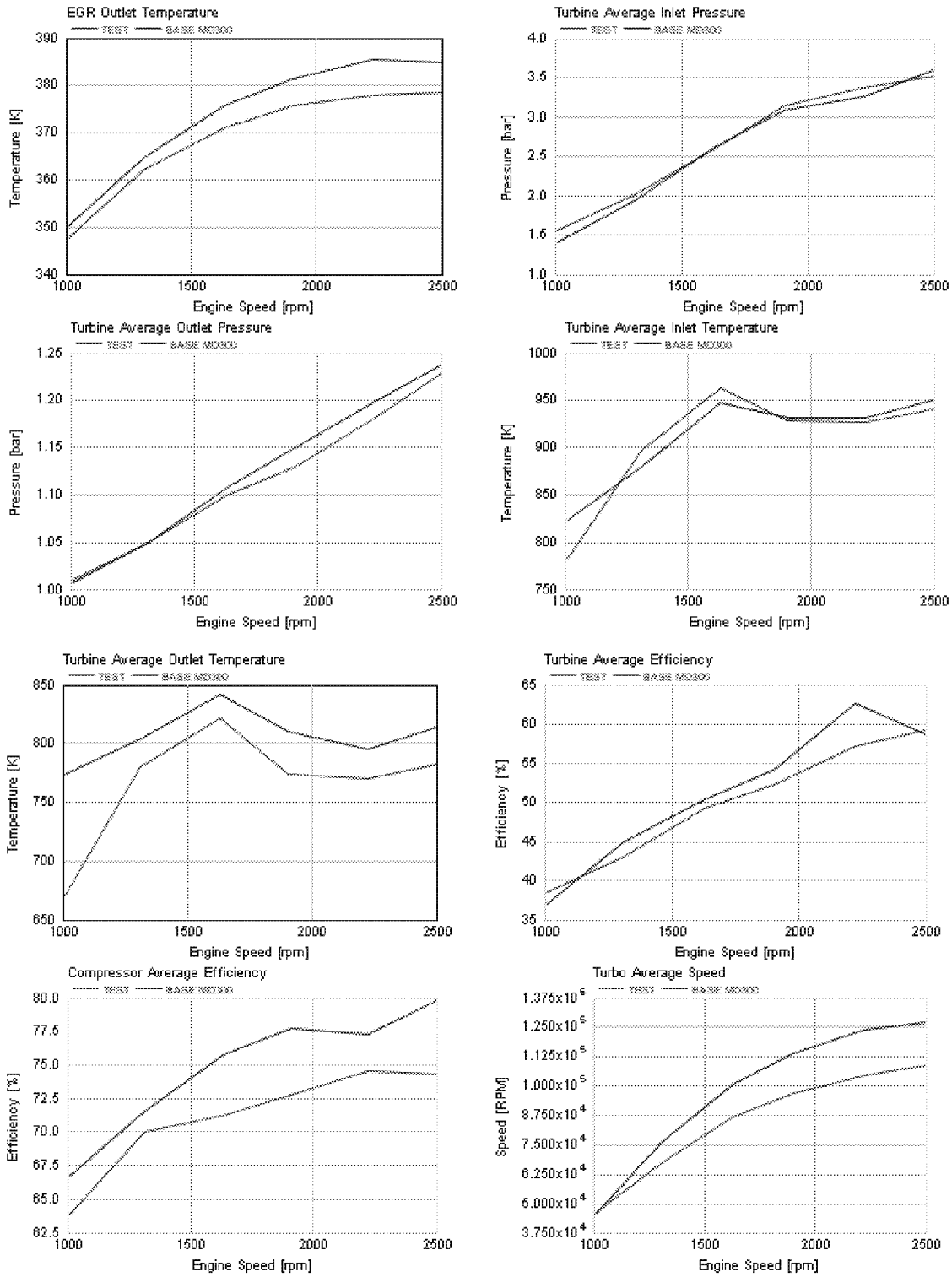

Figure B2.1c (Part 2) Baseline Model Data Correlation at Full Load

2.2 Reduced Exhaust Backpressure

The aim of running the model with reduced exhaust restriction is to simulate the effect of improved flow after-treatment systems for emissions control and the resulting reduction in pumping losses. The baseline GT model was originally setup without modeling the emissions control hardware, but the effective backpressure seen in the exhaust at the VGT exit is simulated by the use of a simple orifice. To model the reduced exhaust backpressure the orifice is resized to achieve the desired target backpressure at the rated condition. In this case, the backpressure has been reduced by 50%, from 24 to 12 kPa. The effect on the engine BSFC is shown in Figure B2.2a. Assuming that the after-treatment effectiveness is retained, there will be no effect on either engine-out or tailpipe emissions of criteria pollutants.

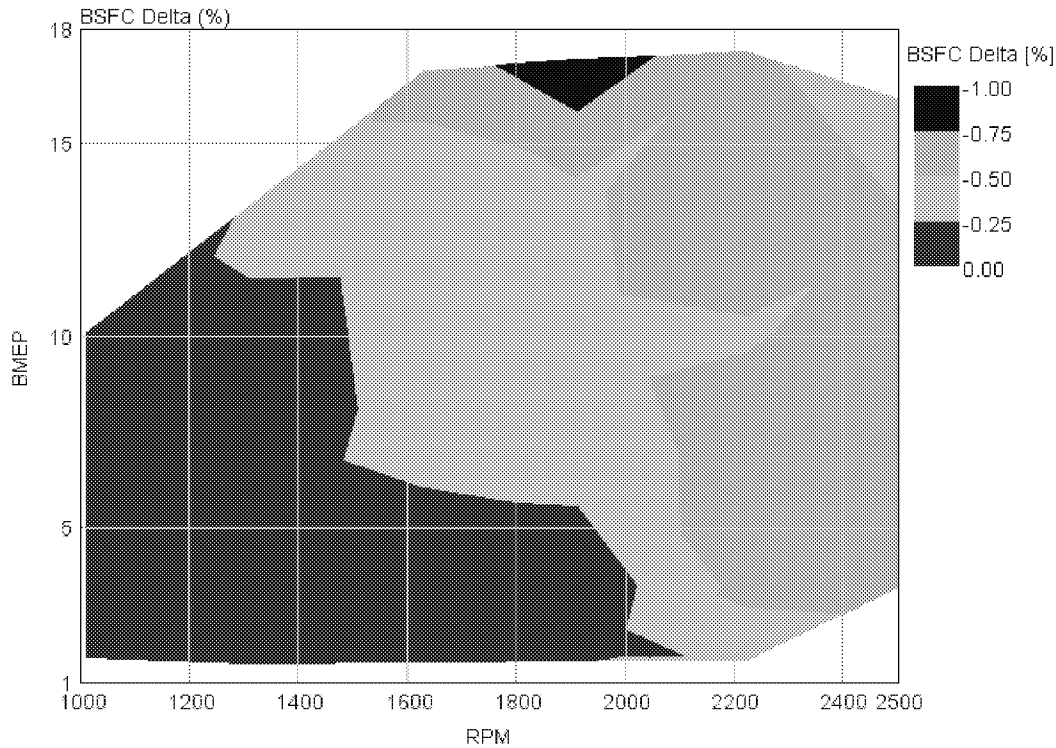

Figure B2.2a Reduced Exhaust backpressure BSFC Improvement

2.3 No EGR

The base ISB engine features a high pressure EGR circuit, with a pre-turbine exhaust manifold supply, an EGR cooler with a bypass valve for when cooling is not required. The valve unit is integrated into the inlet supply system that features an annular ring, which feeds into the inlet pipe pre manifold. To assess the engine performance with no EGR demand, the entire EGR system set of system components was removed from the GT model. The engine was run with the same performance targets but an increased AFR limit (+2 ratios), and the combustion effectively reduced in duration. This technology would involve very high engine-out NOx, and require a very efficient SCR system with a high urea consumption rate.

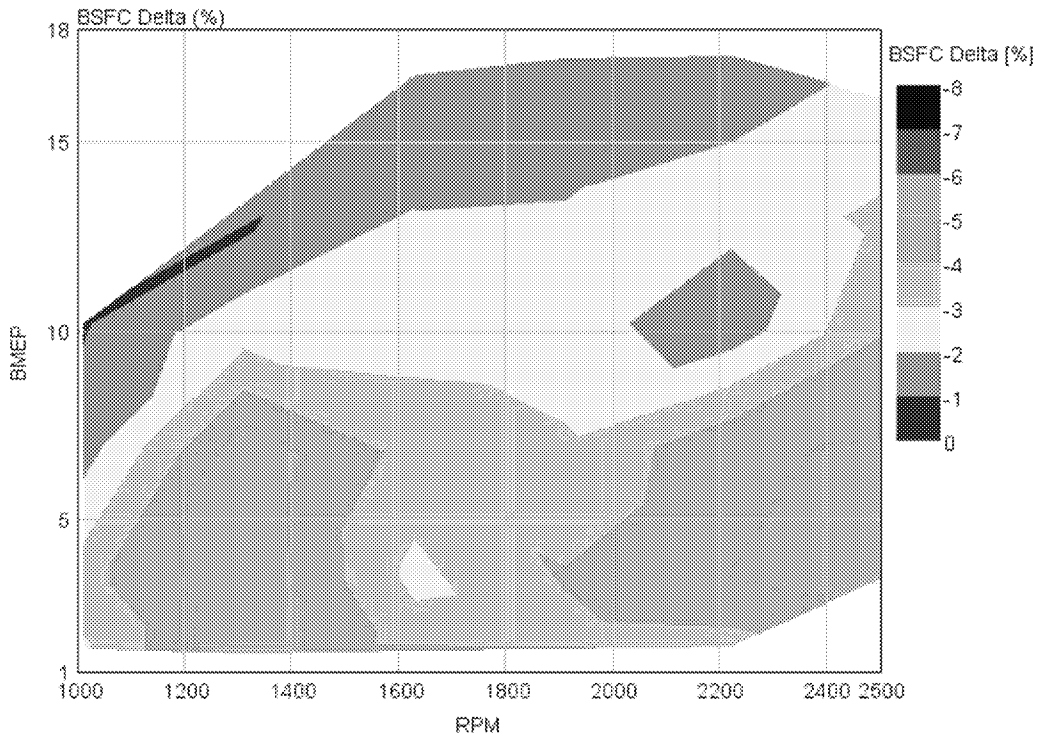

Figure B2.3a. BSFC improvement from EGR removal

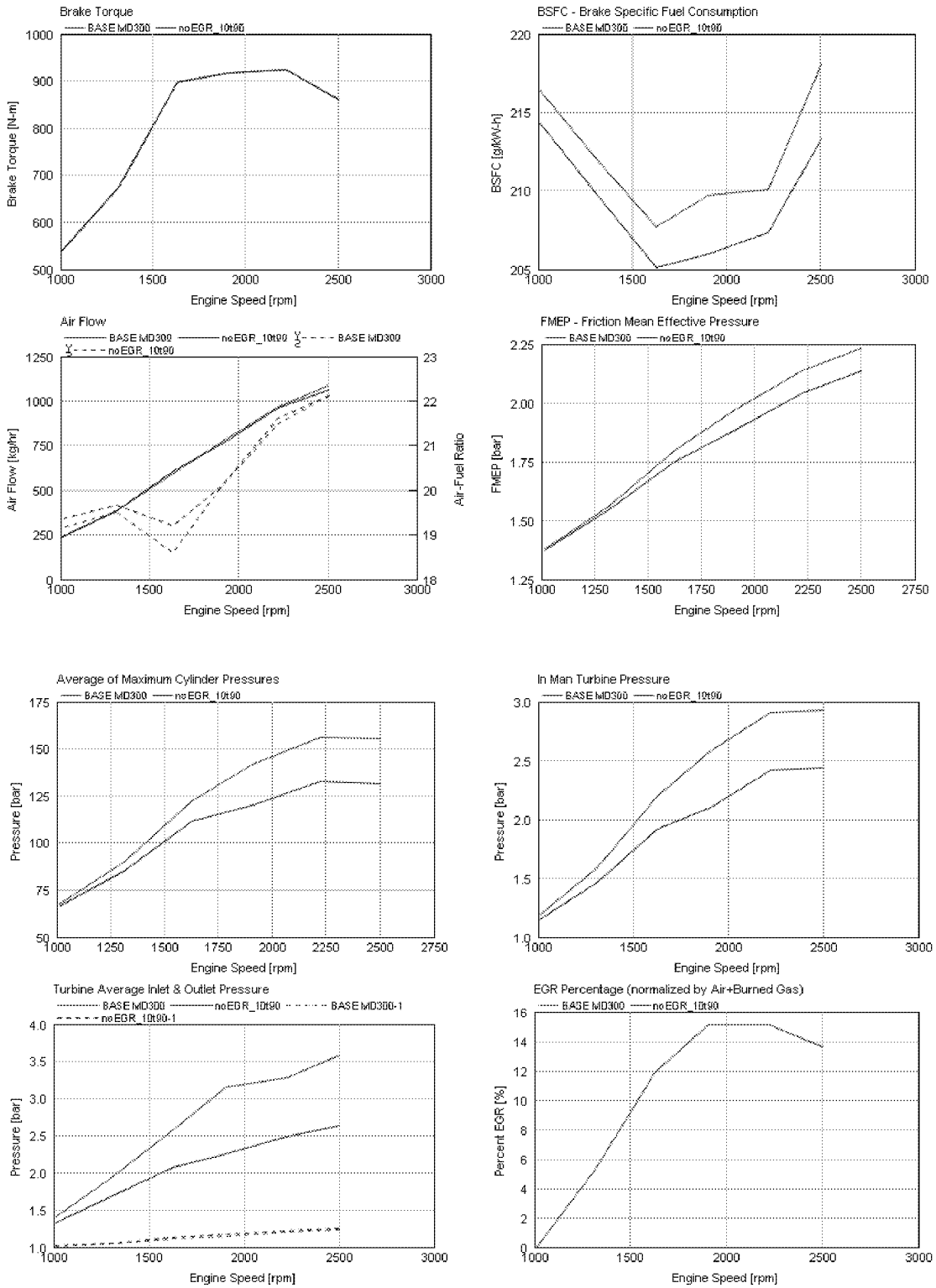

Figure B2.3b. Effect of EGR Removal on Full Load Engine Performance

2.4 Explore Turbo Efficiency Improvement

To simulate an improved efficiency turbo, the base engine model was run with a 5% efficiency increase on both the turbine & the compressor maps. In this case, where the actual engine turbo maps were unavailable and other maps where used and scaled to suit, these maps have been additionally (and globally) scaled to achieve the 5% improvement in efficiency. In a situation where the overall turbocharger efficiency is 50%, a 5% improvement results in a 52.5% overall efficiency. Turbo efficiency improvement can be realized by improvements in turbo designs, bearings, and materials. Reduced pumping losses & improved waste heat energy recovery are typical benefits of improved turbo efficiency. For engines that use EGR there is limited scope for improving turbo efficiency. In these engines, which represent almost the entire market, improved turbocharger efficiency will result in a loss of EGR flow and thus a loss of NOx control. In the case of this engine, there is a reduction in EGR flow with a 5% improvement in turbo efficiency. This will result in higher engine-out NOx, and a greater reliance on aftertreatment conversion efficiency.

The comparison shown is against the baseline engine operating with EGR, unlike the DD15, where the more efficient turbo result was compared against the version with no EGR.

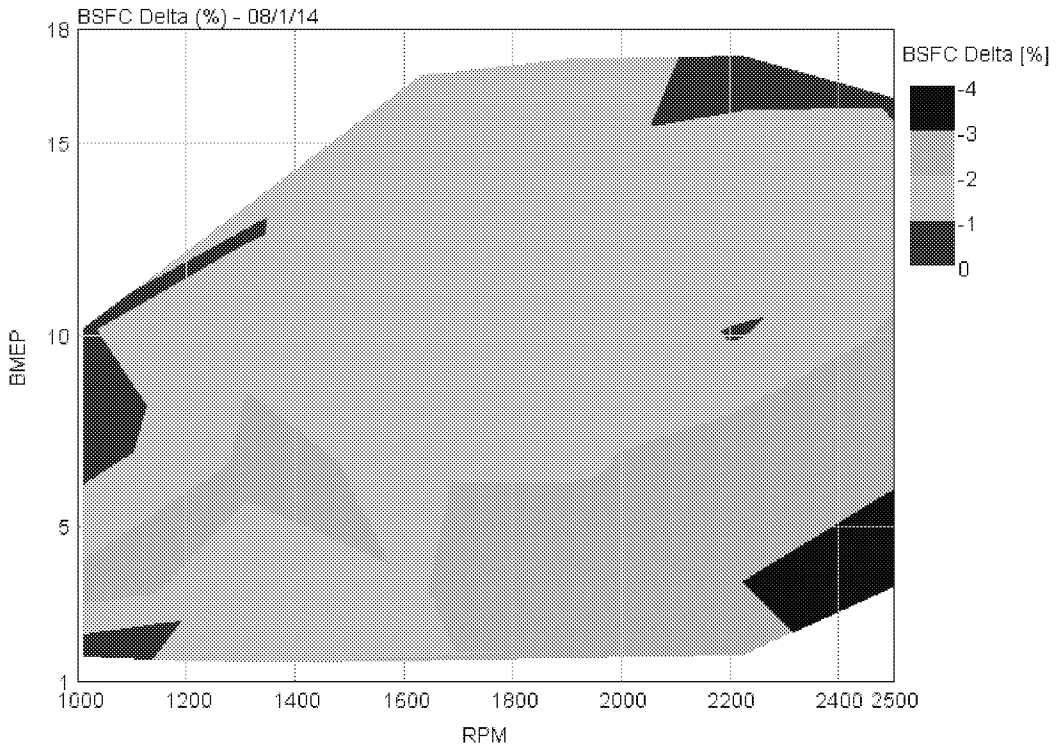

Figure B2.4a. High Efficiency Turbo BSFC Improvement

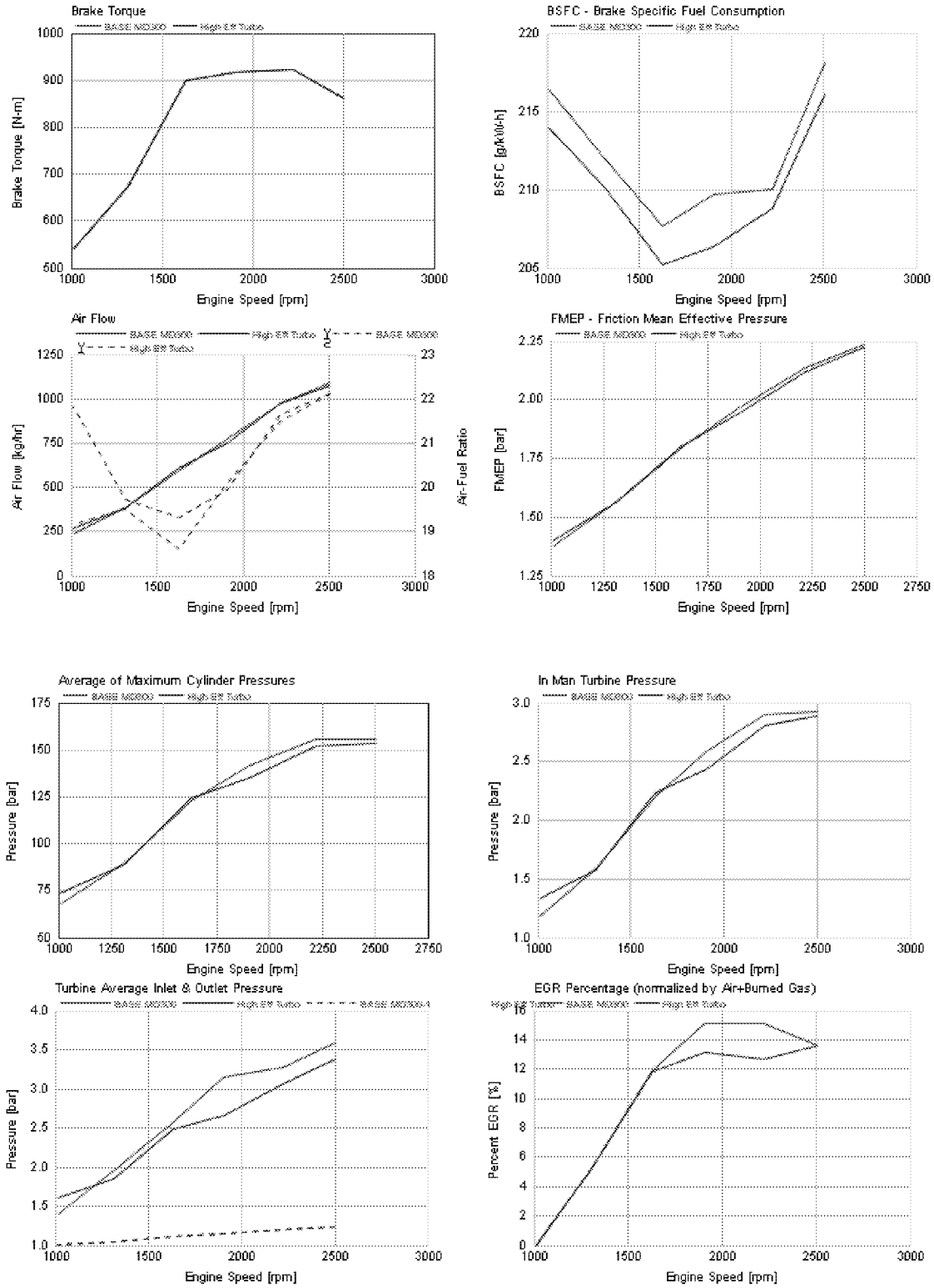

Figure B2.4b. Effect of High Efficiency Turbo on Full Load Engine Performance

2.5 Explore FMEP Improvements

The baseline engine model with a reduced friction map was run at the same conditions of as the baseline model. The friction (FMEP) was reduced on a speed-load relationship, with full load reductions of 10% and part load reduction of up to 35%. As expected, the largest benefits occur at light load and lower engine speeds.

Reducing engine friction can be achieved in several ways, such as low viscosity oils, smaller or dynamic bearings, ring/piston/liner interface improvements, a more efficient fuel pump, as well as smart controlled oil and water pumps. In this study, all the friction improvements where lumped together.

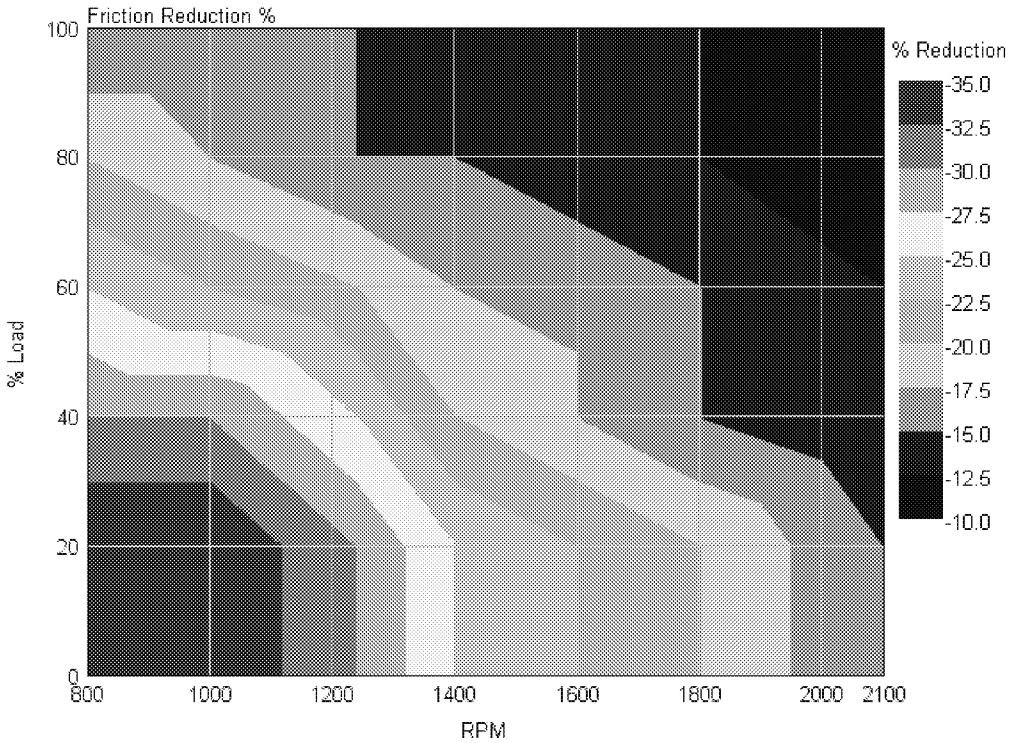

Figure B2.6a. Friction Reduction Assumptions

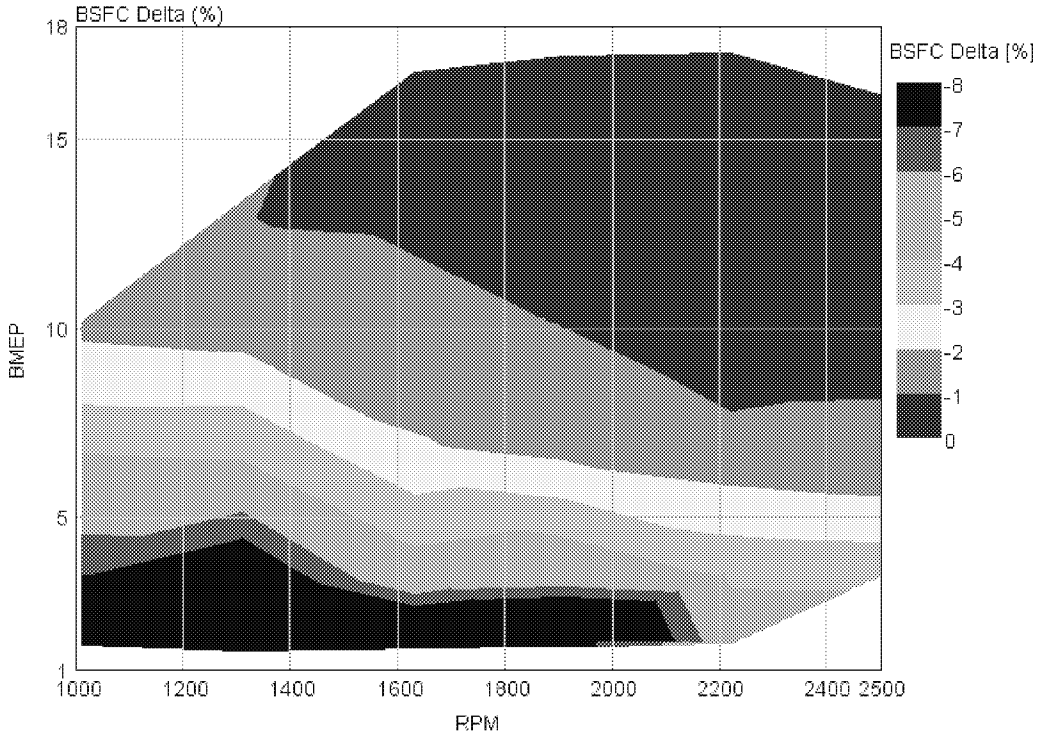

Figure B2.6b. Friction reduction BSFC Improvement over Baseline

3.1 ISB Pickup 385bhp Baseline Validation

- **Basic engine specification**
  - 6.7L inline 6 cylinder
  - Single Variable Geometry Turbo
  - 4 valves per cylinder
  - Diesel
  - 285 kW @ 2350 - 3000 rpm
  - 1150 Nm @ 1600 - 2350 rpm

The GT Power model for this version of the ISB engine was closely based on the validated model from the medium duty 300 bhp analysis. Low speed performance was maintained as per the 300bhp model (below 1300rpm), then power/torque was increased by ~25% across the remainder of the speed range, which was extended to 3000 rpm, as opposed to 2500rpm for the 300bhp engine. For this engine, a number of parameters where either maintained or revised, compared to the 300 bhp engine.

- Same AFR (min ~19:1)
- Reduced EGR flow (see Fig 3.1c)
- Increased maximum cylinder pressure limit (175 bar)
- Re-sized turbo

Although no test data was available to correlate the engine model, published data & benchmark data for similar engines where used to confirm the model predicted a reasonable level of performance.

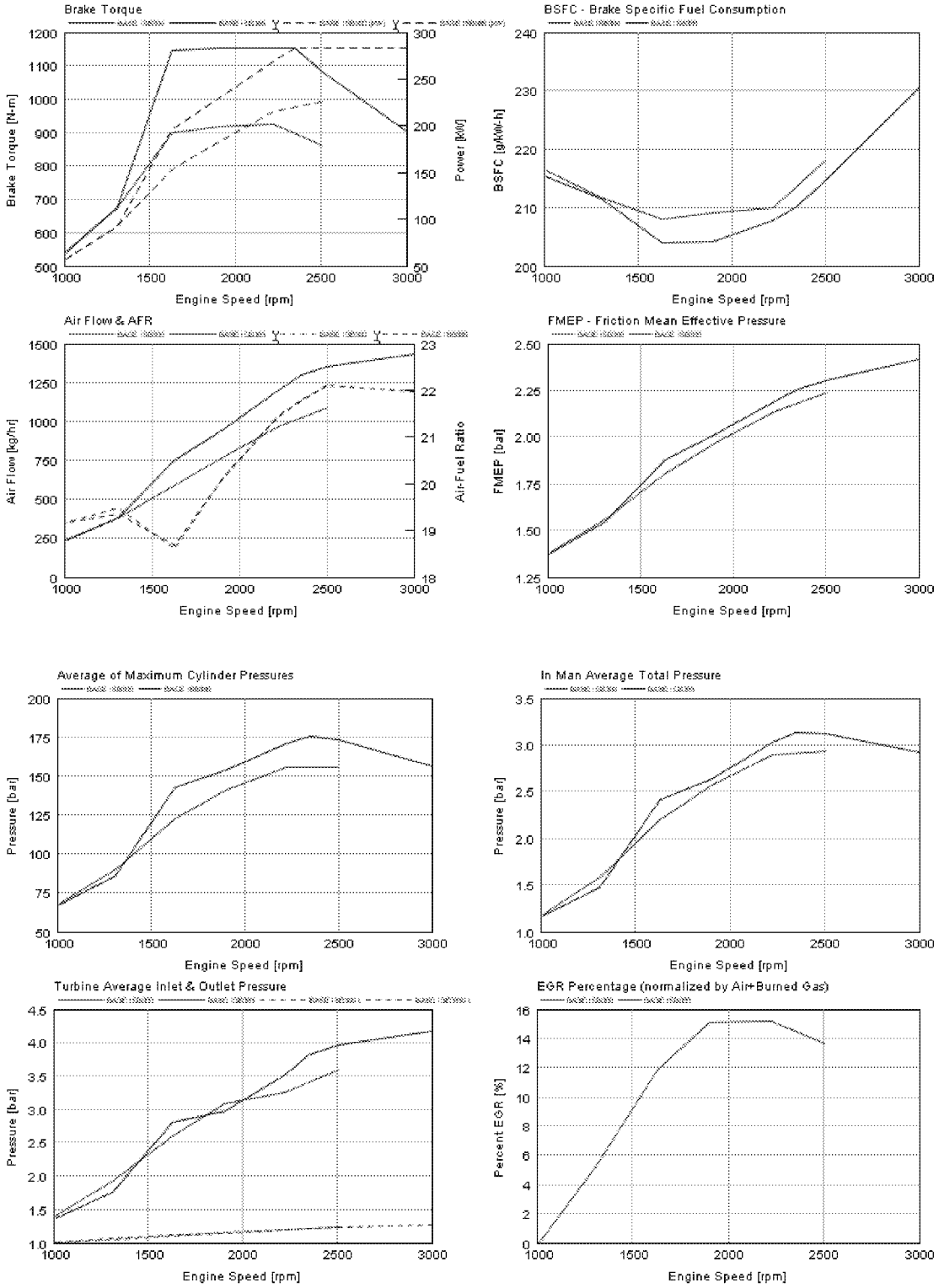

Figure B3.1a (Part 1) ISB MD300 vs PU385 Performance Comparison at Full Load

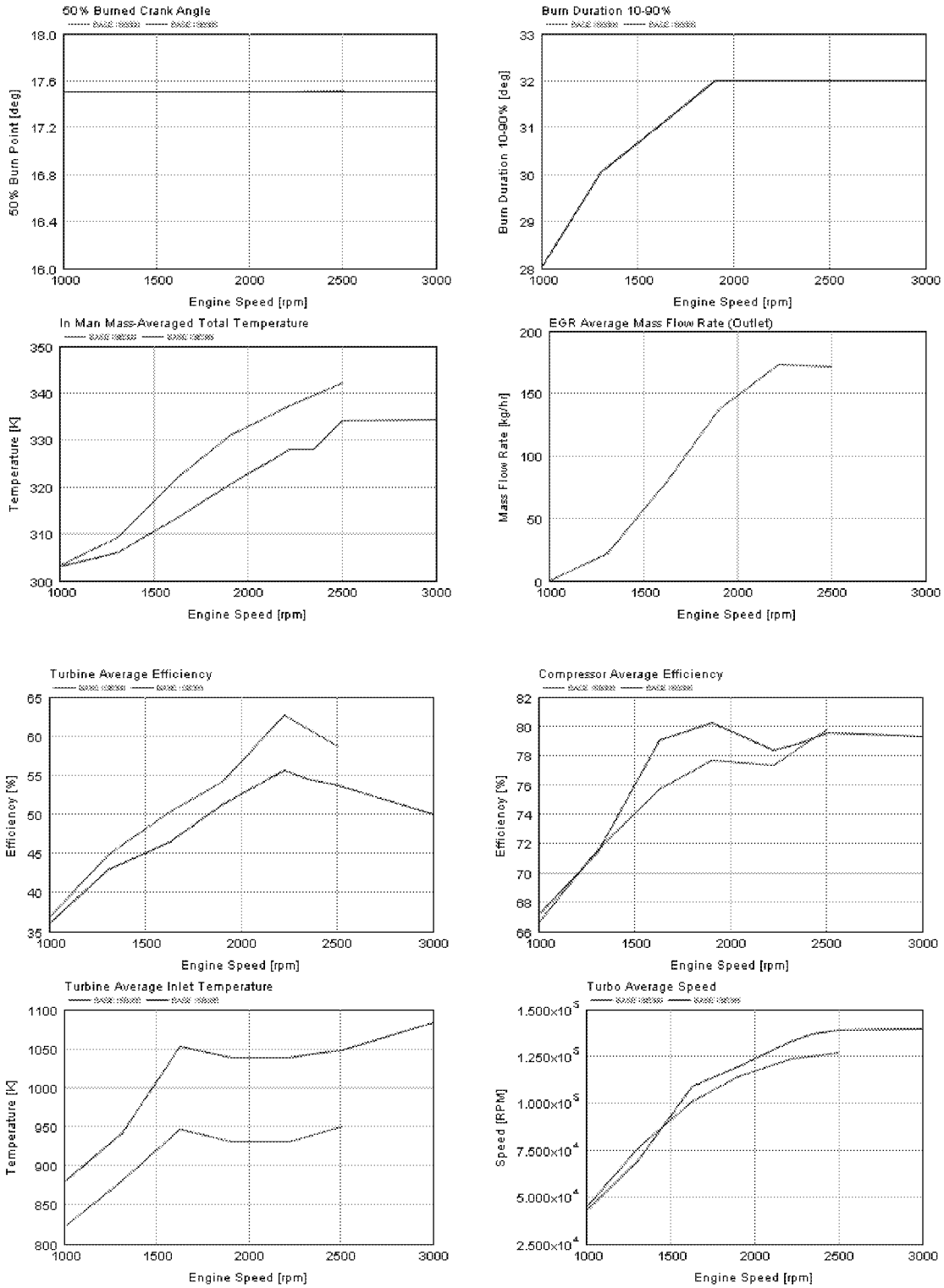

Figure B3.1a (Part 2) ISB MD300 vs PU385 Performance Comparison at Full Load

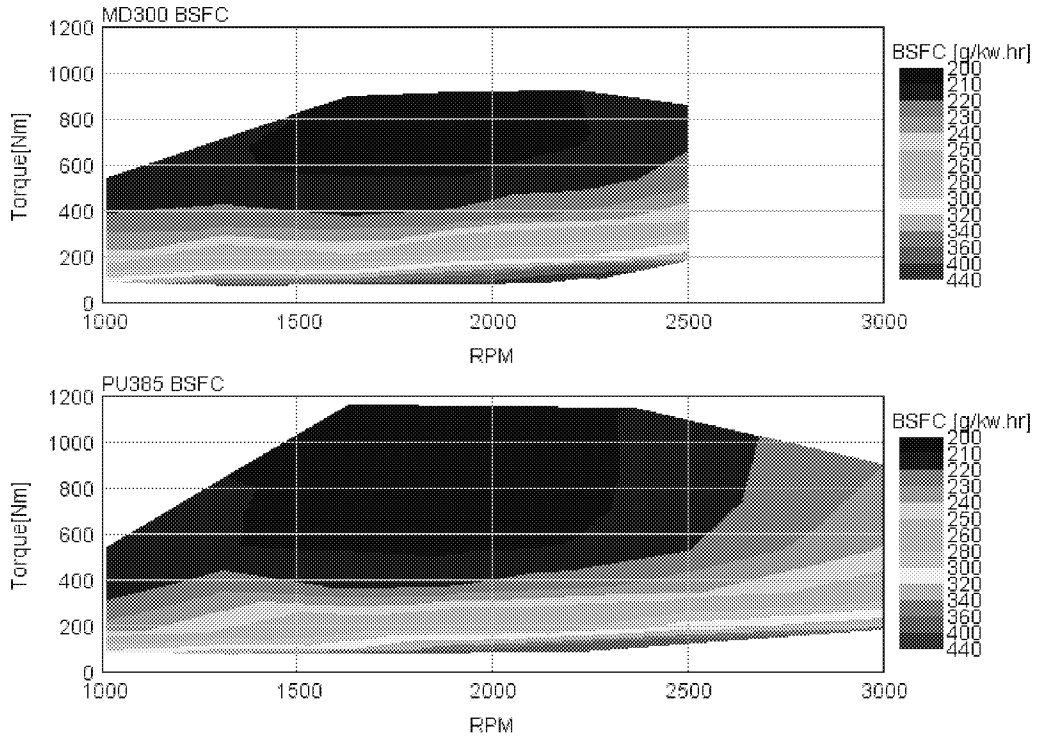

Figure B3.1b ISB MD300 vs PU385 BSFC Comparison

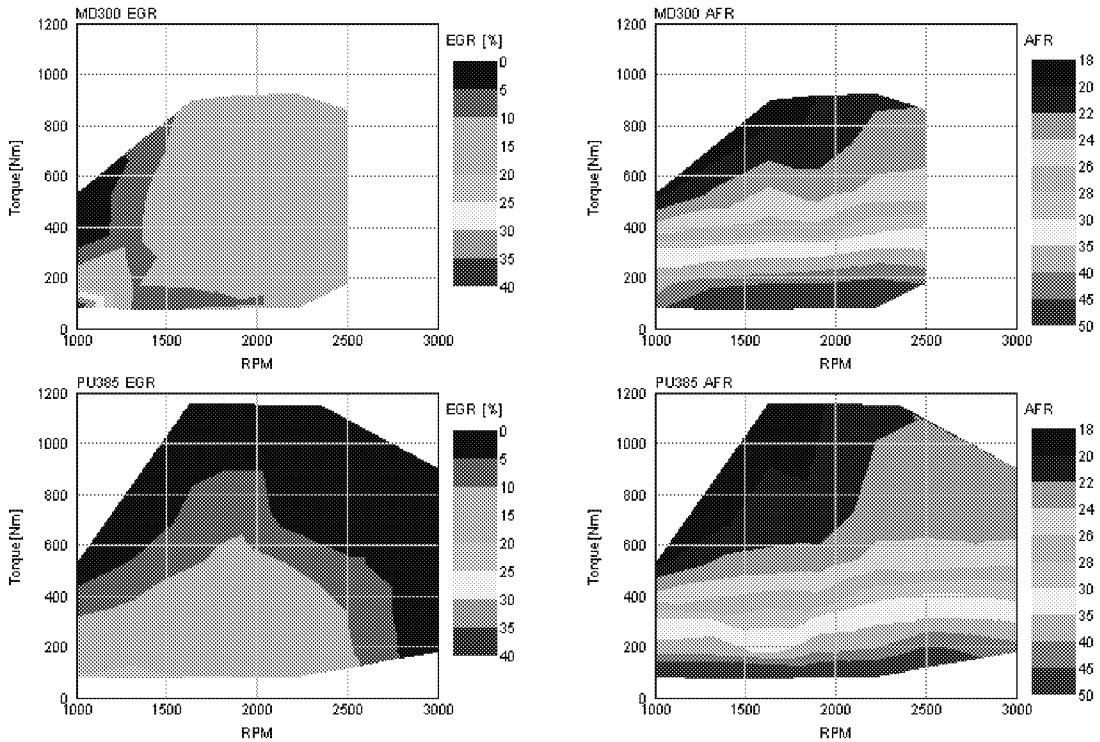

Figure B3.1c ISB MD300 vs PU385 EGR & AFR Comparison

The reason for the lack of EGR flow at higher speeds and loads on the 385 HP pickup version of the engine is the fact that the engine is chassis dynamometer certified for emissions. Since the vehicle drive cycle does not require high RPM or high torque operation, EGR is not required at these conditions to control NOx. The lack of EGR flow at high load is a key factor enabling the very high BMEP of this engine. If EGR was required at full load, the cylinder pressure would increase substantially. Either the power rating would need to be reduced, or the engine would need to be redesigned to tolerate higher cylinder pressure.

3.2 Reduced Exhaust Backpressure

The aim of running the model with reduced exhaust restriction is to simulate the effect of improved flow after-treatment systems for emissions control and the resulting reduction in pumping losses. The baseline GT model was originally setup without modelling the emissions control hardware, but the effective backpressure seen in the exhaust at the VGT exit is simulated by the use of a simple orifice. To model the reduced exhaust backpressure the orifice is resized to achieve the desired target backpressure at the rated condition. In this case, the backpressure has been reduced by slightly over 50%, from 26 to 12 kPa. The effect on the engine BSFC is shown in figure B3.2a. The effect is very small, so the figure only uses two colors despite a scale of 0.25% per color. Assuming that the after-treatment effectiveness is retained, there will be no effect on either engine-out or tailpipe emissions of criteria pollutants.

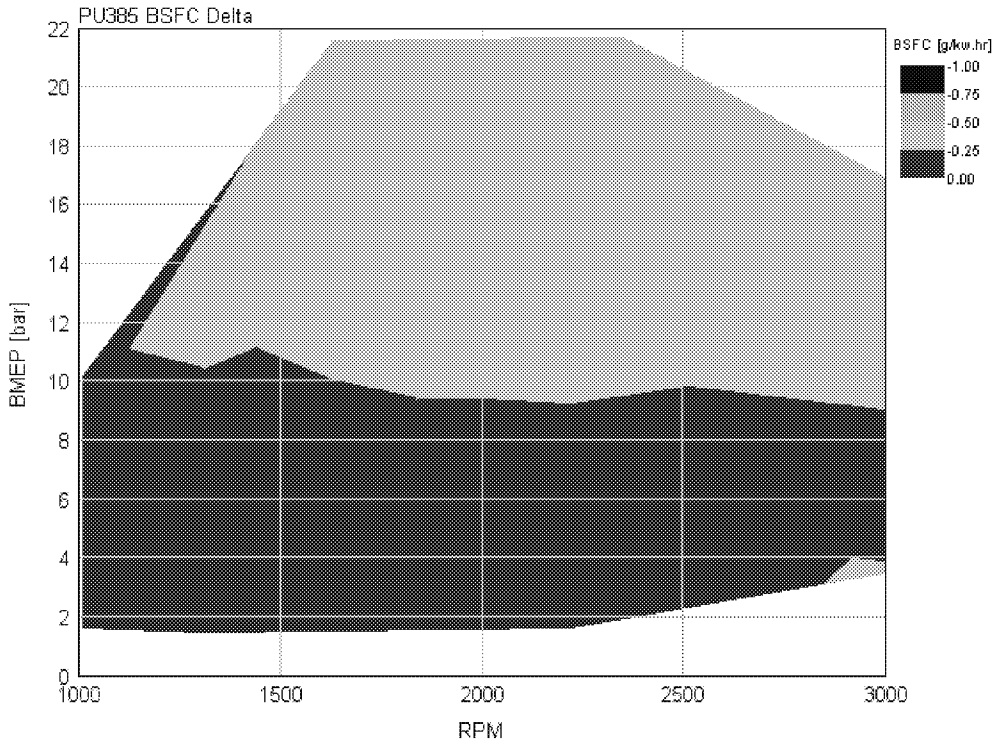

Figure B3.2a Reduced Exhaust backpressure BSFC Improvement

3.3 No EGR

The base ISB engine features a high pressure EGR circuit, with a pre-turbine exhaust manifold supply, an EGR cooler with a bypass valve for when cooling is not required. The valve unit is integrated into the inlet supply system that features an annular ring that feeds into the inlet pipe pre-manifold. To assess the engine performance with no EGR demand, the entire EGR system set of system components was removed from the GT model. The engine was run with the same performance targets but an increased AFR limit (+2 ratios), and the combustion effectively reduced in duration. This technology would involve very high engine-out NOx, and require a very efficient SCR system with a high urea consumption rate.

Although the base 385bhp engine has a relatively low EGR demand across the speed & load range compared to the 300bhp ISB engine, it was still necessary to re-scale the turbo setup to achieve suitable performance at the low load conditions, where the EGR rates are up to ~20% (see Fig 3.1c). This leads to change in performance on the full load curve, even though the EGR demand is unchanged (from zero).

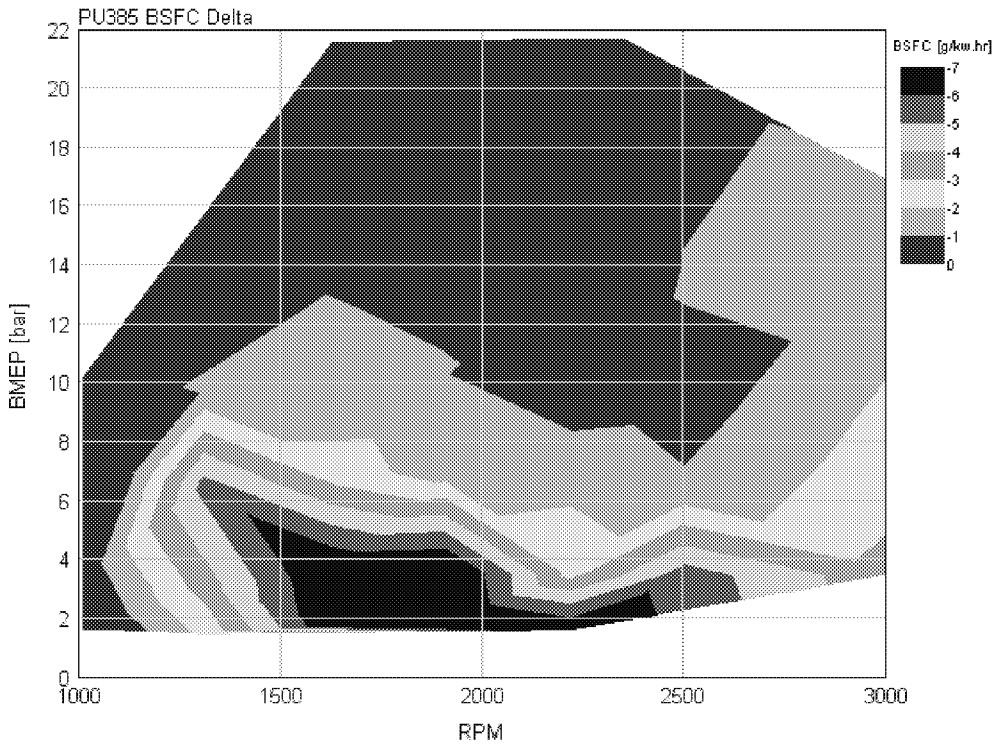

Figure B3.3a. BSFC improvement from EGR removal

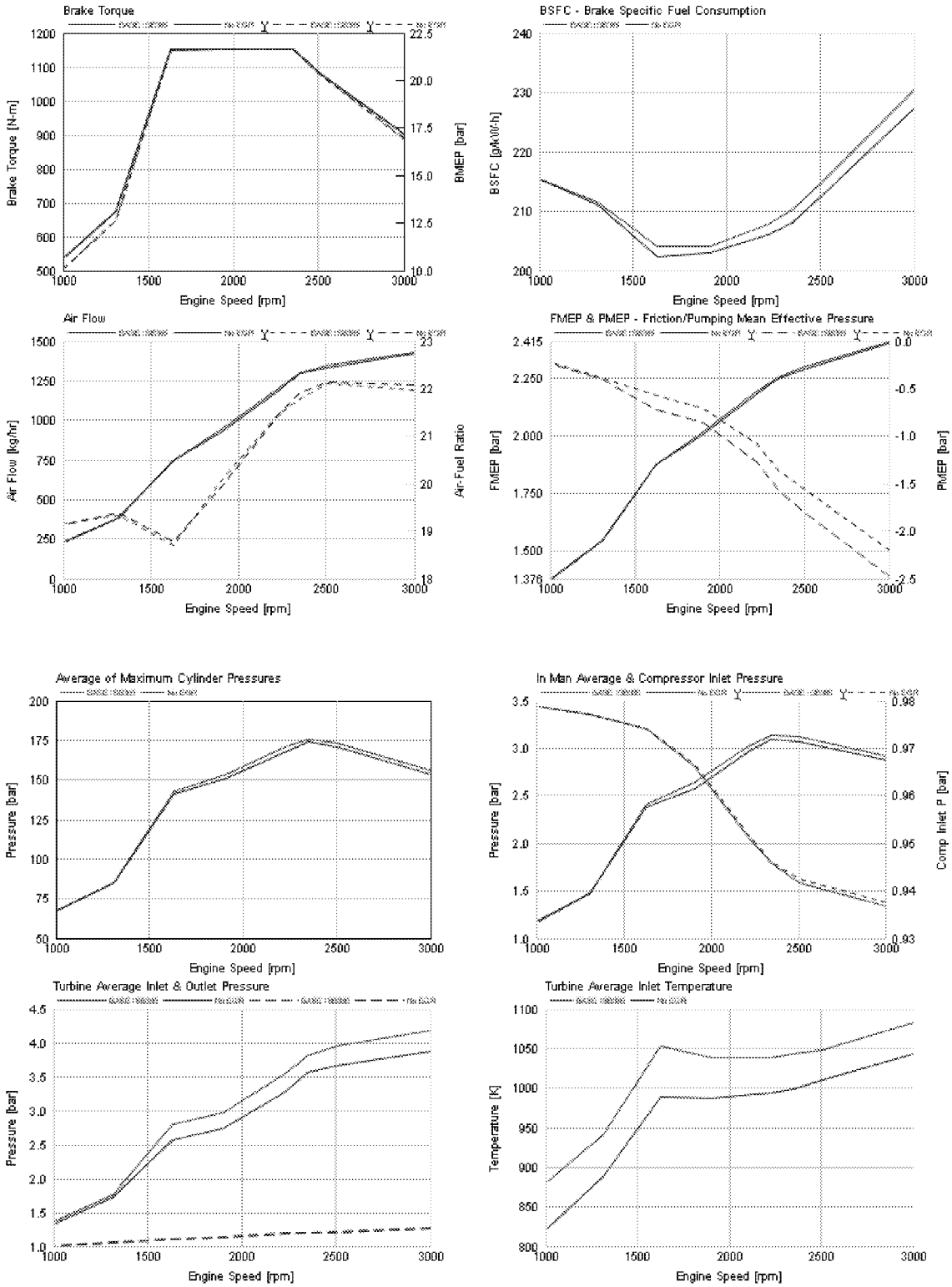

Figure B3.3b. Effect of EGR Removal on Full Load Engine Performance

3.4 Explore Turbo Efficiency Improvement

To simulate an improved efficiency turbo, the base engine model was run with a 5% efficiency increase on both the turbine & the compressor maps. In this case, where the actual engine turbo maps were unavailable and other maps where used and scaled to suit, these maps have been additionally (and globally) scaled to achieve the 5% improvement in efficiency. Turbo efficiency improvement can be realized by improvements in turbo designs, bearings, and materials. Reduced pumping losses & improved waste heat energy recovery are typical benefits of improved turbo efficiency. For engines that use EGR there is limited scope for improving turbo efficiency. In these engines, which represent almost the entire market, improved turbocharger efficiency will result in a loss of EGR flow and thus a loss of NOx control.

The comparison shown is against the baseline engine operating with EGR, unlike the DD15, where the more efficient turbo result was compared against the version with no EGR.

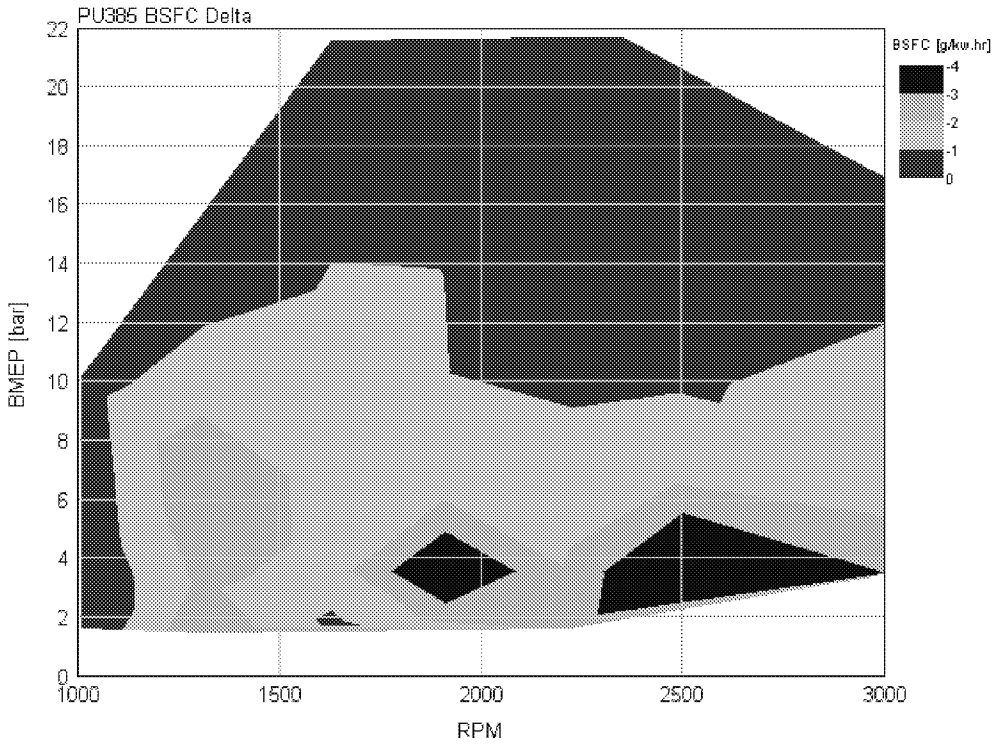

Figure B3.4a. High Efficiency Turbo BSFC Improvement

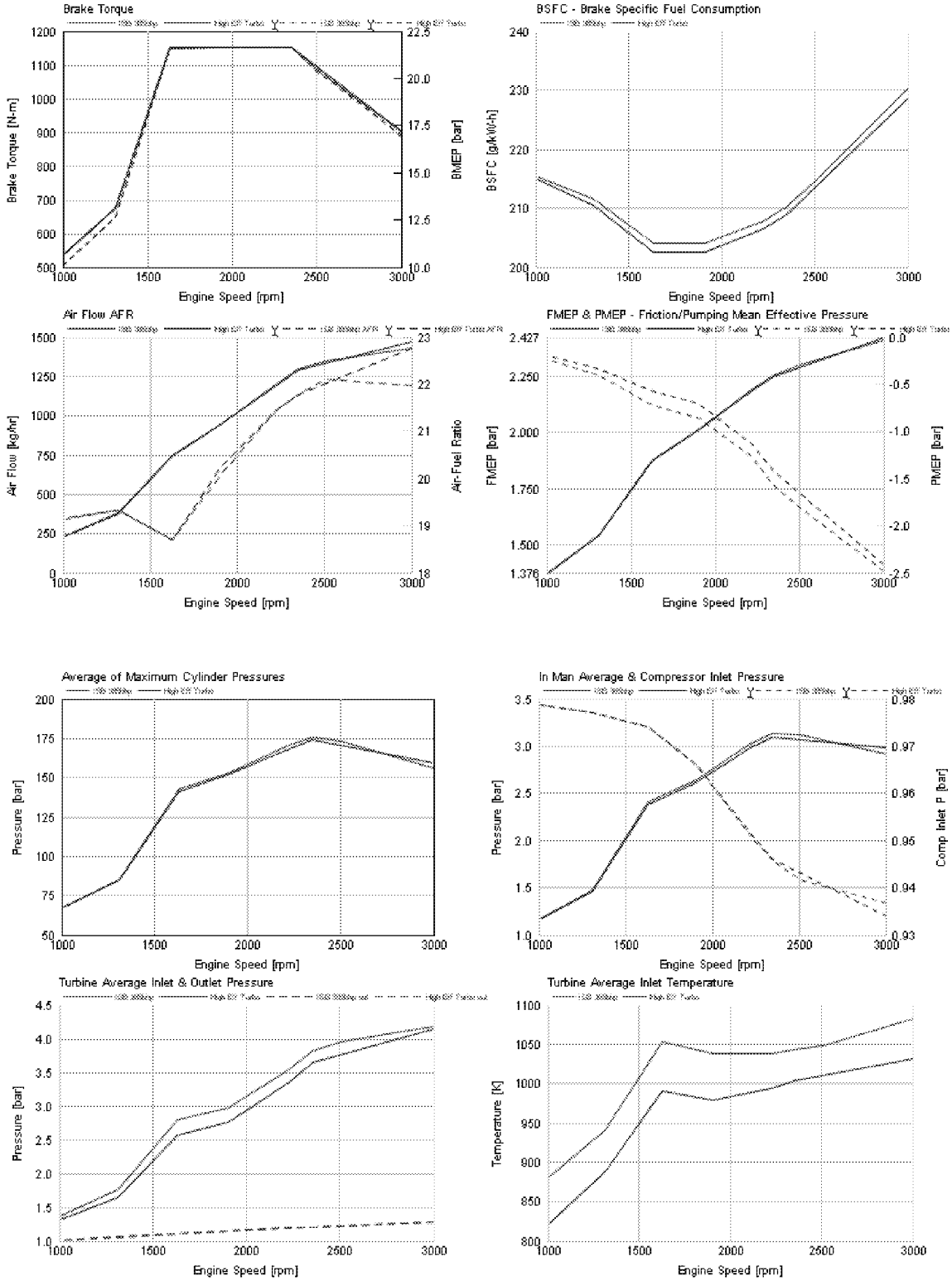

Figure B3.4b. Effect of High Efficiency Turbo on Full Load Engine Performance

3.5 In-line 4 Cylinder 4.5L Engine

An in-line 4-cylinder version of the ISB 385 was constructed, resulting in a displacement of 4.5L. The same BMEP levels as the 6-cylinder version were maintained, so a lower torque level was achieved. The peak torque speed was maintained from 1600 rpm to 2350 rpm. This technology is meant to reflect the performance of a smaller medium duty engine for Class 2b/3 applications. This size of engine is often used in urban area delivery trucks, and could be used in pickup trucks if customers are willing to accept less power in exchange for better fuel efficiency.

The existing single turbine entry exhaust manifold layout was carried over, as was the EGR system. The following model setup parameters & features where maintained as the 6 cylinder model

- Combustion settings
- EGR levels
- AFR
- Friction
- Cylinder pressure limits where maintained,

The FMEP was assumed to be the same as seen on the 6-cylinder, so for a given operating point (speed and BMEP level), the 4-cylinder will have 2/3 of the friction torque.

The combustion characteristics are also the same as for the 6-cylinder engine, and are related to operating BMEP levels (not torque).

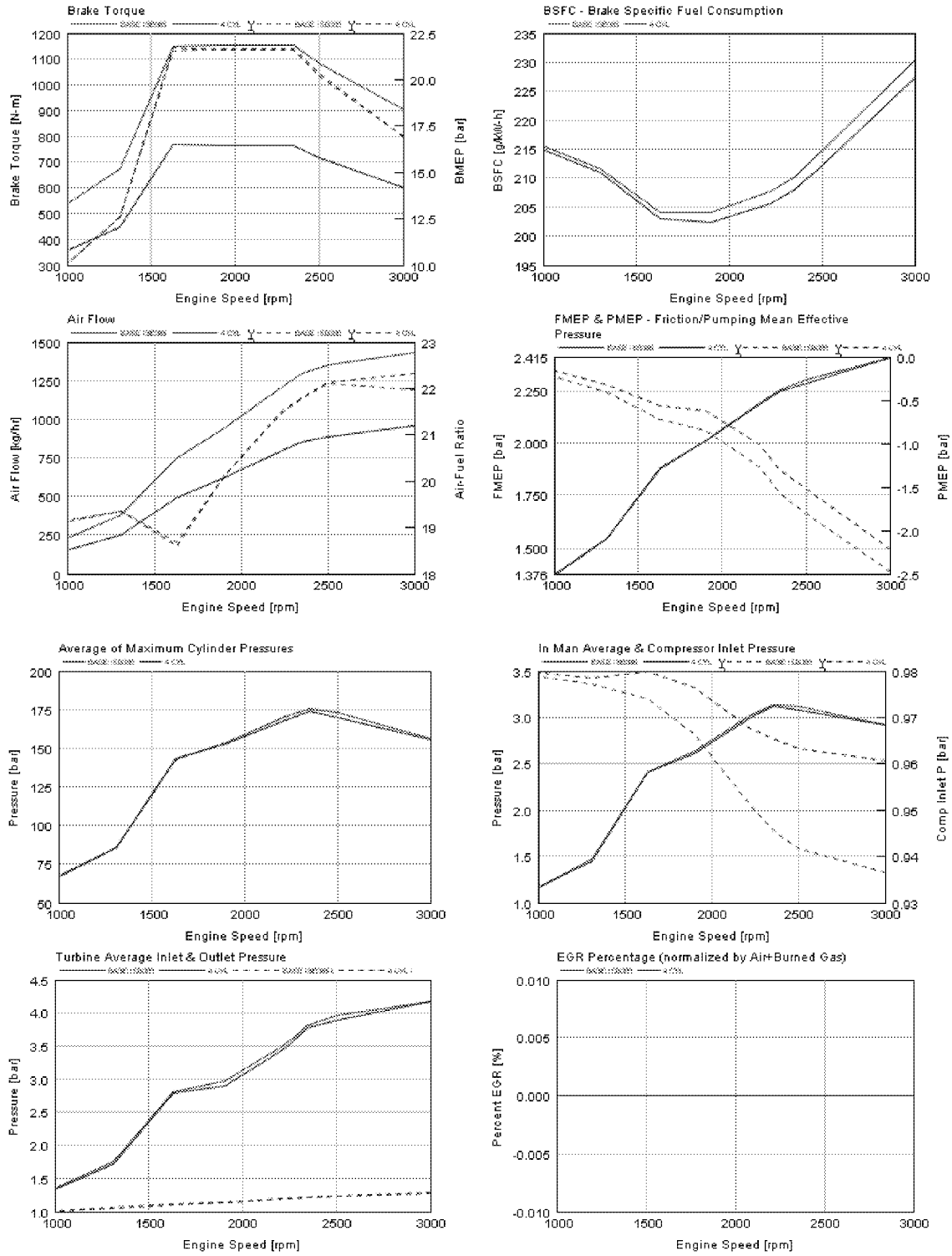

Figure B3.5a. Comparison of 6 & 4 Cylinder ISB versions at Full Load

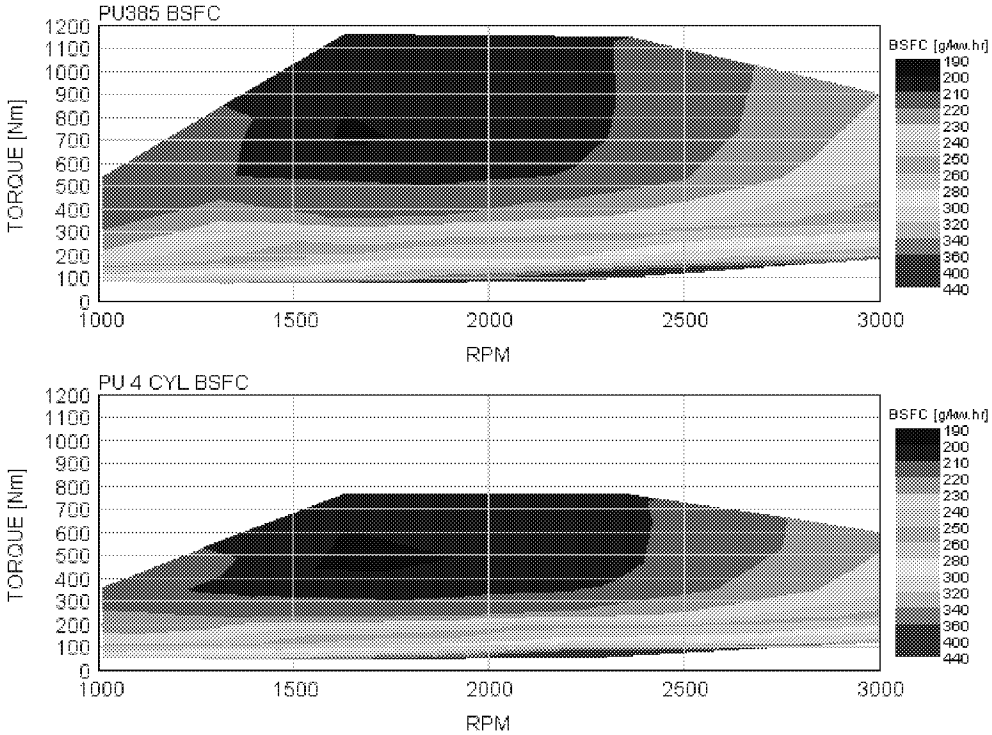

Figure B3.5b. BSFC comparison of 6 & 4 Cylinder ISB Versions

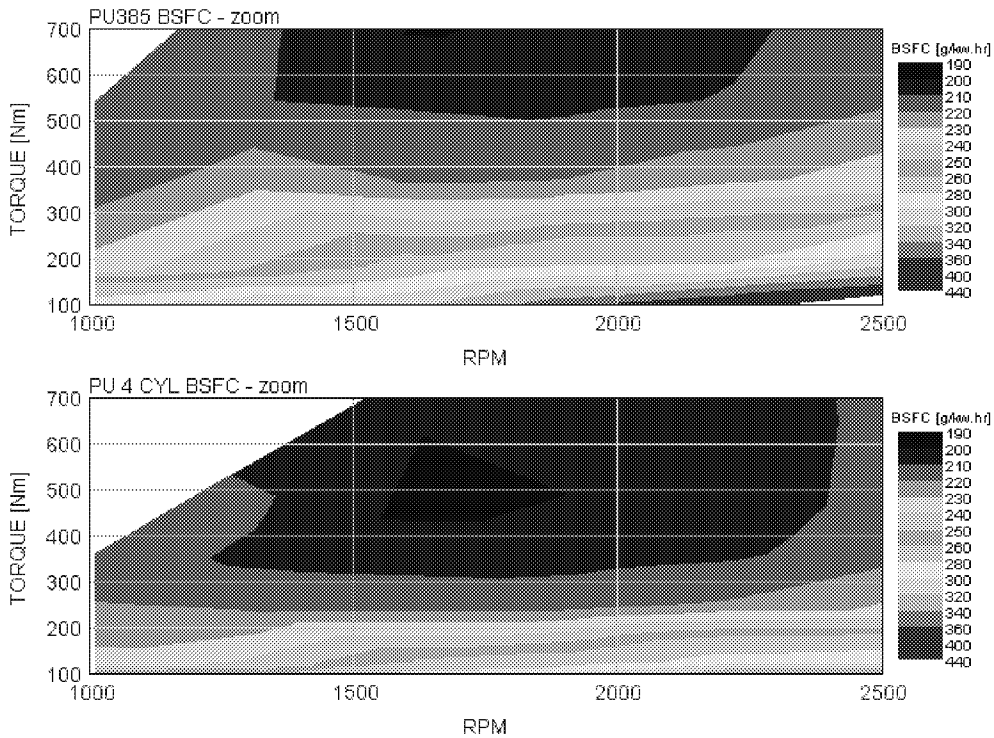

Figure B3.5c. BSFC comparison of 6 & 4 Cylinder ISB Versions

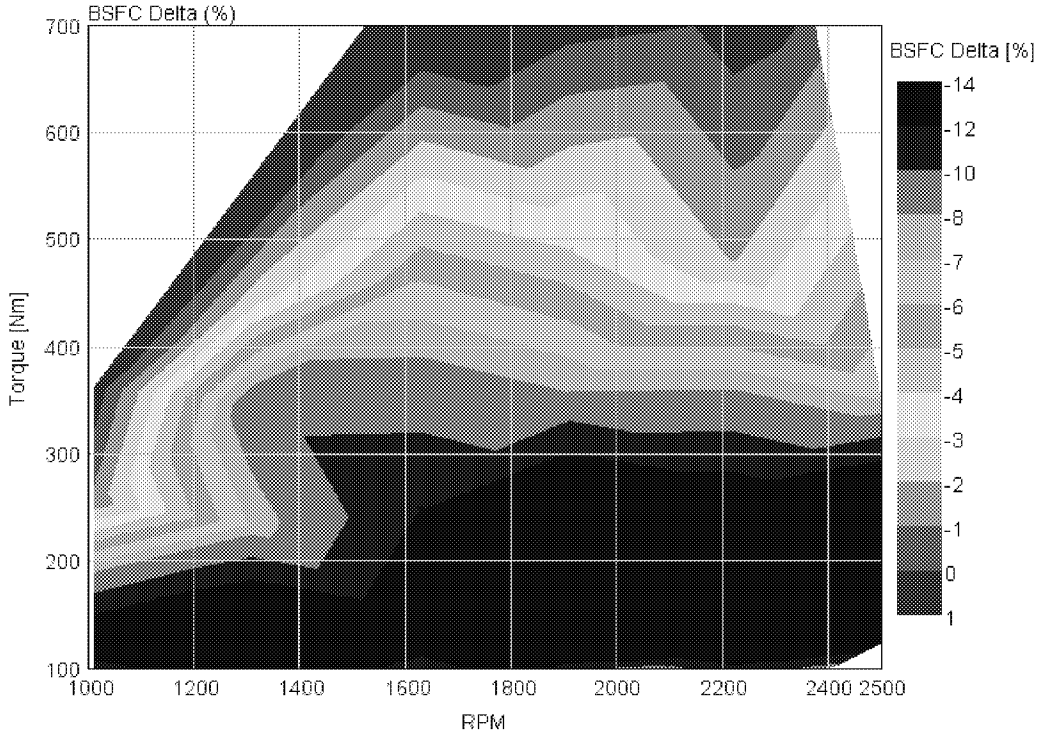

Figure B3.5d. BSFC Delta of 4 Cylinder ISB, Compared to 6 Cylinder

3.6 Explore FMEP Improvements

The baseline 385bhp engine model with a reduced friction map was run at the same conditions of as the base model. The friction (FMEP) was reduced on a speed-load relationship, with full load reductions of 10% and part load reduction of up to 35%. As expected, the largest benefits occur at light load and lower engine speeds.

Reducing engine friction can be achieved in several ways, such as low viscosity oils, smaller or dynamic bearings, ring/piston/liner interface improvements, a more efficient fuel pump, as well as smart controlled oil and water pumps. In this study, all the friction improvements where lumped together.

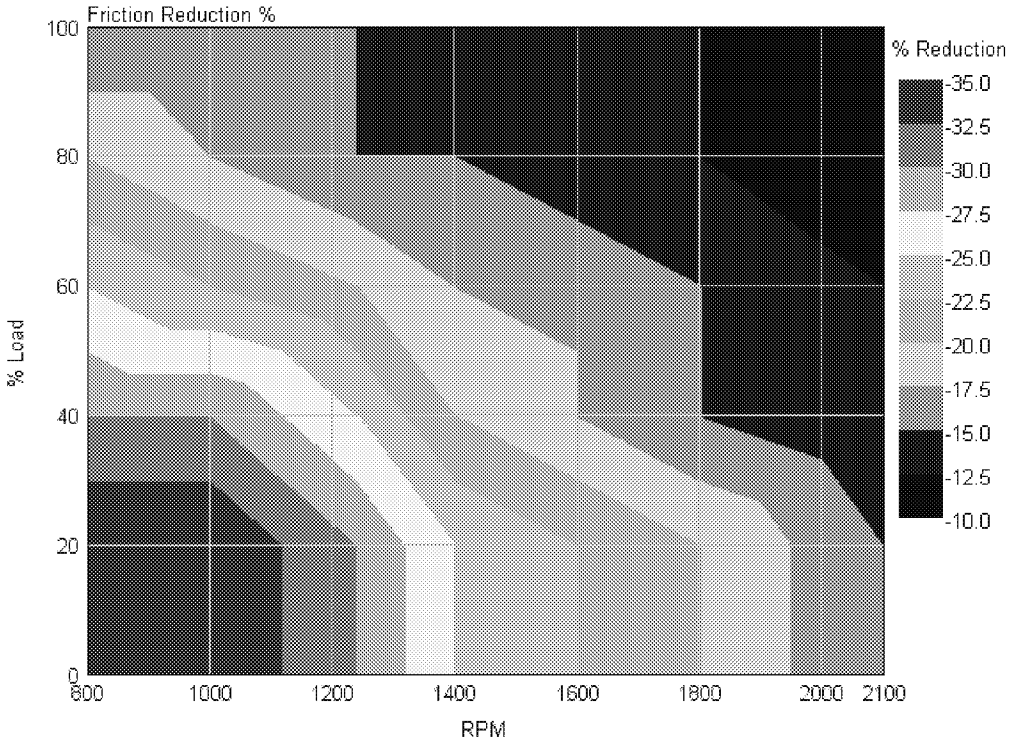

Figure B3.6a. Friction Reduction Assumptions

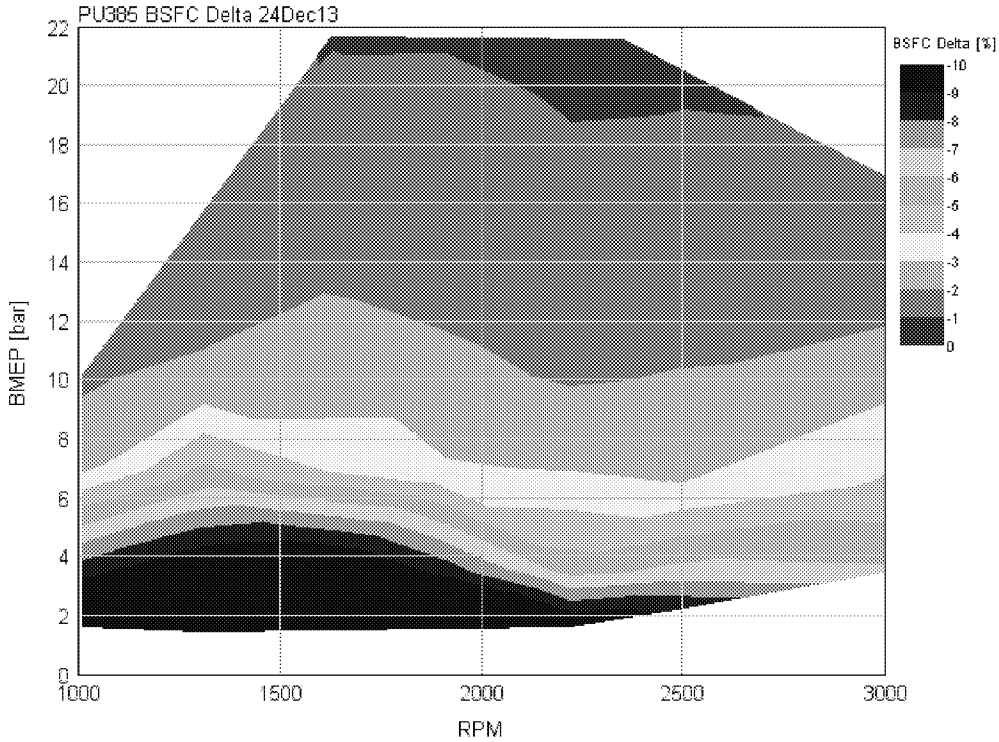

Figure B3.6b. Friction reduction BSFC Improvement over Baseline

APPENDIX C

VEHICLE SIMULATION AND VEHICLE TECHNOLOGIES

Vehicle Simulation and Vehicle Technologies

Objective: Simulate Future Vehicle and Engine Technologies to Demonstrate Fuel Economy Improvement Potential in Class 2b through 7 vehicles utilizing:

- **A range of engines and engine technologies**
- **A range of vehicle technologies**

1. Vehicle Modeling Approach:

1.1. Simulation Tool
1.2. Description of Baseline Vehicle Models
1.2.1. Ram Pickup Truck
1.2.2. Ford F-650 Roll-On Tow Truck
1.2.3. Kenworth T-270 Box Delivery Truck
1.2.4. Kenworth T-700 Tractor-Trailer Truck
1.3. Vehicle Drive Cycles

2. Vehicle Efficiency Technologies

2.1. Reduced Air Conditioner Power Demand
2.2. Reduced Aerodynamic Drag (Cd)
2.3. Reduced Tire Rolling Resistance (Crr)
2.4. Weight Reduction
2.5. Chassis Friction Reduction
2.6. 6X2 Axle Configuration
2.7. Road Speed Governor (Reduced Vmax)
2.8. Transmission Alternatives
2.8.1. 6-Speed, 10-Speed, and 18-Speed AMT Transmissions
2.8.2. 10-Speed Manual Transmission
2.8.3. 5-Speed, 6-Speed, and 8-Speed Torque Converter Automatic Transmissions
2.9. Engine Alternatives
2.9.1. 4.5 and 6.7 Liter Diesel (Pickup Only)
2.9.2. 6.7 and 8.9 Liter Diesel (Classes 4 – 8)
2.9.3. 3.5 V-6 and 6.2 V-8 Gasoline Engines (Classes 2b – 7)
2.9.4. 12.5 Liter and 14.8 Liter Diesel (Class 8 Only)

3. Examples of Vehicle Drive Cycle Operation

C1. Vehicle Modeling Approach

C1.1 Simulation Tool

Southwest Research Institute has developed a number of simulation tools for vehicle performance and fuel economy evaluation. The most popular ones are PSAT and RAPTOR. PSAT (Powertrain System Analysis Toolkit) was the first forward-looking (integral-approach) modeling tool developed in the MATLAB/Simulink environment. PSAT was developed for The United States Council for Automotive Research (USCAR) during the Partnership for a New Generation of Vehicles (PNGV) Initiative. SwRI provided a version of PSAT to Argonne National Lab, who utilized it for its DOE-funded programs and continued to upgrade and sell the tool to the rest of the automotive industry. RAPTOR, on the other hand, was co-developed by SwRI and Chrysler Corp for generating validated NHTSA Corporate Average Fuel Economy (CAFE) numbers on specific vehicle platforms. These two tools are still used in the industry today.

SwRI has also utilized other simulation tools and upgraded them to meet its client's needs. One of these tools is SwRI's Vehicle Simulation Tool (VST). This software is based on NREL's original Advisor vehicle simulator (see Figure C1 below) offered by NREL and utilized worldwide by hundreds of users. The main difference between Advisor and PSAT is that Advisor utilizes a backward-looking simulation algorithm that starts from the vehicle speed requirements during a cycle and then determines the powertrain demand, using a differentiation rather than an integration approach.

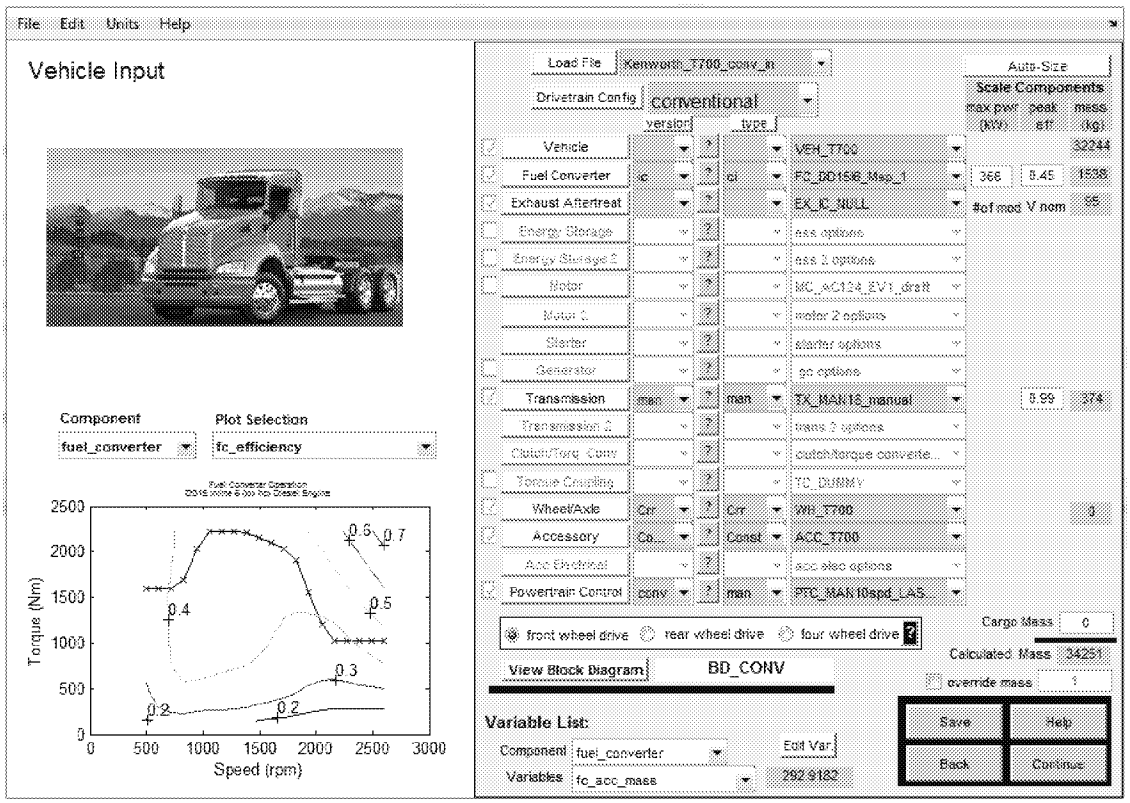

Figure C1. Screenshot of SwRI's VST User Interface

The advantage of using the VST's differentiation approach is that each vehicle variant that is simulated is forced to precisely run the cycle in the same manner, regardless of the vehicle configuration. An integration approach (like PSAT) must utilize a driver model to modulate the accelerator pedal and brakes to follow the cycle. Even though this approach can be more representative of a real driver's behavior, one cannot guarantee that every vehicle configuration will follow the drive cycle in precisely the same way. When small variations in vehicle or powertrain parameters need to be evaluated, which is the case in this NHTSA program, a backwards looking approach is better suited for such simulation requirements. VST uses a backward looking algorithm. In addition, the execution of backward-looking representations can offer other benefits as well, such as an execution speed that is, at least, one order of magnitude faster than forward-looking representations. Since thousands of simulation runs were necessary to conduct this fuel economy study, SwRI chose to use VST for all configurations and analyses described in this report.

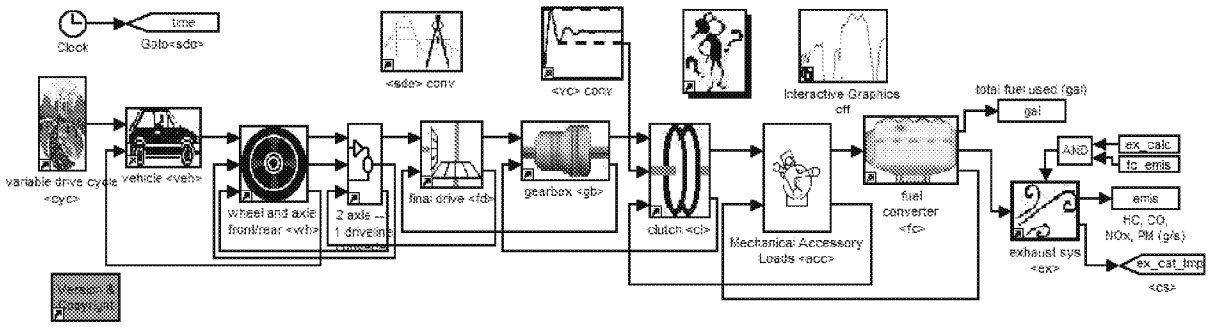

Figure C2. Top-Level Simulink Diagram of the Vehicle Model

SwRI's VST tool incorporates improvements to the original NREL component models, and enhanced functionalities in ways that allow the user to define each component of the vehicle. VST can simulate and post-process the results in an efficient and timely manner. Each component's set of parameters is defined in a MATLAB scripting format that is used in conjunction with a Simulink model shown in Figure C2 above.

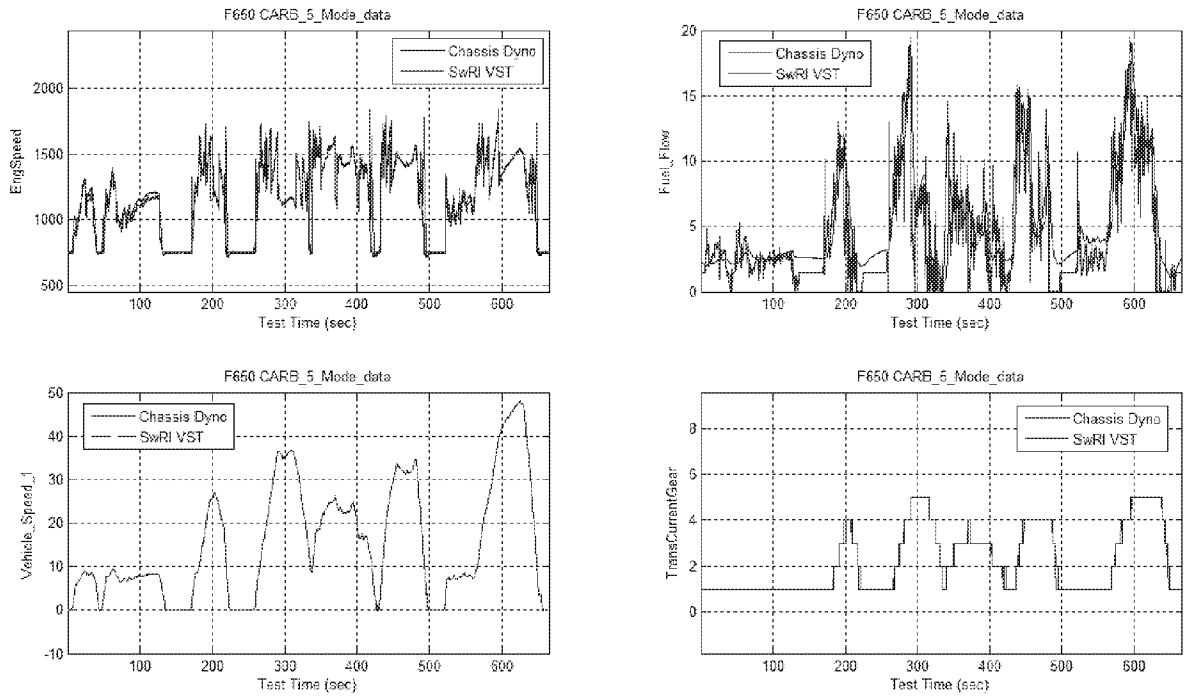

Figure C3. Validation of SwRI's VST Simulation Tool against Chassis Dyno Data for a Representative Vehicle Similar to one of the Vehicles Evaluated in this Study

SwRI's VehSim tool was validated against available chassis dynamometer test data as shown in Figure C3. These results are for the baseline Ram pickup truck with the diesel engine.

The results showed good agreement in following the desired speed trace and transmission shift schedule. As a result, the two engine speed traces are also very similar. The fuel flow trace on the upper right of the figure shows much more fluctuation for the simulation than for the chassis dyno test, but this result is misleading. The chassis dyno fuel flow results are effectively low pass filtered (smoothed) by the fuel flow measurement system. The total quantity of fuel used for fuel economy computations, however, was measured by separate, more accurate volumetric means.

As part of this study, SwRI performed minor custom modifications to the simulation tool in order to accommodate some specific requirements for this study. The most significant modification was the introduction of an adaptive driving cycle algorithm to guarantee that the vehicle drives the same distance regardless of the severity in road grade and powertrain limitations. This was particularly important when assessing the fuel economy of the vehicle on the NESCCCAF cycles with grade. An example of results from the resulting algorithm (see Figure C4) shows the original and the adapted cycle traces. The drive cycle includes periods of 3% grade from around 2900 seconds to 3800 seconds. Because the vehicle does not have enough power to maintain speed on the 3% grade, the actual speed falls short of the target. The algorithm automatically compensates by adding additional time to ensure that the vehicle covers the same distance, regardless of the speed achieved.

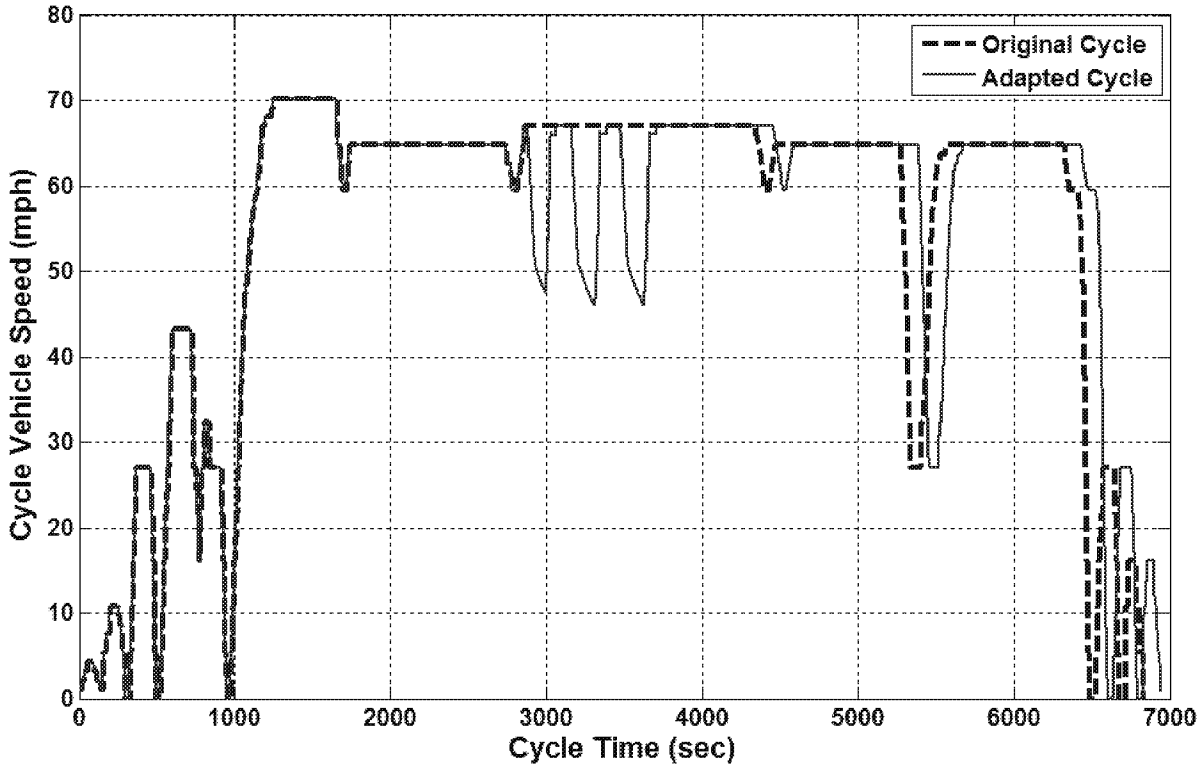

Figure C4. Resulting Cycle from SwRI's New Adaptive Algorithm

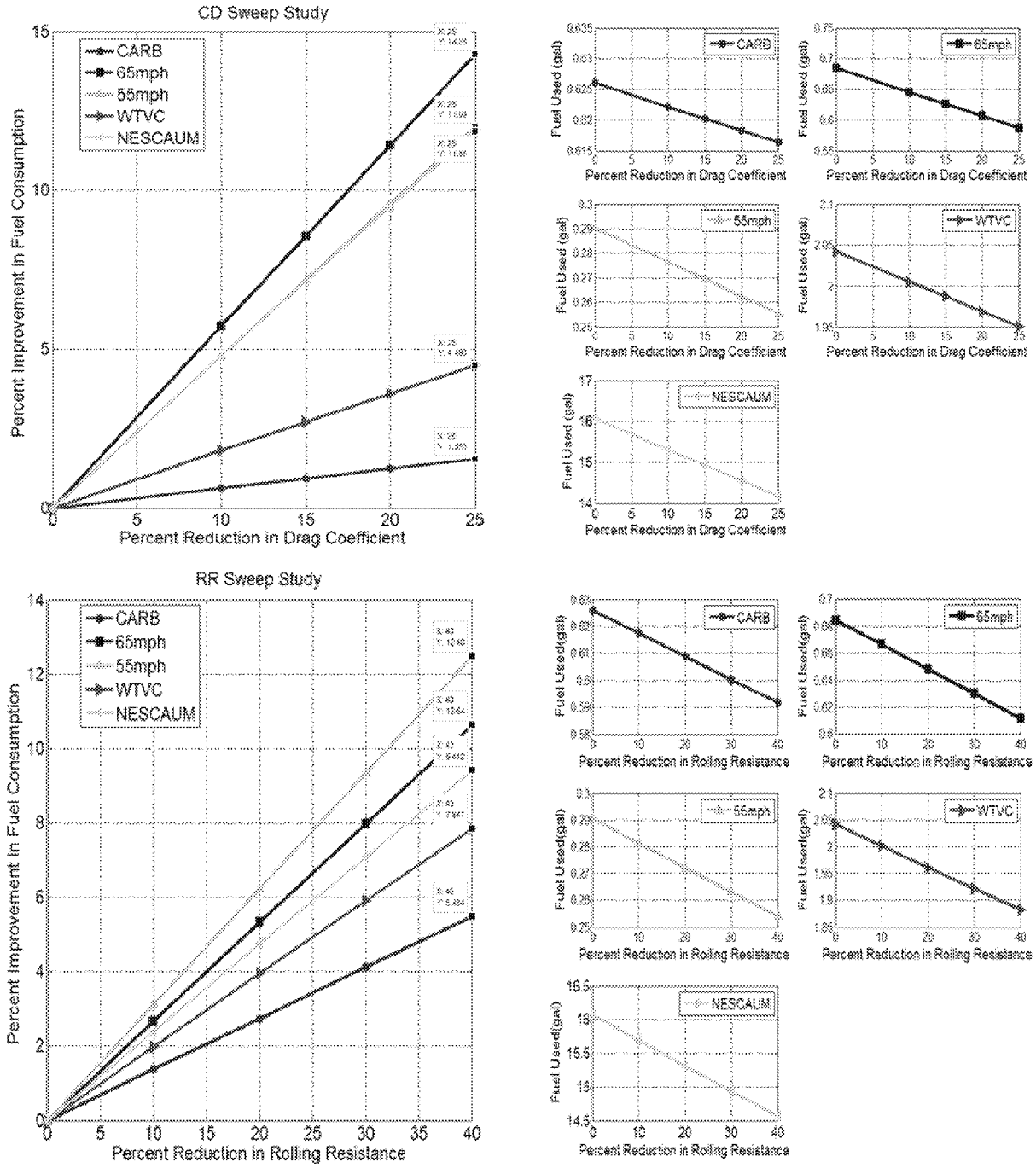

Figure C5. Special Parameter Sweep Studies on the Kenworth T-700 Tractor-Trailer Truck

Finally, some special analyses involving parameter sweeps for selected vehicles were conducted, as shown by the examples above. Figure C5 shows the effect of sweeping aerodynamic drag (Cd) and tire rolling resistance (Crr) over a range of values. These particular parameters produce results which are very linear.

C1.2 Baseline Vehicle Models

This section provides the baseline input parameters that are used for each of the four vehicle models that are covered in this report.

C1.2.1 Ram Pickup

Table C.1. shows the baseline vehicle simulation input parameters of the Ram Pickup model. This model is used to represent Class 2b and 3 vehicles. Note that axle efficiencies are listed in Table C.11.

Table C.1. Input parameters for the Dodge Ram Pickup Truck Model.

	Component	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6
Basic Parameters	**Vehicle Name**	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM	Dodge RAM
	Vehicle Type	Class 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck	CL 2b/3 Truck
	Engine	Baseline 6.7L I6	Diesel 4-Cylinder	Baseline 6.7L I6	Gasoline 3.5L V6	Gasoline 3.5L V6 Downsped	Gasoline 6.2L V8
	Transmission	6-Speed Auto	6-Speed Auto	8-Speed Auto	6-Speed Auto	6-Speed Auto	6-Speed Auto
	Transmission Controller	6-Speed Auto Diesel Schedule	6-Speed Auto 4-Cylinder Diesel Schedule	8-Speed Auto Diesel Schedule	6-Speed Auto Gasoline Schedule	6-Speed Auto Downsped Gasoline Schedule	6-Speed Auto Gasoline Schedule
	Engine/ Transmission Coupling	Torque Converter (stall speed of 2,800 rpm)	Torque Converter (stall speed of 2,420 rpm)	Torque Converter (stall speed of 2,800 rpm)	Torque Converter (stall speed of 2,325 rpm)	Torque Converter (stall speed of 2,090 rpm)	Torque Converter (stall speed of 2,450 rpm)
	Engine RPM (Top Gear at 65 mph)	1,592	1,820	1,595	2,500	2,000	2,500
	Final Drive	3.42:1	3.91:1	3.21:1	5.37:1	4.27:1	5.37:1
	Wheel Radius	0.3726	0.3726	0.3726	0.3726	0.3726	0.3726

C1.2.2 Ford F-650 Tow Truck

Table C.2. provides the baseline input parameters for the Ford F-650 roll-on tow truck. This Class 6 model is one of two trucks used to represent medium-duty vocational vehicles.

Table C.2. Input parameters for the F-650 tow truck model.

	Component	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4	Vehicle 5	Vehicle 6	Vehicle 7
Basic Parameters	**Veh. Name**	F650	F650	F650	F650	F650	F650	F650
	Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
	Engine	Baseline 6.7L I6	Baseline 6.7L I6	Baseline 6.7L I6	Baseline 6.7L I6	Gas 3.5L V6	Gas 3.5L V6 Down sped	Gas 6.2L V8
	Transmission	5-Speed Auto	6-Speed AMT	10-Speed AMT	8-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
	Transmission Controller	5-Speed Auto Diesel Schedule	6-Speed AMT Diesel Sched	10-Speed AMT Diesel Sched	8-Speed Auto Diesel Sched	5-Speed Auto Gas Sched	5-Speed Auto Down sped Gas Sched	5-Speed Auto Gas Sched
	Engine / Transmission Coupling	Torque Converter (stall speed of 2,560 rpm)	Clutch	Clutch	Torque Conv (stall speed of 2,560 rpm)	Torque Conv (stall speed of 2,330 rpm)	Torque Conv (stall speed of 2,090 rpm)	Torque Conv (stall speed of 2,445 rpm)
	Engine RPM (Top Gear at 65 mph)	2,073	2,072	2,072	2,073	3,300	2,576	3,300
	Final Drive	4.33:1	3.08:1	4.22:1	4.62:1	6.89:1	5.38:1	6.89:1
	Wheel Radius	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125	0.4125

C1.2.3 Kenworth T-270 Box Delivery Truck

The baseline input parameters for the Kenworth T-270 box delivery truck are given in Table C.3 below. This Class 6 model is one of two trucks used to represent the medium-duty vocational vehicle segment.

Table C.3. Input parameters for the T-270 box truck model.

	Component	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7
Basic Parameters	**Veh. Name**	T270	T270	T270	T270	T270	T270	T270
	Vehicle Type	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck	Class 6 Truck
	Engine	Baseline 6.7L I6	Baseline 6.7L I6	Baseline 6.7L I6	Baseline 6.7L I6	Gasoline 3.5L V6	Gasoline 3.5L V6 Down sped	Gasoline 6.2L V8
	Transmission	5-Speed Auto	6-Speed AMT	10-Speed AMT	8-Speed Auto	5-Speed Auto	5-Speed Auto	5-Speed Auto
	Transmission Controller	5-Speed Auto Diesel Schedule	6-Speed AMT Diesel Sched	10-Speed AMT Diesel Sched	8-Speed Auto Diesel Sched	5-Speed Auto Gas Sched	5-Speed Auto Down sped Gas Sched	5-Speed Auto Gas Sched
	Engine/ Transmission Coupling	Torque Converter (stall speed of 2,560 rpm)	Clutch	Clutch	Torque Conv (stall speed of 2,560 rpm)	Torque Conv (stall speed of 2,330 rpm)	Torque Conv (stall speed of 2,090 rpm)	Torque Conv (stall speed of 2445 rpm)
	Engine RPM (Top Gear at 65 mph)	2,071	2,068	1,514	2,070	3,300	2,937	3,300
	Final Drive	5.29:1	3.76:1	3.76:1	5.64:1	8.42:1	7.5:1	8.42:1
	Wheel Radius	0.5044	0.5044	0.5044	0.5044	0.5044	0.5044	0.5044

C1.2.4 Kenworth T-700 Tractor-Trailer Truck

The Kenworth T-700 is used to represent long-haul high-roof sleeper tractor-trailer combination trucks. The baseline vehicle simulation input parameters are provided in Table C.4 below.

Table C.4. Input parameters for the T-700 tractor-trailer model.

	Component	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7
Basic Parameters	Vehicle Name	T700	T700	T700	T700	T700	T700	T700
	Vehicle Type	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer	Class 8 Tractor-Trailer
	Engine	Baseline DD15	Down-spd A	Down-spd B	5-Cyl	Baseline DD15	Baseline DD15	Baseline DD15
	Trans-mission	10-Speed AMT	10-Speed AMT	10-Speed AMT	10-Speed AMT	18-Speed AMT	10-Speed Manual	10-Speed 6x2
	Transm Control	10-Speed AMT Shift Sched	10-Speed AMT Down-spd A Sched	10-Speed AMT Down-spd B Sched	10-Speed AMT Sched	18-Speed AMT Sched	10-Speed Manual Sched	10-Speed AMT Sched
	Engine/ Transm. Coupling	Clutch	Clutch	Clutch	Clutch	Clutch	Clutch	Clutch
	Engine RPM (Top Gear at 65 mph)	1,368	1,209	1,050	1,368	1,368	1,368	1,368
	Final Drive	3.36:1	2.97:1	2.58:1	3.36:1	3.36:1	3.36:1	3.36:1
	Wheel Radius	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975

C1.3 Vehicle Drive Cycles

A total of eleven vehicle drive cycles were used in the study. Each cycle is described in this section. The NESCCAF cycle was developed to represent a typical line haul type of operation. There are brief urban/suburban sections at the beginning and end of the cycle, to represent getting out to the highway. The main portion of the cycle consists of five cruise segments at speeds of 65 to 70 MPH. One of the cruise segments has an alternating +/- 1% grade, and a second cruise segment has an alternating +/- 3% grade. The NESCCAF cycle is the only cycle that includes grades. Because tractor-trailer trucks cannot normally maintain cruise speed on a 3% grade, the cycle was given a feature that extended the drive time to force the vehicle to complete the required distance. Figure C6 shows the speed vs. time trace, and Figure C7 shows the grade vs. time trace. This cycle was only used for tractor-trailer trucks.

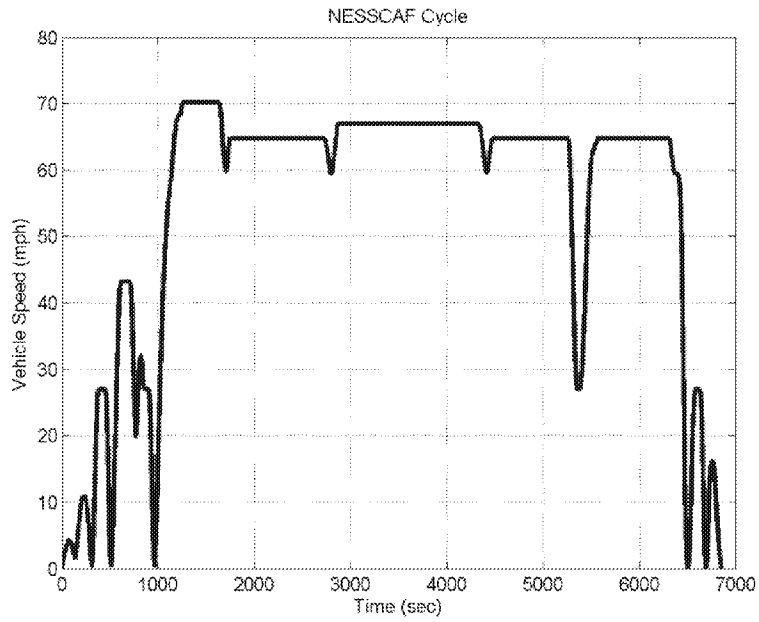

Figure C6. Speed vs. time trace for the NESCCAF cycle.

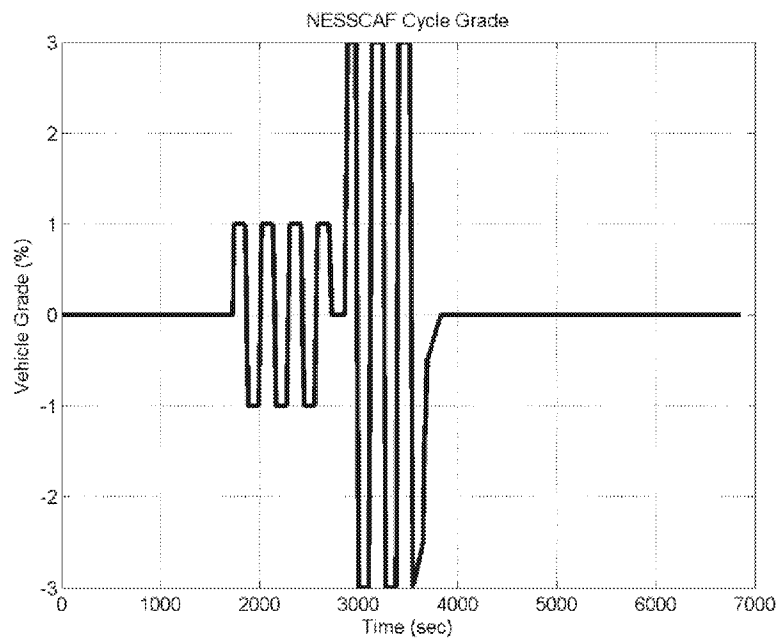

Figure C7. Grade vs. time trace for the NESCCAF cycle.

Figure C8 shows the World Harmonized Vehicle Cycle. This cycle is intended for medium and heavy-duty trucks, and includes urban, suburban, and highway segments. The cycle assumes that a road speed governor is used to limit speed to about 53 MPH, which is required in Europe. The WHVC was used for all vehicles, to provide a way to compare results across different vehicle types.

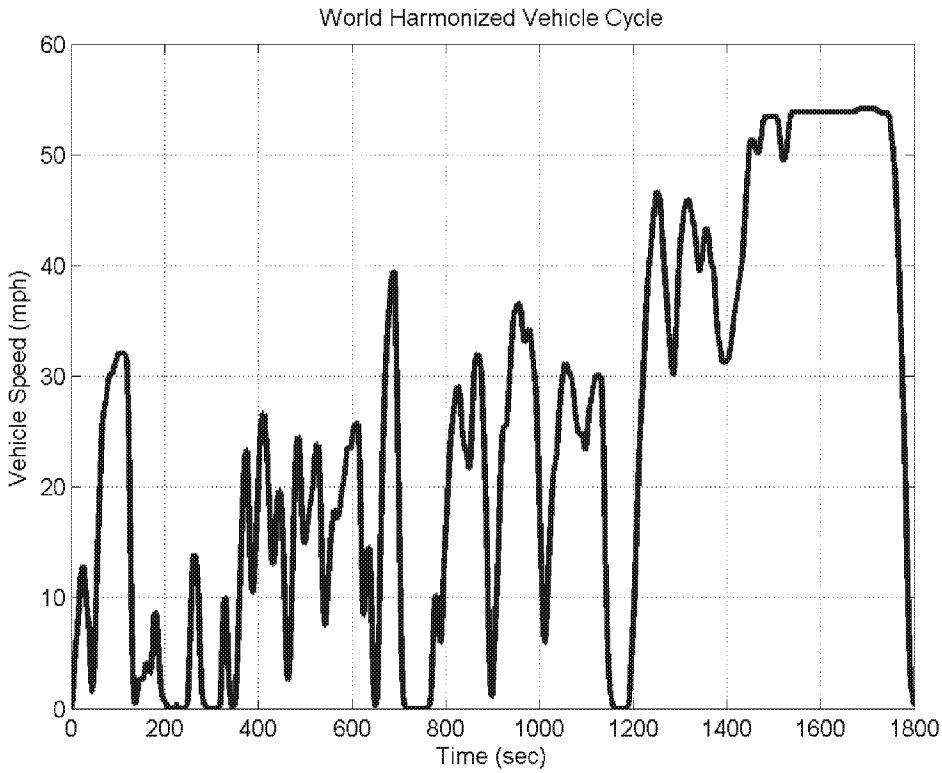

Figure C8. World Harmonized Vehicle Cycle (WHVC)

The FTP-Highway cycle shown in Figure C9 has been used for many years to evaluate light duty vehicle fuel economy. This cycle was developed in the time of the 55 MPH speed limit, so speeds are low compared to typical modern highway driving, and accelerations are gentle. This cycle was only used for the pickup truck.

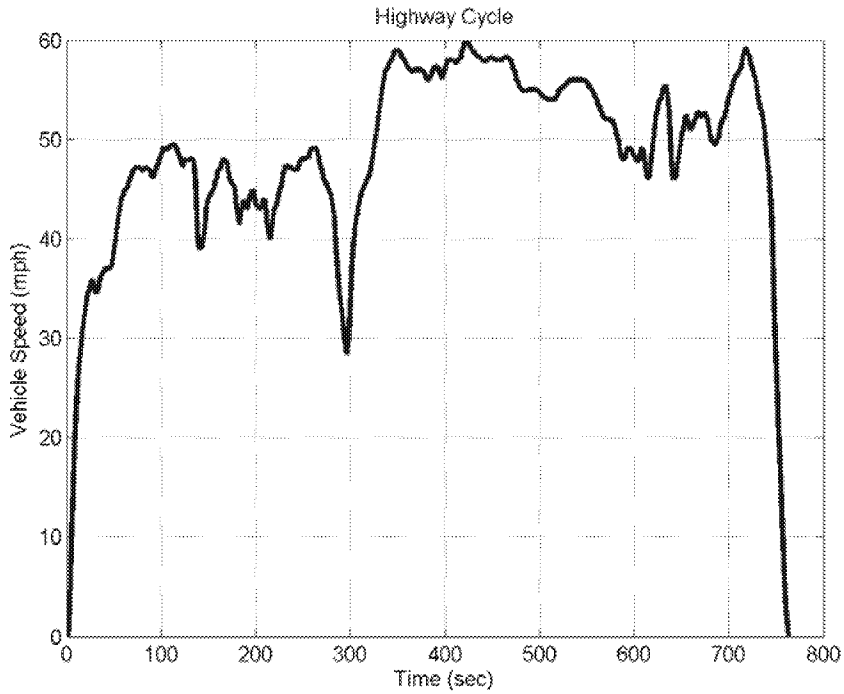

Figure C9. FTP-Highway drive cycle.

The FTP-City cycle shown in Figure C10 has been used for many years to evaluate light duty vehicle fuel economy. The cycle uses relatively gentle accelerations compared to what is found in typical city driving. This cycle was only used for the pickup truck.

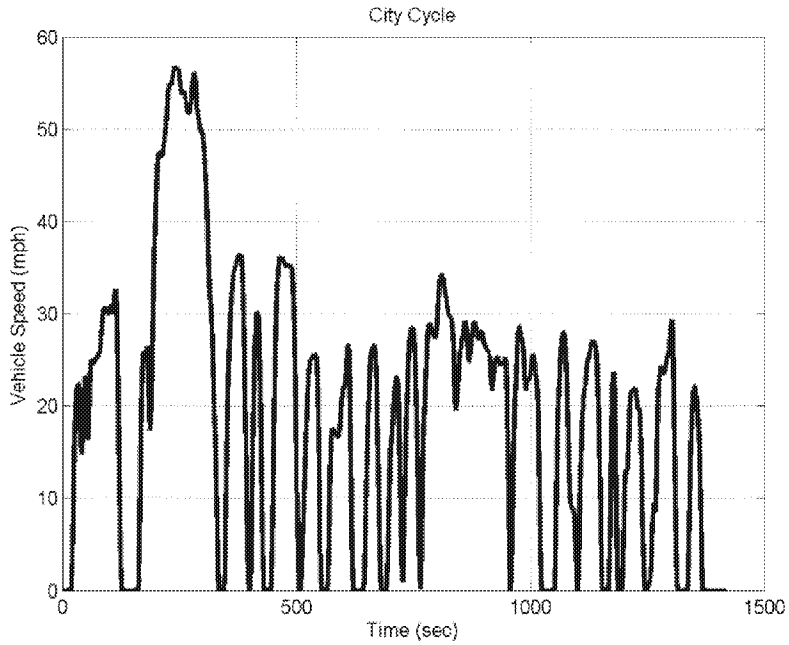

Figure C10. FTP-City drive cycle.

The CARB urban cycle shown in Figure C11 is used in the GEM regulatory model for medium and heavy-duty vehicles. This cycle simulates urban driving for trucks. The CARB cycle was used for all vehicles simulated, except the pickup truck.

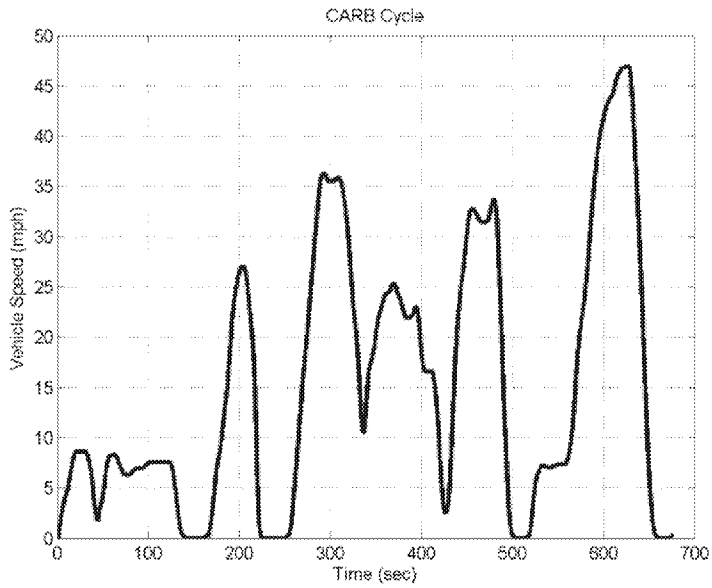

Figure C11. CARB urban truck driving cycle.

The US06 cycle shown in Figure C12 is an aggressive drive cycle for light duty vehicles. It was introduced to help compensate for the overly optimistic fuel economy values generated by the older FTP city and highway cycles. This cycle was only used for the pickup truck.

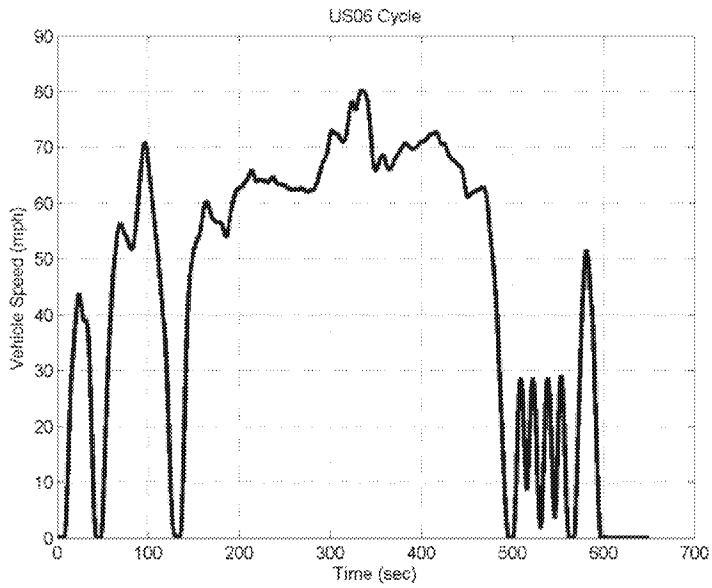

Figure C12. US06 aggressive light duty drive cycle

The SC03 cycle shown in Figure C13 was developed to evaluate the effect of air conditioner use in hot conditions on fuel economy. In this study, the air conditioner was run on all drive cycles, which is not the standard approach. This cycle was used only with the pickup truck.

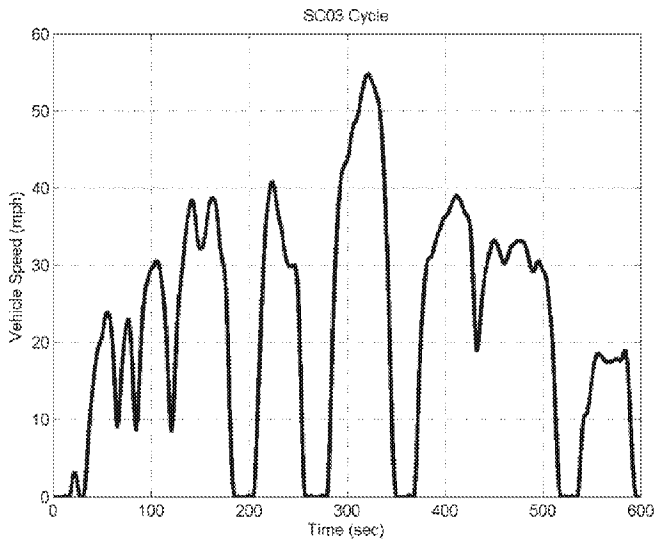

Figure C13. SC03 air conditioner drive cycle

The Parcel cycle shown in Figure C14 was developed to model the drive cycle of a parcel delivery truck. About 50% of the drive cycle time is at idle. This causes fuel consumption at idle to be significant, especially with an automatic, where the torque converter load is significant. The Parcel cycle was only used for the T270 and F-650 medium trucks.

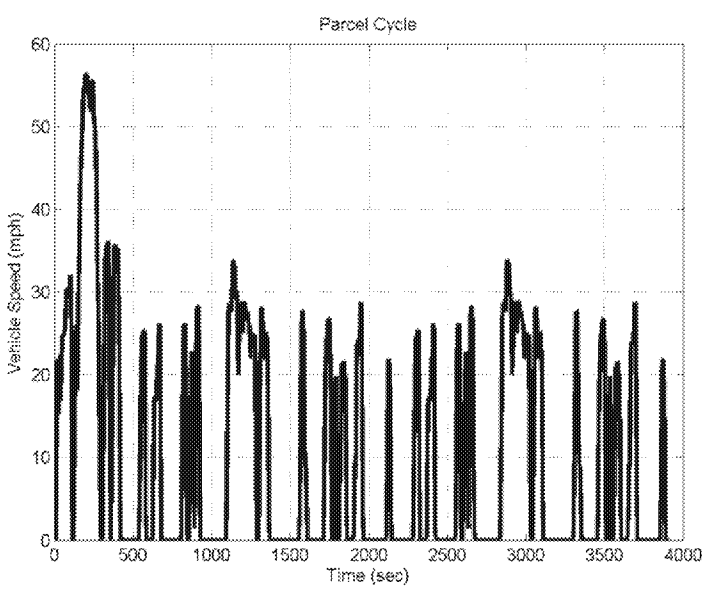

Figure C14. Parcel delivery drive cycle

The Combined International Local and Commuter Cycle (CILCC) shown in Figure C15 was developed to simulate urban driving. The general approach, with steady, very gentle accelerations, steady speed operation, and then gradual deceleration, is similar to the European NEDC cycle. This cycle results in very light loads on the engine. The CILCC cycle was only used for the T270 and F-650 medium trucks.

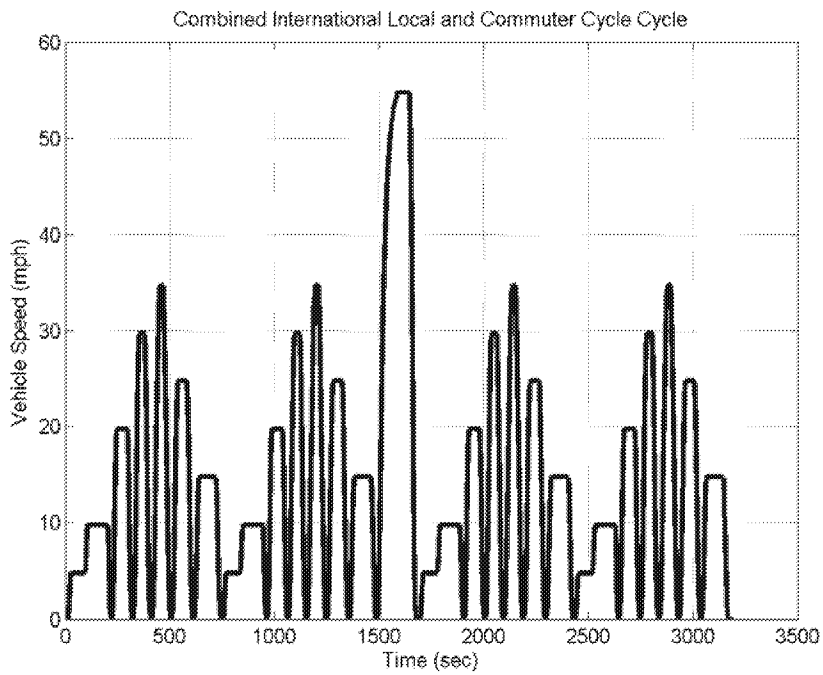

Figure C15. Combined International Local and Commuter drive cycle (CILCC)

There are two remaining drive cycles that were used: the 55 MPH and 65 MPH cruise cycles. These cycles are strictly steady state, with no grades or other changes in load, so they effectively only operate the engine at one speed/load point. These two cycles are part of the GEM vehicle certification model. The 65 MPH cruise was used for all vehicles in the study, while the 55 MPH cycle was used for all vehicles except the pickup truck.

C2. Vehicle Technologies

C2.1 Reduced Air Conditioner Power Demand

Accessory power demand is one of the contributors to overall vehicle power demand. Accessories can be defined as power absorbing devices that are not necessary to run the engine. These include the alternator, power steering pump, and air conditioner. In this report, devices that are required in order to run the engine, such as the water pump, oil pump, and fuel pump, are treated as part of the engine friction. As a representative accessory power demand reduction, the air conditioner system was evaluated. The air conditioner is operating on all vehicles during all drive cycles that are covered in this report. The power demand of the air conditioner system (including compressor, evaporator fan, and condenser fan) was modeled as 1,500 watts. This is a typical power demand for steady-state operation in a hot (90 to 95F) environment

An improved air conditioner system can incorporate features such as a more efficient compressor (such as a scroll design), the use of less reheat, or the use of additional cab insulation. For this project, a reduction in air conditioner demand of 40% was simulated, from a baseline of 1,500 watts to 900 watts. No specific technology approaches were considered, so the only effect on the vehicle is the reduction in power demand.

For all other accessory loads, assumptions were made for the average power demand. The assumptions are listed below Tables C.5 – C.7.

Table C.5 Dodge Ram accessory power demands.

Dodge RAM	air cond pwr	other mech_pwr[1]	acc_mech_pwr
base	1500	2950	**4450**
scale factor	60%	100%	**60%**
offset	0.00	0.00	**0**
number of variations	2	1	**2**
Min(Value)	900	2950	**3850**
Max(Value)	1500	2950	**4450**
Increment Value	600	0	**600**
Variant 1	900	2950	**3850**
Variant 2	1500	-	**4450**
Variant 3	-	-	-
Units	W	W	W

[1] Assumptions: Cooling fan = 1 kW, Alternator = 1 kW, Vacuum Pump = 250 W, Power Steering = 700W

In the drive cycle simulation runs, these average power demands were continuously applied during the entire cycle, including at idle. In practice, many of these loads are quite variable, and may be engine speed and ambient temperature dependent. Because no detailed data for actual accessory power demands on each vehicle was available, SwRI made engineering assumptions for average power demand levels.

Table C.6 F-650 and T-270 accessory power demands.

Ford F650/KW T270	air cond pwr	other mech_pwr[2]	acc_mech_pwr
base	1500	4250	**5750**
scale factor	60%	100%	**60%**
offset	0.00	0.00	**0**
number of variations (max of 3)	2	1	**2**
Min(Value)	900	4250	**5150**
Max(Value)	1500	4250	**5750**
Increment Value	600	0	**600**
Variant 1	900	4250	**5150**
Variant 2	1500	999	**5750**
Variant 3	999	999	**999**
Units	**W**	**W**	**W**

[2] Assumptions: Cooling fan = 2 kW, Alternator = 1 kW, Vacuum Pump = 250 W, Power Steering = 1 kW

Table C.7 T-700 accessory power demands.

KW T700	air cond pwr	other mech_pwr[3]	acc_mech_pwr
base	1500	5150	**6650**
scale factor	60%	100%	**60%**
offset	0.00	0.00	**0**
number of variations (max of 3)	2	1	**2**
Min(Value)	900	5150	**6050**
Max(Value)	1500	5150	**6650**
Increment Value	600	0	**600**
Variant 1	900	5150	**6050**
Variant 2	1500	999	**6650**
Variant 3	999	999	**999**
Units	**W**	**W**	**W**

[3] Assumptions: Cooling fan = 2 kW, Alternator = 1.25 kW, No Vacuum Pump, Power Steering = 1.25 kW, Air Compressor = 650 W

C2.2 Reduced Aerodynamic Drag (Cd)

Aerodynamic drag can be a substantial contributor to overall vehicle power demand, particularly at higher road speeds. Depending on the vehicle type, there is a range of potential for improvement in Cd. Table C.5 below shows the baseline Cd values and potential Cd improvements for each vehicle type. Results shown in Section 5.3.2.2 show that fuel consumption improvements are very linear with changes in Cd value. Therefore, the reader can interpolate or extrapolate from the benefits shown in Section 5 on any vehicle, using any given level of Cd improvement

In this study, changes in Cd are not associated with any specific hardware changes to the vehicle. For the purposes of the study, it was assumed that the OEM would select a hardware set that provides the specified Cd reduction.

Table C.8. Aerodynamic drag baseline values and reductions for each vehicle type.

Vehicle	Drag Coefficient Information					
	Baseline Cd	Baseline CdA	Reduced Cd	Reduced CdA	Cd w/ Trailer	Cd Reduced w/ Trailer
Dodge RAM	0.400	1.505	0.36 (10%)	1.354 (10%)	0.560	0.504(10%)
Ford F650	0.619	3.151	0.557 (10%)	2.836 (10%)	--	--
KW T270	0.514	5.033	0.437 (15%)	4.278 (15%)	--	--
KW T700	--	6.481	--	4.861 (25%)	0.639	0.479 (25%)

C2.3 Reduced Tire Rolling Resistance (Crr)

Tire rolling resistance is a major contributor to overall vehicle power demand. For all of the vehicles involved in this study, a 30% reduction in tire rolling resistance was assumed. The specific tire features required to obtain this change in rolling resistance, and any trade-offs with other aspects of tire performance, were not considered. As shown in Section 5.3.2.3, the fuel consumption benefit of a reduction in Crr is very linear. As a result, the reader can interpolate or extrapolate from the benefits shown in Section 5 on any vehicle, using any given level of Crr improvement or increase.

The tire rolling resistance data used for all vehicle simulations comes from coastdown testing. In coastdown tests, there is no way to separate tire rolling resistance from driveline friction (transmission output shaft, driveshaft and axle). Axle efficiency test data was used to quantify the contribution from axle friction, while engineering judgment was used to split the remaining rolling resistance between tires (96%) and the transmission output and driveshaft

(4%). The coastdown testing was run on tires that were broken in but near the full tread depth. Lab data on the tires used in the coastdown testing is not available.

For the tractor-trailer vehicle, separate Crr values were used for the steer tires, drive tires, and trailer tires. For the medium-duty trucks, a single Crr value was used for the steer and drive tires. When the simulation models were run, only the average Crr value was used, so the effect of weight distribution at different payloads was not taken into account. These Crr values came from truck coastdown test runs and were divided between steer, drive, and trailer values using engineering judgment, so they will not match with values required by any particular standard, such as SmartWay or the 2014 GHG standards. Table C.9 provides the baseline Crr values and the improvement assumptions for each vehicle type. The Crr values for each vehicle were obtained from coast-down test results.

Table C.9. Tire rolling resistance baseline values and reductions for each vehicle type.

Vehicle	Rolling Resistance				
	Baseline				Reduced
	Steer	Drive	Trailer	Average	
Dodge RAM	N/A	N/A	N/A	0.007800	0.054600
Ford F650	N/A	N/A	N/A	0.010068	0.007047
KW T270	N/A	N/A	N/A	0.010967	0.007677
KW T700	0.00535	0.00650	0.00482	0.005608	0.003926

Table C.10 below shows the effect of payload on the distribution of tire load and rolling resistance for a tractor-trailer truck. The average Crr value shown in Table C.9 was calculated at 50% payload.

Table C.10. Effect of payload on weight and rolling resistance distribution.

Description	Steer Axle Weight, lb	Drive Tandem Weight, lb	Trailer Tandem Weight, lb
0% Payload case, Total vehicle weight 33960 lb.			
Load distribution of empty tractor-trailer*	11000	15460	7500
% weight carried by axle or tandem	32%	46%	22%
Jan 2015 SmartWay thresholds for Crr tires, kg/T (ISO 25850)	6.5	6.6	5.1
Rolling resistance contribution of axle to Crr(veh), kg/T	2.11	3.00	1.13
Total effective vehicle rolling resistance coefficient, Crr(veh), kg/T		6.24	
% Contribution of axle, tandem to total effective vehicle Crr(veh)	34%	48%	18%
100% Payload case, Total vehicle weight 80000 lb.			
Load distribution of 46040-lb payload tractor-trailer	12000	34000	34000
% weight carried by axle or tandem	15%	43%	43%
Jan 2015 SmartWay thresholds for Crr tires, kg/T (ISO 25850)	6.5	6.6	5.1
Rolling resistance contribution of axle to Crr(veh), kg/T	0.98	2.81	2.17
Total effective vehicle rolling resistance coefficient, Crr(veh), kg/T		5.95	
% Contribution of axle, tandem to total effective vehicle Crr(veh)	16%	47%	36%
* Assuming steer axle weight does not vary greatly due to engine weight on axle.			

C2.4 Weight Reduction

Vehicle mass (weight) has two effects. First, it takes energy to accelerate the vehicle mass up to a desired speed. The energy put into accelerating the vehicle is largely lost as brake heat when the vehicle slows down. The second consequence of vehicle mass is that rolling resistance is proportional to mass. If vehicle mass can be reduced, less power is required to accelerate the mass, and less power is required to overcome rolling resistance. Mass reduction can be achieved in a number of ways, including:

- Material substitution, such as replacing steel with aluminum or a composite
- Design changes to eliminate mass that is not required to achieve the target capability and durability

Unfortunately, many fuel saving, emissions, and safety technologies add mass. Maintaining a given truck empty weight takes a consistent weight reduction effort to offset new features that added for both regulatory and vehicle performance reasons.

The effect of vehicle mass on light duty vehicle fuel efficiency is significant. Large fuel economy benefits can be obtained by reducing light duty vehicle mass. Considered from the point of view of freight efficiency, light duty vehicles are extremely inefficient. A 4,000 pound light duty vehicle transporting a 200 pound person has a "cargo" constituting less than 5% of the

total vehicle mass. If the empty weight of our example light duty vehicle is reduced 10% (400 pounds), the total mass of vehicle plus cargo is reduced by 9.5%. Heavy duty trucks, on the other hand, may have a cargo mass greater than that of the vehicle. Take for example a tractor-trailer with an empty weight of 34,000 pounds and a loaded weight of 80,000 pounds. If the empty weight is reduced by 10%, the total mass of truck + cargo is reduced by only 4.25%, half as much as in our light duty example.

Table C.11 shows the empty weights and payload weights for each vehicle in the project. The specific technologies or features added to achieve the weight reduction were not specified. The assumption was made that the OEM would provide a set of changes required to achieve the target weight reduction. The following weight reductions were applied to each vehicle to evaluate the effect of a reduction in empty weight:

Vehicle	Weight Reductions
Ram Pickup	500 Pounds
F-650 Tow Truck	1100 Pounds
T-270 Box Truck	1100 Pounds
T-700 Tractor-Trailer	2200 Pounds, 4400 Pounds

These weight reductions were applied to the tare weights shown in Table C.11 below.

Table C.11. Vehicle empty weights and payloads used in simulations. "Tare" weight is equivalent to "curb weight".

Weights in Pounds	RAM diesel			RAM gasoline		
	Tare	Payload	Total	Tare	Payload	Total
0% payload	6876	0	6876	6376	0	6376
ALVW	6876	1562	8438	6376	1562	7938
100% GCW	6876	18124	25000	6376	18124	24500

Weights in Pounds	F650 diesel			F650 gasoline		
	Tare	Payload	Total	Tare	Payload	Total
0% payload	15640	0	15640	15139	0	15139
50% payload	15640	3180	18820	15139	3180	18319
100% payload	15640	6360	21999	15139	6360	21499

Weights in Pounds	T270 diesel			T270 gasoline		
	Tare	Payload	Total	Tare	Payload	Total
0% payload	17141	0	17141	16640	0	16640
50% payload	17141	4430	21571	16640	4430	21070
100% payload	17141	8860	26001	16640	8860	25500

Weights in Pounds	T700 diesel		
	Tare	Payload	Total
0% payload	33960	0	33960
50% payload	33960	23020	56980
100% payload	33960	46039	79999

The percentage of fuel consumption reduction that is provided by a given percent weight reduction is a function of several parameters:

- Drive cycle
- Coefficient of rolling resistance
- Vehicle payload

A given percent weight reduction will provide a larger percent fuel savings on a drive cycle with frequent stops and starts. This is because inertia loads represent a higher portion of the total power demand on a highly transient cycle. If the coefficient of rolling resistance is high, there will be a larger benefit from a weight reduction, since rolling resistance will be a larger portion of overall power demand. As the payload increases, a given percentage weight reduction on the empty vehicle becomes a smaller percentage of the test weight, so the percent fuel savings decreases. Refer to the results in Section 3 to see how percentage weight reductions translate into different fuel savings for the four vehicles, over a range of drive cycles and payloads.

C2.5 Chassis Friction Reduction

Chassis friction includes losses in the axle, U-joints, and wheel bearings. An improvement in axle efficiency, for example, can lead to a reduction in overall chassis friction power demand. In this study, no effort was made to evaluate individual chassis friction technologies, except for the use of a 6X2 drive axle configuration in the tractor-trailer truck (See Section C2.6 below). Table C.12 shows the percentage of vehicle power demand accounted for by chassis friction at a steady speed of 65 MPH, along with the level of improvement that has been simulated for each vehicle type.

Table C.12. Chassis friction levels at 65 MPH, and friction reduction assumptions

Chassis Friction	Dodge RAM	Ford F650	KW T270	KW T700
Driveline Spin Losses (N/N)	0.000197	0.000488	0.000606	0.00023
Axle Loaded Torque Efficiency (%)	97.5	97.5	97.5	97.5
Driveline Spin Losses Reduction (%)	30%	30%	30%	20%

C2.6 6X2 Axle Configuration

One way to reduce chassis friction on a tractor-trailer truck is to reduce the number of drive axles from the standard value of two, down to one. A two drive axle configuration is referred to as a 6X4, while a single drive axle configuration is referred to as a 6X2. When two drive axles are used, there are two sets of spin losses that need to be overcome, rather than only one. Note that the single axle needs to have a higher torque capacity than the tandems, so it will typically have a higher spin loss than the rear axle in a tandem pair. Another source of losses in the tandem is that the front axle in a tandem needs to split the power between the two axles. This involves additional gear sets and oil seals, which are losses that do not occur with a single drive axle. In the tandem axle case, it is assumed that the input torque is split equally between the front and rear drive axles. The front drive axle is assumed to be 95% efficient while the rear is assumed to be 97.5% efficient. In the single drive axle case, all of the torque is transmitted to the wheels with an efficiency of 97.5%.

The single drive axle has a downside: reduced traction. The standard legal weight limit on a tandem axle set is 34,000 pounds, and the limit for a single axle in a tandem pair is 17,000 pounds. So, for a fully loaded tractor trailer at 80,000 pounds, there is only 17,000 pounds, or 21.25% of the total vehicle weight, on the drive axle of a 6X2 configuration. This can lead to problems in low friction environment surfaces, such as snow, ice, sand, or even wet pavement. Trucks that need to go off-road, or which frequently operate in snow and ice, are not good candidates for a 6X2 configuration. One way to deal with the traction issue is to use the air suspension to temporarily lift the non-driven axle in situations where traction becomes a problem.

In this project, the 6X2 configuration is compared to the standard 6X4 configuration on the Kenworth T-700 tractor-trailer truck.

C2.7 Road Speed Governor (Reduced V_{max})

Road speed governors are widely used by large truck fleets as a fuel saving technology. The governor limits the road speed to a value set by the owner. Road speed governors can also be used to gain credits under the GEM model, but in this case the governor has to be set at the factory either permanently or for a defined number of miles, and cannot be changed by the owner.

In this study, road speed governors were evaluated only on the Kenworth T-700 tractor-trailer. Results can be found in Section 5.3.2.7.

C2.8 Transmission Alternatives

A wide range of transmissions have been evaluated in this program. Section C1.2 shows which transmissions were evaluated in each vehicle model. This section describes the individual transmissions in detail.

Table C.13 Transmission Parameter Tables for All Vehicle Configurations

	Dodge RAM	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6
Transmission Parameters	Num of Gears	6	6	8	6	6	6
	1	3.231	3.231	4.696	3.231	3.231	3.231
	2	1.837	1.837	3.130	1.837	1.837	1.837
	3	1.410	1.410	2.104	1.410	1.410	1.410
	4	1.000	1.000	1.667	1.000	1.000	1.000
	5	0.816	0.816	1.285	0.816	0.816	0.816
	6	0.625	0.625	1.000	0.625	0.625	0.625
	7	-	-	0.839	-	-	-
	8	-	-	0.667	-	-	-
	TC Stall K Factor	9.35	9.35	9.35	11.55	8.74	11.55
	TC Stall Torque Ratio	1.74	1.74	1.74	2.16	1.7	2.16

	F650	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7
Transmission Parameters	Num of Gears	5	6	10	8	5	5	5
	1	3.102	9.01	12.796	4.696	3.102	3.102	3.102
	2	1.8107	5.27	9.251	3.13	1.8107	1.8107	1.8107
	3	1.406	3.220	6.761	2.104	1.406	1.406	1.406
	4	1.000	2.040	4.901	1.667	1.000	1.000	1.000
	5	0.7117	1.36	3.579	1.285	0.7117	0.7117	0.7117
	6		1.000	2.611	1.000	-	-	-
	7	-	-	1.888	0.839	-	-	-
	8	-	-	1.38	0.667	-	-	-
	9	-	-	1	-	-	-	-
	10	-	-	0.73	-	-	-	-
	TC Stall K Factor	10.26	-	-	10.26	11.55	8.74	11.55
	TC Stall Torque Ratio	2.71	-	-	2.71	2.16	1.70	2.16

	T270	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7
Transmission Parameters	Num of Gears	5	6	10	8	5	5	5
	1	3.102	9.01	12.796	4.696	3.102	3.102	3.102
	2	1.8107	5.27	9.251	3.13	1.8107	1.8107	1.8107
	3	1.406	3.220	6.761	2.104	1.406	1.406	1.406
	4	1.000	2.040	4.901	1.667	1.000	1.000	1.000
	5	0.7117	1.36	3.579	1.285	0.7117	0.7117	0.7117
	6	-	1.000	2.611	1.000	-	-	-
	7	-	-	1.888	0.839	-	-	-
	8	-	-	1.38	0.667	-	-	-
		-	-	1	-	-	-	-
		-	-	0.73	-	-	-	-
	TC Stall K Factor	10.26	-	-	10.26	11.55	8.74	11.55
	TC Stall Torque Ratio	2.71	-	-	2.71	2.16	1.70	2.16

	T700	Veh 1	Veh 2	Veh 3	Veh 4	Veh 5	Veh 6	Veh 7
Transmission Parameters	Num of Gears	10	10	10	10	18	10	10
	1	12.796	12.796	12.796	12.796	14.4	12.796	12.796
	2	9.251	9.251	9.251	9.251	12.29	9.251	9.251
	3	6.761	6.761	6.761	6.761	8.56	6.761	6.761
	4	4.901	4.901	4.901	4.901	7.300	4.901	4.901
	5	3.579	3.579	3.579	3.579	6.050	3.579	3.579
	6	2.611	2.611	2.611	2.611	5.16	2.611	2.611
	7	1.888	1.888	1.888	1.888	4.380	1.888	1.888
	8	1.38	1.38	1.38	1.38	3.74	1.38	1.38
	9	1	1	1	1	3.2	1	1
	10	0.73	0.73	0.73	0.73	2.73	0.73	0.73
	11	-	-	-	-	2.29	-	-
	12	-	-	-	-	1.95	-	-
	13	-	-	-	-	1.62	-	-
	14	-	-	-	-	1.38	-	-
	15	-	-	-	-	1.17	-	-
	16	-	-	-	-	1	-	-
	17	-	-	-	-	0.86	-	-
	18	-	-	-	-	0.73	-	-

C2.8.1 6-Speed, 10-Speed, and 18-Speed AMT Transmissions

The 6-speed and 10-speed AMT transmissions were evaluated as alternative transmissions in the medium duty applications (Kenworth T-270 and Ford F-650). The 10-speed AMT was the standard transmission in the long haul Kenworth T-700 tractor trailer truck. The 18-speed AMT was used as an alternative in the T-700. Proprietary SwRI test data was used to quantify the efficiency of each gear as a function of input torque. Eaton provided proprietary shift schedules for the 6- and 10-speed transmissions. SwRI modified these schedules slightly to achieve smooth transitions during the drive cycles – in other words, to avoid situations of excessive gear hunting. SwRI developed a shift schedule for the 18-speed transmission, based on the 10-speed schedule. Table C13 above details the gear ratios and other characteristics of these transmissions.

Table C13 above shows the transmission ratios for the 6-speed AMT transmission. The data can be found in the Veh 2 column for both the T-270 and F-650 portions of the table.

Table C13 above shows the transmission ratios for the 10-speed AMT transmission. The data can be found in the Veh 3 column for both the T-270 and F-650 portions of the table. The

same data is also shown for the T-700 tractor in every column *except* Vehicle 5. Table C13 above also shows the transmission ratios for the 18-speed AMT transmission in the T-700 section in the column Vehicle 5.

C2.8.2 10-Speed Manual Transmission

The 10-speed manual transmission is mechanically identical to the 10-Speed AMT. The only changes are the deletion of the automated shifting system, and the use of a shift map with increased upshift speeds to represent a more "typical" driver. SwRI does not have extensive vehicle data available, which would be required to develop a validated shift schedule. As a result, it was decided to increase upshift RPM by 200 RPM at full load as an approximation.

C2.8.3 Automatic Transmissions

A variety of torque converter automatic transmissions were used for the Ram pickup and the medium duty trucks (T-270 and F-650). The standard transmission for the pickup truck simulation model was the Aisin 6-speed automatic. This is the transmission used in the 2014 Ram with the 385 HP rating of the Cummins ISB engine. SwRI does not have access to factory efficiency data, torque converter match, and shift schedules, so SwRI used existing data and engineering judgment to develop the required parameters. Alternative torque converter matches were developed for the 3.5 liter V-6 and 6.2 liter V-8 gasoline engines. Table C13 provides data on the 6-speed Aisin transmission.

Table C13 above shows the transmission ratios for the 6-speed torque converter automatic transmission in the Dodge Ram section in all columns *except* Vehicle 3.

For the T-270 and F-650 medium-duty trucks, the standard transmission is a 5-speed Allison 2000 Series. This is actually a 6-speed box, but for many applications, 6th gear is not used. The explanation for this is that 6th gear is a tall overdrive ratio, which causes the driveshaft speed to be well above engine speed. High driveshaft speeds lead to two potential problems. One issue is that the driveshaft length must be limited, in order to avoid driveshaft whirl. The fix for this issue is to use a multi-piece driveshaft with carrier bearings, so that each driveshaft segment is short enough to avoid whirl.

The second issue with a tall overdrive ratio is that it increases the frequency of any imbalance forces that may occur in a driveshaft. Unbalance forces in the driveshaft excite the powertrain bending resonances of the engine/transmission assembly. If the frequency of driveshaft rotation matches the lowest powertrain bending resonance somewhere in the operating range of the engine, mechanical failures of the flywheel housing are likely. Fixing this issue requires an increase in powertrain bending frequency. This is normally obtained by optimization

of the flywheel housing structure. Occasionally, the transmission housing may also need to be stiffened. In some cases, it is not possible to achieve the target powertrain bending resonance frequency with conventional stiffening measures. In these cases, external brackets which tie the engine block directly to the transmission housing may be required. Some example values:

Maximum engine speed: 2,800 RPM
Overdrive ratio: 0.62:1
Maximum driveshaft speed: 2,200/0.62 = 4,516 RPM = 75.3 Hz
Target powertrain bending frequency with 15% margin: 86.6 Hz

Powertrain bending excitation normally becomes a problem when the vehicle is going downhill and the driver is using the engine for braking. Under these conditions, the engine can be motored above its normal maximum speed. This causes high driveshaft speed, and thus high rotating imbalance force frequency. Shaft whirl is also more likely to be a problem in downhill operation with engine overspeed.

The 2012 model T-270 and F-650 trucks that were modeled in this project both lock out 6th gear. As of 2014, Ford has modified their truck to make use of 6th gear. Kenworth now offers both 5 and 6-speed versions of the Allison transmission, depending on the vehicle specification. The trend appears to be moving towards drivelines that can accommodate taller overdrive ratios.

Different torque converter matches were selected for the ISB diesel and the two gasoline engines. Allison provided proprietary efficiency data, which was input to the vehicle simulation model. Details of the 5-speed torque converter automatic transmission used in the T-270 and F-650 trucks are shown in Table C13 above, in columns Veh 1, Veh 5, Veh 6, and Veh 7.

As an upgrade to the 5 and 6-speed automatics, an 8-speed unit was evaluated. The advantages of an 8-speed over the baseline 5 and 6-speed units include closer ratios and a wider ratio range. The biggest advantage of the 8-speed is that it has a higher mechanical efficiency than the baseline transmission. SwRI used proprietary efficiency test data from the most efficient 8-speed light truck transmission now available, and scaled it to match the requirements of this project.

By scaling, we mean the following. Assume that the transmission subjected to physical testing has a torque limit of 500 Nm, but our engine provides 1000 Nm. Thus, the transmission's performance needs to be scaled up by a factor of 2. If the tested transmission has an efficiency of 97% at 300 Nm, we would then input an efficiency of 97% at 600 Nm for the simulation.

There are three primary sources of benefit for the 8-speed in vehicle operation:

1. The wider ratio range allows for a taller top gear for cruise
2. The closer gear spacing should allow the engine to be kept in a more efficient part of its operating map
3. The improved mechanical efficiency should reduce fuel consumption during all types of operation

In practice, advantage 2 proved to be very minor. The 5 and 6-speed transmissions actually do a very good job of keeping the engine in an efficient part of the map. Advantage 3 proved most significant, since the 8-speed is about 2% more efficient across much of the operating range.

Table C13 above shows the transmission ratios for the 8-speed torque converter automatic transmission in the Dodge Ram section in column Vehicle 3. The same data is also shown in the T-270 and F-650 sections in column Vehicle 4.

C2.9 Engine Alternatives

C2.9.1 4.5 and 6.7 Liter Diesel for Pickup (Class 2b/3)

The baseline engine for the pickup was a 385 HP 6.7 liter diesel. Several engine technologies were explored on this engine, and a 4.5 liter 4-cylinder variant was developed to explore downsizing. Details are provided in Appendix B.

C2.9.2 6.7 Liter Diesel for Classes 4 – 7

The baseline engine for the T-270 and F-650 medium-duty trucks was a 300 HP rating of the 6.7 liter diesel. Several engine technologies were explored on this engine. In addition, an 8-cylinder 8.9 liter derivative was created to cover heavier duty Class 8 vocational applications. This engine model will be used in future simulations. Details of the medium-duty diesel engines are provided in Appendix B.

C2.9.3 3.5 V-6 and 6.2 V-8 Gasoline Engines for Class 2b – 7 Vehicles

Gasoline engines were explored as alternatives to the diesel on the Ram pickup and also in the T-270 and F-650 vocational trucks. The smaller V-6 represents a downsized, turbocharged, direct injection alternative. The 6.2 V-8 is a more traditional naturally aspirated, port injected engine. Several technologies were explored on each engine type. Details of the gasoline engines and their technologies are provided in Appendix A.

C2.9.4 12.5 and 15 Liter Diesel Engines for Class 8

The baseline engine for the Kenworth T-700 long-haul tractor-trailer truck is a 485 HP rating of the 15 liter diesel. A wide range of technologies have been applied to this engine, including both downsizing (to 12.5 liters) and downspeeding. Details on these engines and technologies are provided in Appendix B.

C3 Examples of Vehicle Drive Cycle Operation

The figures below provide examples of how the engine operates on various vehicle drive cycles and payloads. These figures are very useful in a number of ways:

1. Verification of transmission shift points
2. Evaluation of drive cycle / payload aggressiveness
3. Evaluation of how well the powertrain setup (transmission and final drive ratio) keep the engine in its most efficient operating area, for a given power demand

These plots are rather complex, so some description is required. All plots have engine speed on the X-Axis, and engine torque on the Y-axis. The thick black upper curve is the engine torque curve, and the thick black lower curve (below zero torque) is the engine motoring curve. This is the torque required to spin the engine when fuel is shut off. The curved lines with numbers (205, 210, 215, etc.) are lines of constant brake specific fuel consumption, or BSFC. The engine is most efficient when it operates in the area of lowest BSFC. The blue circles show where the engine operates during the drive cycle, with the size of the blue circle indicating how much time the engine spends at or near that speed/load point. The blue circles give a good understanding of how hard the engine has to work on a given drive cycle, and how efficiently it works.

Figures C.6 and C.7 compare the NESCCAF and WHVC drive cycles. Note that the primary engine cruise point is at higher speed and torque on the NESCCAF cycle. This is because the NESCCAF has cruise speeds of 65 to 70 MPH, while the WHVC is a European cycle with a cruise speed around 53 MPH. The WHVC includes more low speed, light load city and suburban driving than the mostly-highway NESCCAF cycle. There is also more full load operation on the NESCCAF cycle, because of the +/- 1% and +/-3% grades imposed by this cycle.

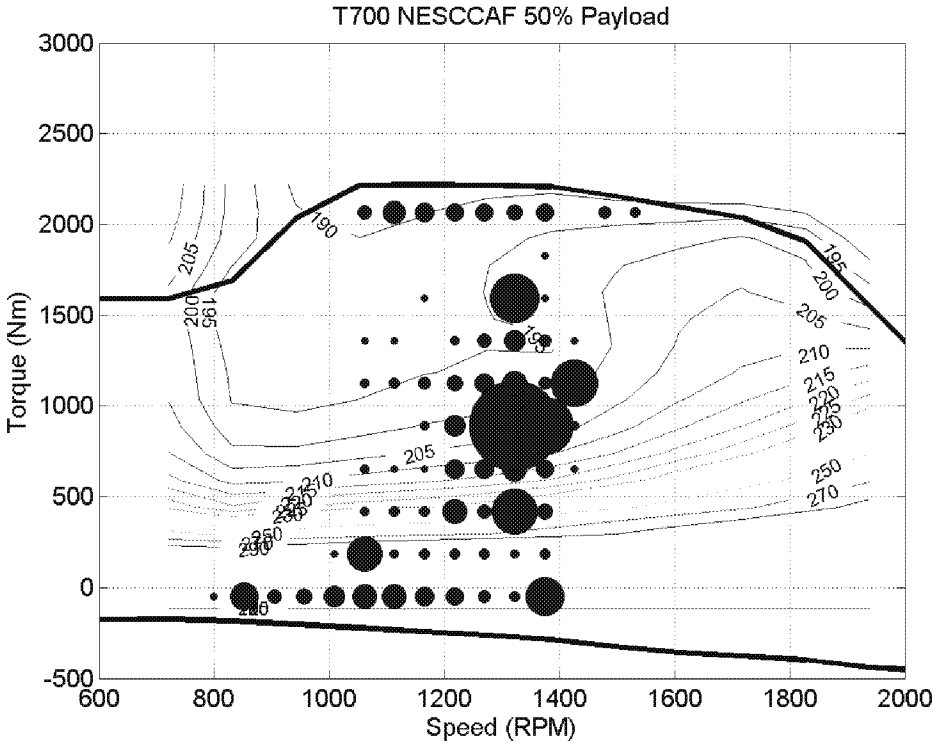

Figure C6. Engine operating map for the T-700 truck on the NESCCAF drive cycle at 50% payload.

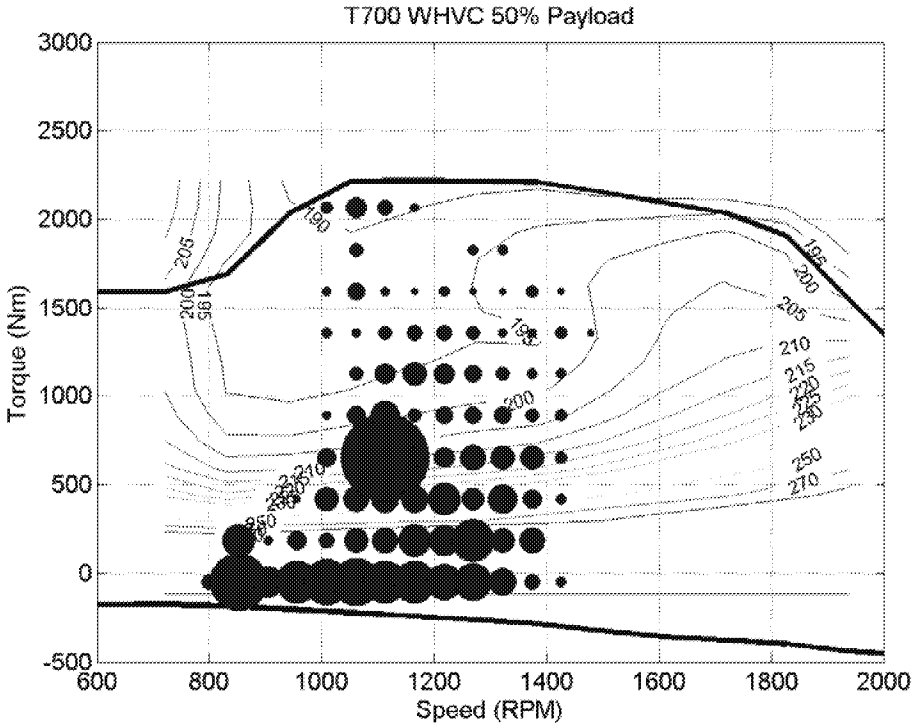

Figure C.7 Engine operating map for the T-700 truck on the WHVC drive cycle at 50% payload.

The next pair of figures compares the 65 MPH cruise operating point for the baseline engine in the T-700 tractor-trailer against the Downspeed 2 configuration. Downspeed 2 has a higher torque curve and a taller axle ratio, which reduces engine speed at 65 MPH.

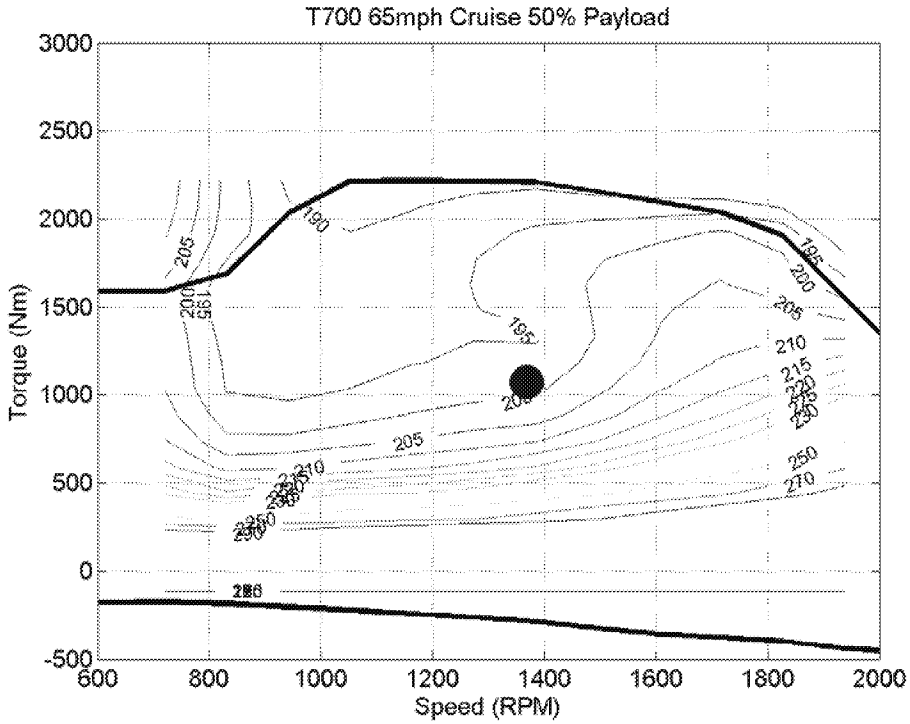

Figure C.8 Engine map for the T-700 baseline truck at 65 MPH and 50% payload.

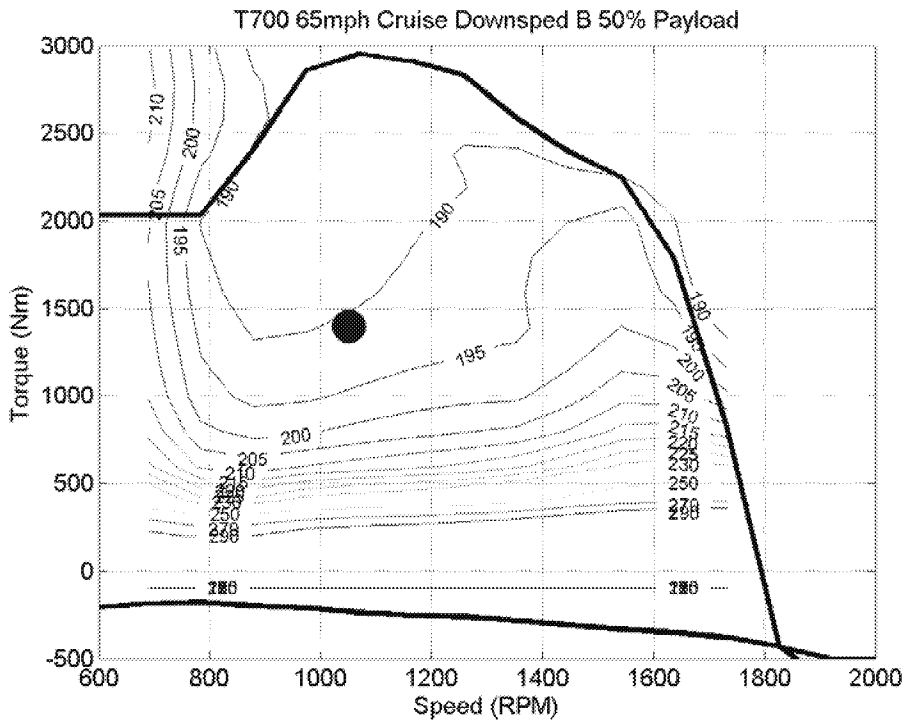

Figure C.9 Engine map for the T-700 Downspeed 2 truck at 65 MPH and 50% payload.

Note in comparing Figures C.8 and C.9 that the engine efficiency at the cruise load point improves with downspeeding. The baseline engine in Figure C.8 is operating at a point just under 200g/kW-hr, while the downspeed version is well under 195 g/kW-hr. There is about a 4% difference in engine efficiency at these two operating points.

The next four figures look at different engine types in the T-270 box delivery truck, all on the WHVC. First, Figures C.10 and C.11 compare the 6.7 liter diesel against the 6.2 liter gasoline V-8. The main cruising point for the diesel engine is around 1600 RPM and 450 Nm of torque, while the gasoline V-8 cruises at about 2650 RPM and 250 Nm of torque. Despite the big difference in engine operating point, both engines are operating near their sweet spot at cruise, and both have sufficient torque headroom to deal with some grade or with a desire to accelerate, without requiring a downshift.

Figures C.12 and C.13 compare the baseline 3.5 V-6 and the downspeed + EGR version of the 3.5 V-6 in the same vehicle and on the same drive cycle (T-270 box truck on the WHVC at 50% payload). The baseline 3.5 V-6 cruises at about 2650 PM and 250 Nm of torque, just like the V-8 in Figure C.11. The BSFC of the baseline 3.5 V-6 at the cruise point is about 240 g/kW-hr. The downspeed + EGR version of the 3.5 V-6 cruises at about 2200 RPM and 300 Nm, where the engine has a BSFC of about 225 g/kW-hr, a 6% to 7% improvement over the baseline. Both the lower cruise speed and EGR contribute to the improved efficiency of the downspeed + EGR engine.

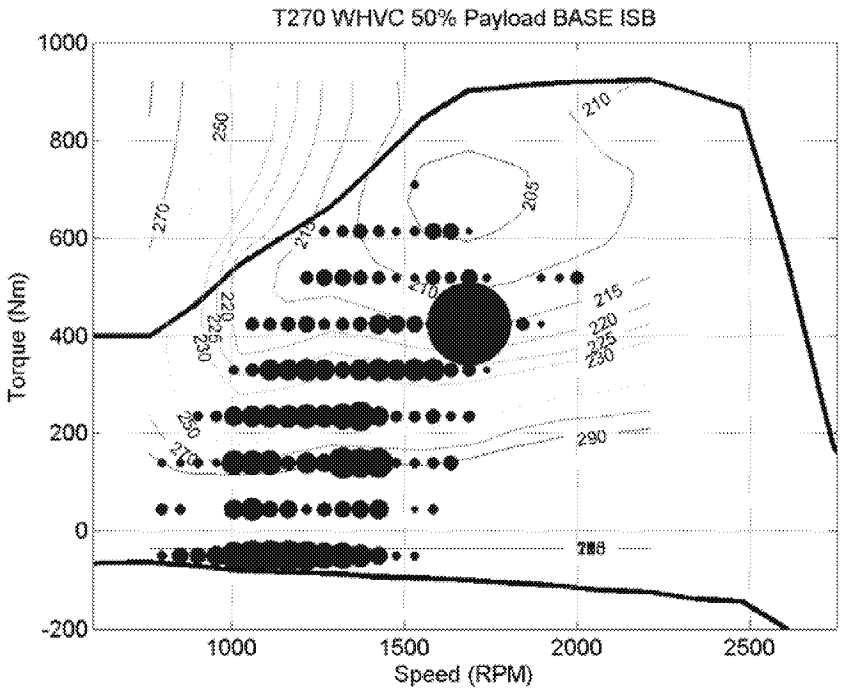

Figure C.10 Engine operating map for the T-270 truck with the baseline 6.7 liter diesel on the WHVC at 50% payload.

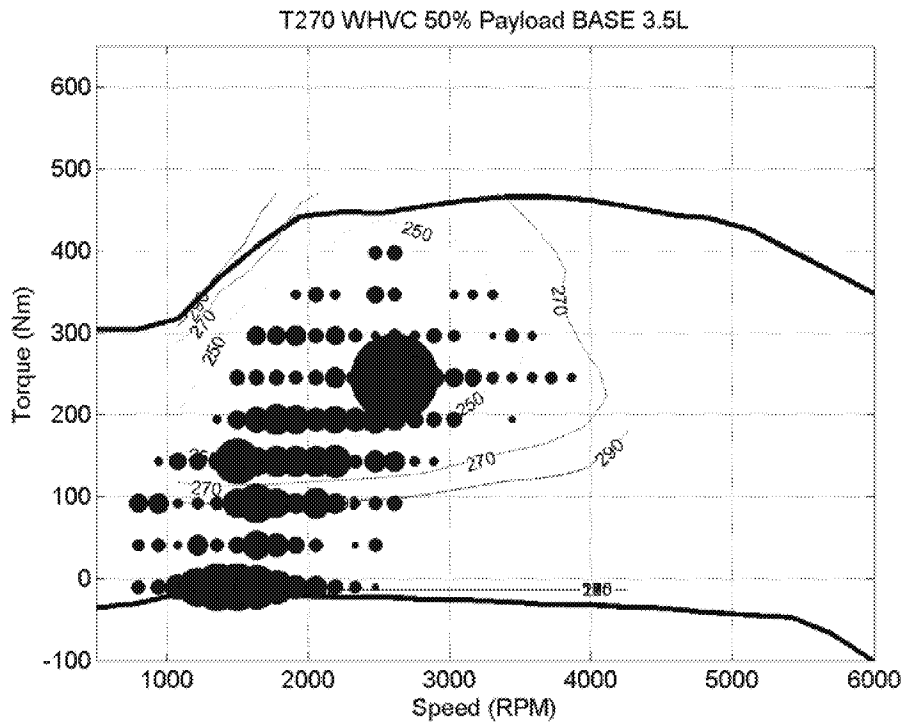

Figure C.11 Engine operating map for the T-270 truck with the baseline 6.2 liter V-8 gasoline engine on the WHVC at 50% payload.

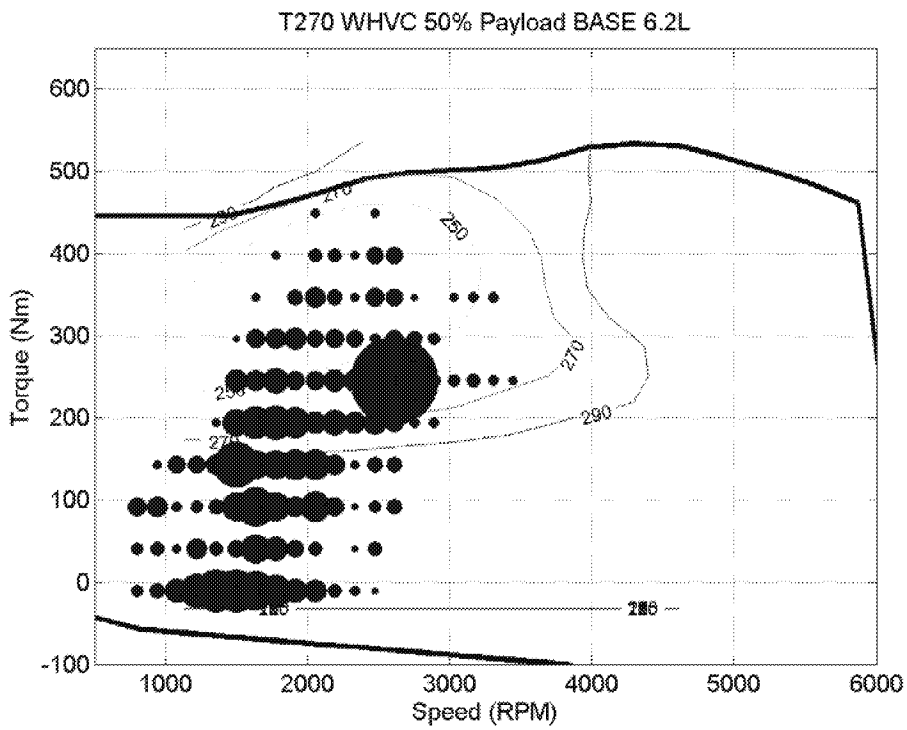

Figure C.12 Engine operating map for the T-270 truck with the baseline 3.5 V-6 on the WHVC at 50% payload.

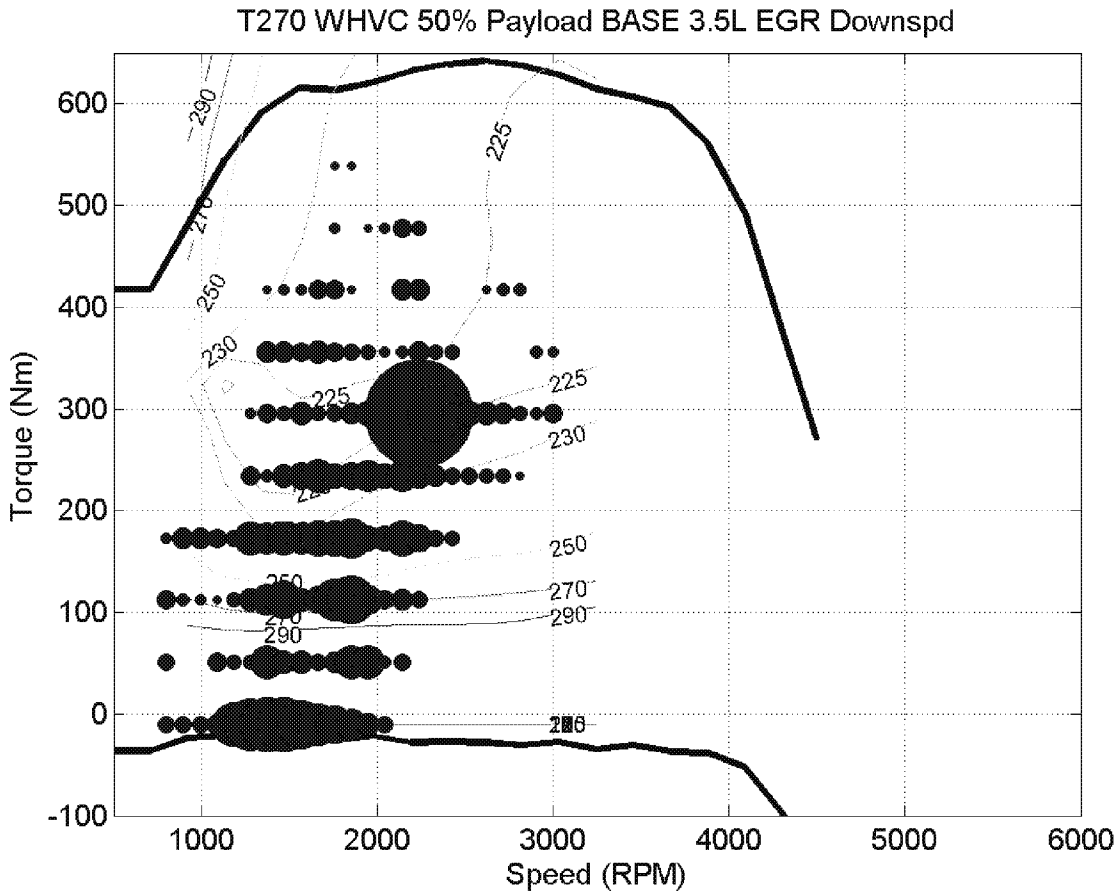

Figure C.13 Engine operating map for the T-270 truck with the Downspeed + EGR 3.5 V-6, on the WHVC at 50% payload.

The next figure provides results on the Ram pickup truck. Figure C.14 shows the Ram with the baseline diesel on the WHVC at ALVW (50% of the payload that can be loaded in the truck bed, but no trailer). This compares with Figure C.10 above, where the same basic engine is operating on the same test cycle, but in a larger and heavier vehicle. The T-270 truck (Figure C.10) has a cruise point at about 1650 RPM and 425 Nm. In the smaller Ram pickup, the cruise point is around 1250 RPM and 200 Nm. In fact, for the Ram, the engine never exceeds 1700 RPM or 400 Nm, even though the rating for the pickup has both a higher speed range and higher torque than the medium truck version of the diesel engine. For the pickup truck, rated speed is 3000 RPM, and peak torque is 1150 Nm. Note that for the pickup truck on this gentle drive cycle, the engine load never reaches the most efficient range. This suggests that a downsized engine could provide large benefits, which indeed matches the results shown in Section 3.3.6.2.

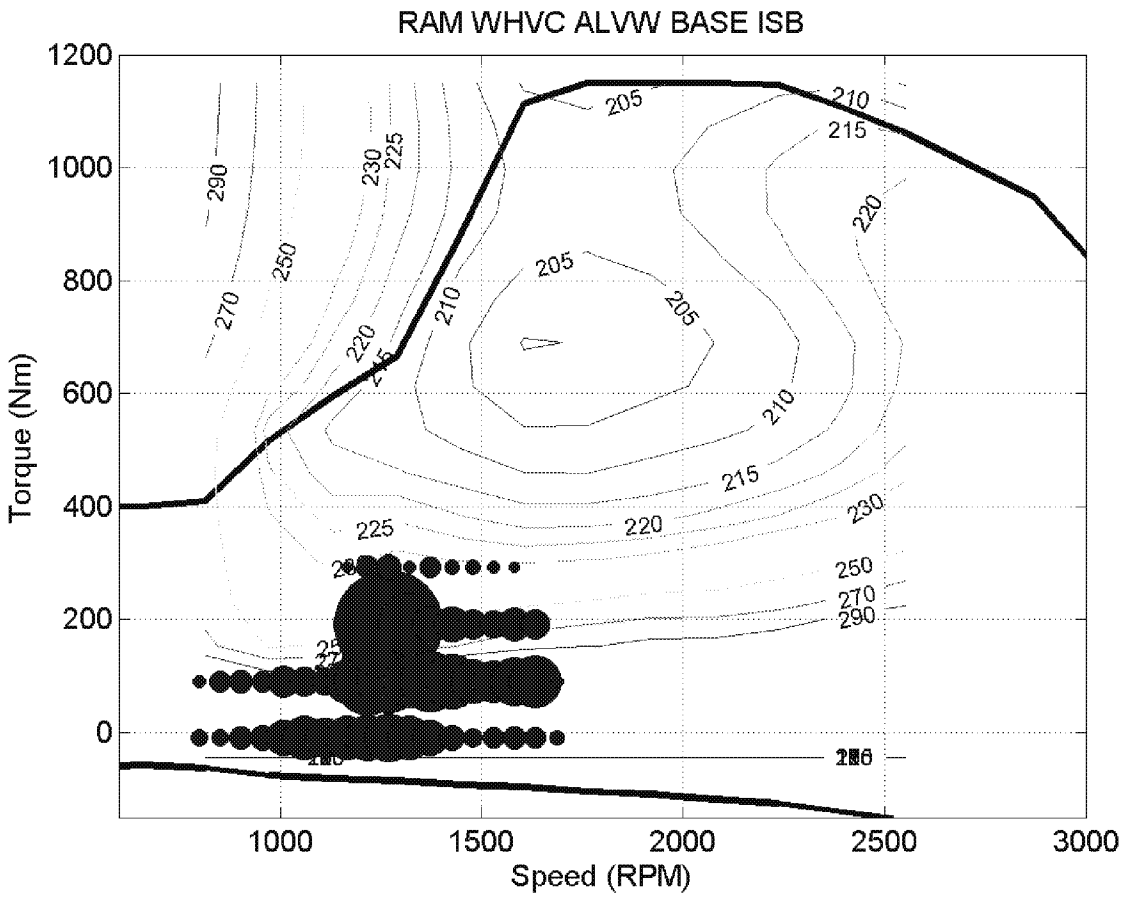

Figure C.14 Engine operating map for the Ram pickup truck with the baseline 6.7 liter diesel, on the WHVC at ALVW (8,438 pounds vehicle test weight).

The final pair of figures shows the baseline Ram diesel on the much more aggressive US06 drive cycle. Figure C.15 shows the results at zero payload (6,876 pounds), while Figure C.16 shows the results at full GCW (25,000 pounds). At zero payload, the engine reaches 2000 RPM and up to 900 Nm. Full load is never quite reached, and the engine operates below the most efficient area on most of the cycle. At GCW, the vehicle is unable to follow the drive cycle about 10% of the time, so the engine is at full load a significant portion of the time, as the vehicle tries to catch up with the drive cycle requirements. The maximum engine speed is around 2900 RPM, with significant time at the peak torque of 1150 Nm. Note that even on this severe duty cycle, the transmission does a good job of keeping the engine near its most efficient operating range whenever possible.

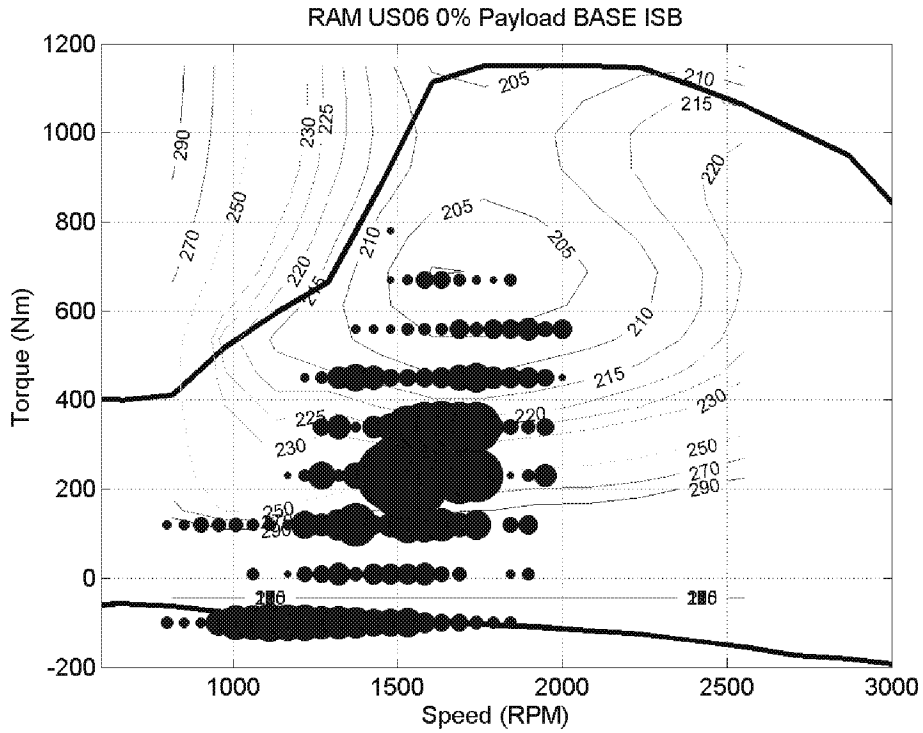

Figure C.15 Engine operating map for the Ram pickup truck with the baseline 6.7 liter diesel, on the US06 at zero payload.

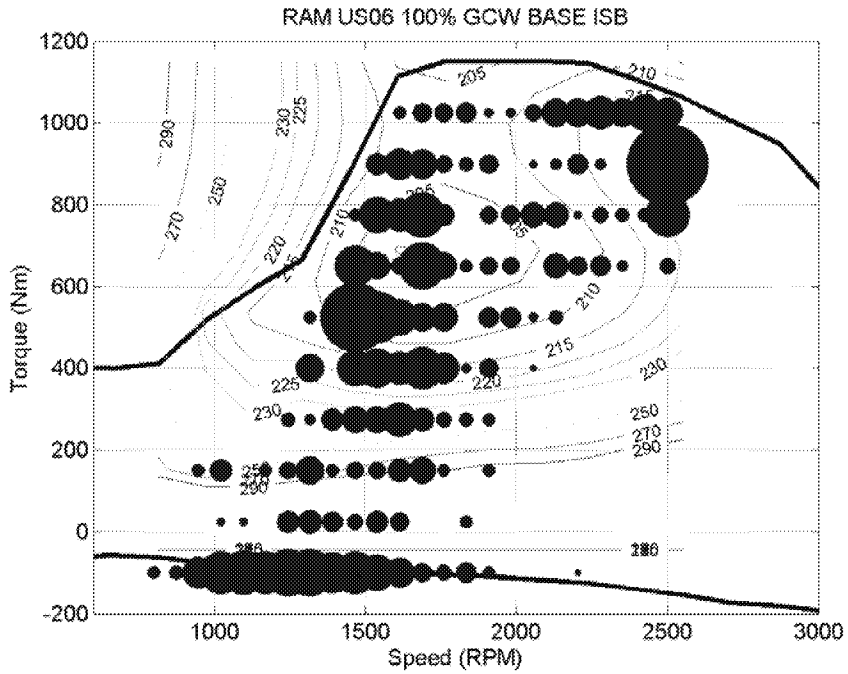

Figure C.15 Engine operating map for the Ram pickup truck with the baseline 6.7 liter diesel, on the US06 at full GCW (25,000 pounds).

APPENDIX D

BOTTOMING CYCLE MODEL DESCRIPTION

Bottoming Cycle Model Description

The Bottoming Cycle is one form of waste heat recovery that may be applied to internal combustion engines. The objective is to take heat that is otherwise "wasted" or rejected to the environment and convert as much of it as possible to useful shaft work. In an engine, the most common and useful sources of this heat are the exhaust stream, the EGR cooler (as applicable), and possibly the coolant and aftercooler systems. The conversion from heat to work is done using the Rankine Cycle. The Rankine cycle has been used for many decades as a primary steam power plant, fueled by coal or wood or virtually any heat source. The bottoming cycle is so named because it is taking heat from the "bottom" of the engine cycle and converting it to additional work.

The Rankine cycle, as shown schematically in Fig D1, is composed of four primary items:

1. Pump
2. Evaporator or boiler
3. Expander (turbine or piston)
4. Condenser

The cycle fluid is selected to have the desired properties, namely a boiling point in the range of the cycle's heat source. The fluid comes out of the condenser as a liquid and is pumped to high pressure in the pump. The fluid is then boiled to vapor phase in the evaporator. The heat for this heat exchanger is supplied from one or more of the waste heat streams. This hot, high pressure vapor fluid is then expanded through the expander, which is the stage where energy is extracted from the cycle. The shaft work produced through the expander can be used to generate electricity or in the vehicle bottoming cycle case, can also be geared back into the engine shaft output. After the expansion, the vapor will go through the condenser, where it rejects heat to ambient, allowing the vapor to condense to a liquid so that the pump can be used to re-pressurize it.

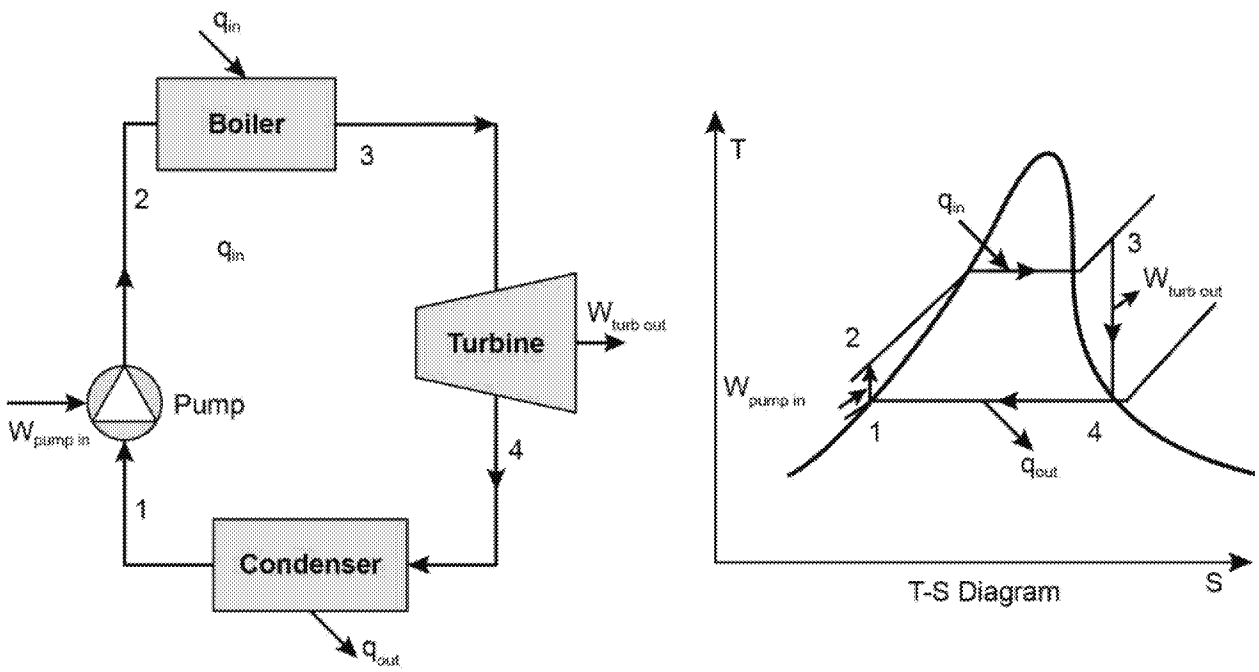

Figure D1. Concept sketch of a Rankine cycle waste heat recovery system.

Because the pump operates on an incompressible liquid, the work to compress the liquid is much less than the work expanded from the hot vapor, providing a positive net work output. The thermal efficiency of the cycle is defined as net work output / heat input. In general terms, this is the most important efficiency-type grading of a thermodynamic cycle. However, in the bottoming cycle, the heat input is low cost. The main "cost" of operation of the Rankine cycle is providing for the heat rejection. In a mobile application, this requires heat exchangers, which tend to increase the frontal area of the vehicle and reduce opportunities for aerodynamic improvement, and/or require higher fan power to assist the heat exchangers in rejecting the heat. Therefore, a more pertinent "efficiency" value for the mobile bottoming cycle might be net work output / rejected heat.

There are many variations upon the basic Rankine cycle, including regenerators. The regenerator applies part of the rejected heat from the condenser to the pump outlet liquid in a pre-heater, which both reduces the heat that must be rejected to ambient as well as reduces the amount of heat input required in the evaporator, for the same cycle conditions.

In our approach to the Rankine bottoming cycle, the following simplifications are made:

1. The pump is 100% efficient and can provide flowrate desirable to the Rankine cycle without regard to engine speed.
    a. A sensitivity study showed that for R245fa, a drop to 50% pump efficiency reduced the net work out of the Rankine cycle by 7-8%. So for example, if with 100% pump efficiency assumption the cycle was putting out 5 kW to add to the engine's 200 kW, with the 50% pump efficiency, it would drop to 4.6 kW. For the water cases, the pump work is a much smaller portion and the 50% efficiency change is minimal, dropping the Rankine cycle output by ≤ 0.5% in all cases.
2. The evaporator heat exchange process is governed by a minimum required temperature difference (ΔT) from one fluid to the other at any point in the heat exchange process. Unless otherwise noted, this ΔT is set to 14°C (25°F).
3. The expander is assumed to have a 70% isentropic efficiency, regardless of flow or pressure ratio. It is not constrained in any way by the speed of the diesel engine. This is consistent with the approach of electrically coupling the expander and the engine.
4. The power coupling between the expander and the engine is electrical, consisting of a generator attached to the expander and an electric motor attached to the engine output where it can add power. The assumed efficiency of each of these devices is 91%, meaning that the composite efficiency of transmission is 91% squared, or 82.8%. This is again, independent of speed or power level, but applied as a percentage of the power to be transmitted.
5. The condenser outlet temperature is specified as an input, according to good engineering judgment of the analyst. Unless otherwise noted, this value is set to 50°C (122°F), which implies that the condenser is ambient-air cooled.
6. The control of the system is such that the condenser outlet condition is maintained at saturation pressure of the fluid at the condenser outlet temperature.
7. The pump is controllable to provide desired outlet pressure, up to and including 35 bar-absolute (507 psia).
8. To maintain reasonable cost and packaging, the condenser heat output is limited. This has the effect of providing full theoretical performance up through roughly 80% engine load, above which the bottoming cycle output is basically fixed due to this limitation. Operating time above this level is minimal for most driving cycles, and to size the system for full engine power output requires a significant increase in cost of the condenser as well as packaging issues and high

parasitic losses for such a large cooling system. Unless otherwise noted, this limit is set at 80 kW.

Two fluids were selected for initial analysis: water and R245fa. Water has thermodynamic property advantages but is subject to freezing if the vehicle is parked in a cold climate. It also optimizes to very low flow rates, which may have an impact on component efficiencies. It is also a benign substance with regards to any leaks that may occur and with regards to servicing. There may be issues with its corrosiveness however.

R245fa is stable and has relatively good thermodynamic properties suitable for use as a bottoming cycle fluid. The main drawbacks to using R245fa are that its usable temperature range is limited to <250°C due to thermal degradation concerns. This reduces the potential cycle efficiency while using this fluid. R245fa also has a high global warming potential (GWP) of around 1000, although alternatives are being developed with lower GWPs which are otherwise very similar in thermodynamic performance to R245fa.

For a bottoming cycle applied to an engine, the potential sources of heat to the bottoming cycle include:

- Engine coolant
- Aftercooler
- Exhaust stack
- EGR cooler.

These are listed in order from the lowest to the highest temperature heat source. After some initial investigation, engine coolant and aftercooler were eliminated as being too low temperature of a source (engine coolant) or not being consistently high enough temperature (aftercooler). The exhaust stack and EGR cooler are considered as heat sources for this study.

Using the EGR cooler as a heat source is dependent on whether the engine is equipped with EGR. Since some of the other engine technologies that are studied include removal of EGR, this is a concern. But if the engine does have EGR, there are several advantages to using the EGR cooler as a heat source:

1. It is the highest temperature heat source, being placed before the temperature reducing effect of the turbocharger turbine
2. The EGR heat exchanger already exists, reducing the marginal cost of adding heat exchangers to support the bottoming cycle
3. The heat that is being brought into the system was already a heat load on the cooling system that had to be rejected

Drawbacks to the EGR cooler are more minor, but include the fact that the bottoming cycle, depending on configuration, may not be able to accommodate all of the EGR cooler's heat load, so that a supplemental EGR cooler may be required in addition to the bottoming cycle's EGR cooler.

The exhaust stack has another set of advantages and disadvantages. The main advantage is that is it the largest heat source on the engine. It is also relatively accessible, although not quite as physically close to the rest of the bottoming cycle as one might desire. Due to the concern of keeping the aftertreatment system as hot as possible during operation, the heat exchanger is placed downstream of the aftertreatment, requiring some longer-than-desired plumbing runs. The other negative to the exhaust stack as a heat source is that heat is brought into the system that used to carry itself away through the tailpipe. Keeping in mind that the bottoming cycle's efficiency is on the order of 10-20% means that roughly 80-90% of the heat brought in via the exhaust stack heat exchanger will now have to be rejected in the condenser, which is problematic as discussed earlier.

Both the EGR cooler and the exhaust stack heat exchanger must operate in hot, corrosive environments, and as a result must be made of high quality, premium materials.

The bottoming cycle described thus far is considered the *simple* bottoming cycle. Various improvements and embellishments are available including a recuperator, which is examined in this study. The recuperator constitutes a heat exchanger placed between the turbine outlet vapor and the pump outlet liquid. This allows recovery of a portion of the heat that would otherwise be rejected in the condenser by the pump outlet water. This both increases the thermal efficiency of the bottoming cycle and reduces the heat rejection.

The base configuration studied for this report was a simple cycle with the heat addition in two pieces: first from an exhaust stack heat exchanger (pre-heater) and then from the EGR cooler (superheater). Alternatives include a configuration with no EGR cooler and a configuration with a recuperator.

Shown in Figure D2 below is a schematic of the engine/bottoming cycle system for the base configuration studied. The numbers refer to bottoming cycle stations. Table 1 provides temperatures and pressures at those stations, as well as some of the performance values for one engine operating point with the base configuration with water as the bottoming cycle fluid for reference. This point is over the 80 kW condenser heat rejection limit that is utilized for most of the study, but is provided as one of the higher output, higher temperature and pressure points studied.

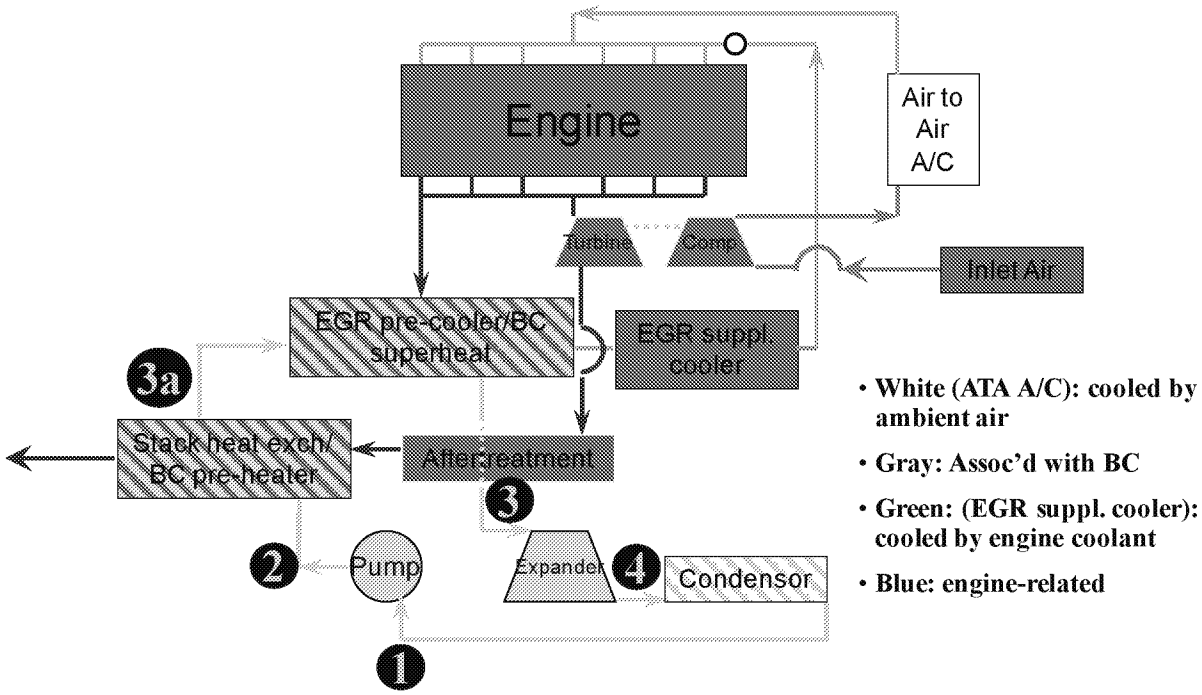

Figure D2: Engine/Bottoming Cycle Schematic

In Table 1 below, T1 and P1 represent the pump inlet conditions, while T2 and P2 are the pump outlet conditions, assuming a 100% pump efficiency. T3a and P3a are the outlet conditions of the exhaust stack heat exchanger, which serves as the pre-heater for the bottoming cycle circuit. T3 and P3 are the outlet conditions of the EGR heat exchanger, which serves as the superheater for the bottoming cycle. T3 and P3 also represent the inlet conditions for the expander, which extracts work from the bottoming cycle fluid. T4 and P4 are the outlet conditions of the expander, after work has been extracted.

The next column shows the condenser heat rejection. In this particular example, the value is shown in red, because it exceeds the self-imposed limit of 80 kW. This problem is fixed by either reducing the fluid mass flow in the bottoming cycle system, or by limiting the amount of heat input. The most effective approach to meeting the heat rejection requirement is a function of the fluid type. The next column shows the total heat input from the two heat exchangers. The following three columns provide the thermal efficiency of the bottoming cycle, the percentage of input heat that has to be rejected by the condenser, and the ratio of bottoming cycle power to engine power.

The bottoming cycle is assumed to drive an electric generator, and then an electric motor geared to the engine crankshaft, so the final two columns show the net electric power that is provided to the engine crankshaft, and the ratio of electric power input to engine power. This final column represents the overall benefit of the bottoming cycle at a given operating point.

Table 1: Bottoming Cycle Example Operating Point

T1	P1	T2	P2	T3a	P3a	T3	P3	T4	P4	**Cond Heat Rej**	Net Work	Gross Heat Input	Eff	% heat input rejected	Wbc / Wengine	Net Elec Work	Wbc_elec/ Wengine
°C	MPa	°C	MPa	°C	MPa	°C	MPa	°C	MPa	kW	kW	kW	%	%	%	kW	%
50	0.012	50.1	**3.47**	242.1	3.47	528	3.46	126.9	0.022	95.6	29.27	125	23.4	77	9.1	24.24	7.5

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May 2015

Commercial Medium- and Heavy-Duty (MD/HD) Truck Fuel Efficiency Technology Cost Study

Final Report

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16. Abstract

This report accompanies the work performed by Southwest Research Institute (SwRI) in collaboration with the DOT National Highway Traffic Safety Administration (NHTSA) on fuel efficiency and emissions reduction technologies. Technologies are evaluated for medium-duty (MD) and heavy-duty (HD) fuel vehicles for model years 2019 and beyond. Based on the list of technologies and configurations identified by SwRI, this report examines the costs of implementation in constant 2011 U.S. dollars, in the areas of: 1) incremental retail prices and 2) life cycle cost elements.

Incremental retail prices are evaluated relative to the prices of the specific baseline technologies that would otherwise be used in the vehicles if the fuel efficiency and emissions reduction technologies were not implemented. These prices include the technology components as well as their installation and incorporation in the vehicle. Incremental retail prices account for all costs associated with the manufacturers and suppliers' production and sale of the technologies to the retail purchaser. The life cycle cost element portion of the assessment examines the costs of using the technologies during the vehicles' lifetimes and are intended to inform separate full-scale life cycle analysis. This report provides the overall details of the costing methodology and findings of the study.

Note: This report was subjected to external peer review per OMB guidelines for a Highly Influential Scientific Assessment (HISA). Materials from the peer review process are publicly available in accompanying documents.

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Executive Summary

This report accompanies the work performed by Southwest Research Institute (SwRI) in collaboration with the U.S. Department of Transportation (DOT) and the National Highway Traffic Safety Administration (NHTSA) on fuel efficiency and emissions reduction technologies. Technologies are evaluated for medium-duty (MD) and heavy-duty (HD) fuel vehicles for model years 2019 and beyond. Based on the list of technologies and configurations identified by SwRI, this report examines the costs of implementation in constant 2011 U.S. dollars, in the areas of: 1) incremental retail prices and 2) life cycle cost elements.

Incremental retail prices are evaluated relative to the prices of the specific baseline technologies that would otherwise be used in the vehicles if the fuel efficiency and emissions reduction technologies were not implemented. These prices include the technology components as well as their installation and incorporation in the vehicle. Incremental retail prices account for all costs associated with the manufacturers and suppliers' production and sale of the technologies to the retail purchaser.

The life cycle cost element portion of the assessment examines the costs of using the technologies during the vehicles' lifetimes. In addition to the initial purchase costs of the technologies, the technologies' effects on fuel consumption, brake maintenance, major overhaul intervals, vehicle life, and other operations and maintenance (O&M) costs are quantified if the data were available (life cycle cost element data such as O&M were difficult to determine given new technologies had little in the field deployment for extended periods of time). Life cycle cost elements reported here are intended to inform a broader separate full life cycle analysis that takes into account additional factors such as fuel expenses outside the scope of this report.

Due to the limited timeframe and funding available for the study, this analysis relied on exiting MD/HD literature for price inputs, and it relied on peer reviewed documents if available. Direct surveys of manufacturers and teardown analysis were not possible.

Specific fuel efficiency and emissions reductions technologies for engines and vehicles were selected and modeled by SwRI (with input from NHTSA, Environmental Protection Agency, California Air Resources Board, and others). The costs corresponding to each of these technologies are estimated in this report. The technologies are divided into three applications: Class 2b&3, Vocational, and Line Haul. The Class 2b&3 application encompasses the light heavy-duty vehicles, operating with either gasoline or diesel engines, while at the other end of the spectrum, the Line Haul application encompasses the heaviest Class 8 diesel vehicles used in long distance duty cycles. The Vocational application spans a range of weight classes and is represented by Class 4 to Class 7 medium heavy-duty vehicles. Vocational also includes straight trucks up through Class 8, such as dump trucks, cement trucks, and refuse trucks (these vehicles were not specifically addressed in this study).

The methodology for determining incremental retail prices relies on a thorough literature review (peer reviewed or other highly credible sources available at the time of the literature search) for all target technologies to identify ranges of price points. The data reported here draw heavily upon the most recent peer reviewed National Research Council studies of medium- and heavy-duty vehicle technologies, in which OEMs agreed to provide detailed cost information during site visits and interviews.[1,2] From published studies and data, prices of fuel efficiency and emissions reduction technologies are reported as incremental retail prices.

The ranges of values found in the literature are scaled to project incremental prices using manufacturing volume-dependent cost curves. The cost curves are calculated from two components:

- Direct costs, which encompass materials, labor, and other relatively fixed costs of technology manufacture
- Indirect costs, which are divided into production overhead (warranty, R&D/engineering, and depreciation and amortization), corporate overhead, selling and dealer support (distribution, marketing, dealer support, and dealer discount), and net income to the manufacturer

Indirect costs are derived from direct costs using an adjusted multiplier. This multiplier contains two main factors (indirect cost factors and manufacturing process improvements) that determine the final incremental price of the technology to the purchaser over increasing production volume. The first main factor is derived from research conducted for the U.S. Environmental Protection Agency (EPA) and reflects manufacturer costs that are difficult to allocate to specific production activities, such as R&D, corporate operations, dealer support, and marketing.[3,4,5] Taking into account the complexity of the technology, this type of cost reduction results from short- and long-term indirect cost factors, as shown in Table E1. The time based short- and long- term

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[1] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.

[2] National Research Council, "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report," The National Academies Press Pre-Publication copy, 2014

[3] Rogozhin, A., M. Gallaher, W. McManus. "Automotive Industry Retail Price Equivalent and Indirect Cost Multipliers." Prepared by RTI International and Transportation Research Institute, University of Michigan for the U.S. Environmental Protection Agency. February 2009.

[4] Rogozhin, A., M. Gallaher, A. Lentz, W. McManus. "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers." Prepared by RTI International and Transportation Research Institute, University of Michigan for the U.S. Environmental Protection Agency. July 2010.

[5] U.S. Environmental Protection Agency, "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA report # EPA-420-R-12-901, August 2012

indirect cost factors are used to estimate the decrease in costs as the cumulative manufacturing volume increases over time. The indirect cost factors account for differences in the technical complexity of the required vehicle modifications and adjust for increasing production volumes as new technologies become assimilated into the manufacturing process. The indirect costs portion of the incremental price is further broken out into four elements: production overhead, corporate overhead, selling and dealer support, and net income. The relative contributions of each of these elements to the total indirect cost are based on research by Argonne National Laboratory for the U.S. Department of Energy that examined and modified Argonne National Laboratory's incremental cost components of implementing new vehicle technologies.[6,7]

Table E1. Indirect Cost Factors

Low Technology Complexity		Medium Technology Complexity		High 1 Technology Complexity		High 2 Technology Complexity	
Short-Term	Long-Term	Short-Term	Long-Term	Short-Term	Long-Term	Short-Term	Long-Term
1.24	1.19	1.39	1.29	1.56	1.35	1.77	1.50

The second main factor of the adjusted multiplier reflects improvements in the manufacturing process that take place as the technology matures (newness of the technology as it applies to the manufacturing process). As described by the Center for Automotive Research, manufacturing process efficiencies that are learned over time are captured in this type of cost reduction and are expressed as an annual percent improvement from the previous year (Table E2).[8] Advanced Electronics and electronic control systems are the newest technology to be incorporated into the manufacturing process. Electrical Machines (such as motor, generator, gears, and electrical accessories) are more mature than Advanced Electronics in the manufacturing process. Developing Technologies are mature technologies in the manufacturing process but are still developing (such as mass reduction materials).

Table E2. Manufacturing Process Improvements

Advanced Electronics	Electrical Machines	Developing Technologies
3%	1%	0.5%

[6] Cuenca, R.M., L.L. Gaines, A.D. Vyas. "Evaluation of Electric Vehicle Production and Operating Costs." Prepared by Argonne National Laboratory for the U.S. Department of Energy. ANL/ESD-41. November 1999.

[7] Vyas, A., D. Santini, R. Cuenca. "Comparison of Indirect Cost Multipliers for Vehicle Manufacturing." Prepared by Argonne National Laboratory for the U.S. Department of Energy. April 2000.

[8] Center for Automotive Research. "The U.S. Automotive Market and Industry in 2025." June 2011.

The indirect cost factors and the manufacturing process improvements (newness) then are multiplied together to derive the adjusted multipliers that make up the volume-dependent technology cost curves for each of the identified technologies. From the cost curves, incremental prices at different manufacturing volumes can be calculated.

All prices are presented on a *cumulative* volume basis across the entire market (time based units/year was a proxy to apply adjustment factors for production volume); no distinctions are made among specific suppliers, factories, or manufacturing lines. It is important to note that because prices are for cumulative volumes, volumes across vehicle classes may be additive. For example, if the same gasoline engine is used in both Class 2b&3 and Vocational vehicles, the industry total volume for a technology on that engine will include volumes from both vehicle categories. As a result, the incremental price of the technology may be lower than the price according the volume in a single vehicle category. Technologies that apply only to a single vehicle category will accumulate volumes more slowly than those technologies that apply to multiple categories.

Projections of future price contain risk. As the technology matures, it may become more or less expensive, or it may prove unable to achieve the expected benefits. Only limited conclusions can be drawn from the evaluation of the technology price results in this report. These price results will be combined by the agencies with technology performance results in subsequent analyses to allow calculation of cost/benefit ratios for each technology.

The following tables (Table E3, Table E4, and Table E5) summarizes the reduction in total incremental prices with increasing cumulative production volumes at four points along the cost curves for the three vehicle applications.

Table E3. Class 2b&3 Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Coolant/Oil Pump (G)	50,000	300,000	600,000	1,000,000	180.00	165.38	157.03	154.52
Coolant/Oil Pump (D)	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	620.00	520.44	453.38	423.87
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	620.00	509.66	443.98	415.08
Cylinder Deactivation	50,000	300,000	600,000	1,000,000	287.50	264.15	250.81	246.81
Stoichiometric GDI	50,000	300,000	600,000	1,000,000	625.00	574.24	545.23	536.53
Lean Burn GDI w/ SCR	50,000	300,000	600,000	1,000,000	1,930.00	1,773.24	1,683.68	1,656.81

Turbocharging & Downsizing	50,000	300,000	600,000	1,000,000	1,390.00	1,277.10	1,212.60	1,193.25
Engine Downspeeding	50,000	300,000	600,000	1,000,000	2,600.00	2,388.82	2,268.17	2,231.98
Low Friction Engine Oil (G) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	7.50	7.16	6.95	6.84
Low Friction Engine Oil (D) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	14.00	13.37	12.97	12.76
Engine Friction Reduction (G)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Engine Friction Reduction (D)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Stop / start (G)	50,000	300,000	600,000	1,000,000	700.00	643.14	610.66	600.92
Stop / start (D)	50,000	300,000	600,000	1,000,000	1,500.00	1,378.17	1,308.56	1,287.68
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	19,500.00	16,368.75	14,259.38	13,331.25
HEV (High 2)	50,000	300,000	600,000	1,000,000	19,500.00	16,029.66	13,963.98	13,055.08
Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Improved 2b & 3 Aerodynamics	50,000	300,000	600,000	1,000,000	280.00	267.37	259.30	255.27
Improved Transmissions (G)	50,000	300,000	600,000	1,000,000	480.00	441.01	418.74	412.06
Improved Transmissions (D)	50,000	300,000	600,000	1,000,000	875.00	803.93	763.33	751.15
Low Rolling Resistance Tires (per tire)	5,000,000	30,000,000	60,000,000	100,000,000	16.00	15.28	14.82	14.59
Weight Reduction (500 pounds)	300,000	1,800,000	3,600,000	6,000,000	2,000.00	1,909.76	1,852.18	1,823.39
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

Table E4. Vocational Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Coolant/Oil Pump (G)	50,000	300,000	600,000	1,000,000	180.00	165.38	157.03	154.52
Coolant/Oil Pump (D)	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46

Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	635.00	533.03	464.34	434.12
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	635.00	521.99	454.72	425.13
Cylinder Deactivation	50,000	300,000	600,000	1,000,000	287.50	264.15	250.81	246.81
Stoichiometric GDI	50,000	300,000	600,000	1,000,000	625.00	574.24	545.23	536.53
Lean Burn GDI w/ SCR	50,000	300,000	600,000	1,000,000	1,930.00	1,773.24	1,683.68	1,656.81
Stoichiometric GDI + EGR	50,000	300,000	600,000	1,000,000	1,430.00	1,313.85	1,247.49	1,227.59
Turbocharging & Downsizing	50,000	300,000	600,000	1,000,000	1,390.00	1,277.10	1,212.60	1,193.25
Engine Downspeeding	50,000	300,000	600,000	1,000,000	2,600.00	2,388.82	2,268.17	2,231.98
Low Friction Engine Oil (G) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	7.50	7.16	6.95	6.84
Low Friction Engine Oil (D) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	14.00	13.37	12.97	12.76
Engine Friction Reduction (G)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Engine Friction Reduction (D)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Stop / start (G)	50,000	300,000	600,000	1,000,000	700.00	643.14	610.66	600.92
Stop / start (D)	50,000	300,000	600,000	1,000,000	1,500.00	1,378.17	1,308.56	1,287.68
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	32,000.00	26,861.54	23,400.00	21,876.92
HEV (High 2)	50,000	300,000	600,000	1,000,000	32,000.00	26,305.08	22,915.25	21,423.73
Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Improved Transmissions (G)	50,000	300,000	600,000	1,000,000	750.00	689.08	654.28	643.84
Improved Transmissions (D)	50,000	300,000	600,000	1,000,000	1,325.00	1,217.38	1,155.90	1,137.45
AMT vs. Manual	50,000	300,000	600,000	1,000,000	1,050.00	964.72	915.99	901.38
Dual Clutch Automatic (High 1)	50,000	300,000	600,000	1,000,000	2,700.00	2,266.44	1,974.38	1,845.87
Dual Clutch Automatic (High 2)	50,000	300,000	600,000	1,000,000	2,700.00	2,219.49	1,933.47	1,807.63

Low Rolling Resistance Tires (per tire)	700,000	4,200,000	8,400,000	14,000,000	30.50	29.12	28.25	27.81
Automatic Tire Pressure Control	50,000	300,000	600,000	1,000,000	800.00	763.90	740.87	729.35
Weight Reduction (1,000 pounds)	300,000	1,800,000	3,600,000	6,000,000	6,000.00	5,729.27	5,556.53	5,470.16
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

Table E5. Line Haul Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Advanced Bottoming Cycle (High 1)	50,000	300,000	600,000	1,000,000	14,900.00	12,507.40	10,895.63	10,186.44
Advanced Bottoming Cycle (High 2)	50,000	300,000	600,000	1,000,000	14,900.00	12,248.31	10,669.92	9,975.42
Coolant/Oil Pump	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	525.00	440.70	383.91	358.92
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	525.00	431.57	375.95	351.48
Low Friction Engine Oil (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	102.50	97.88	94.92	93.45
Engine Friction Reduction	50,000	300,000	600,000	1,000,000	282.00	269.28	261.16	257.10
Reduced Aftertreatment Backpressure	50,000	300,000	600,000	1,000,000	727.50	694.67	673.73	663.26
Air handling Improvement	50,000	300,000	600,000	1,000,000	1,125.00	1,033.62	981.42	965.76
Mechanical Turbocompound	50,000	300,000	600,000	1,000,000	2,500.00	2,296.94	2,180.94	2,146.13
Electric Turbocompound (High 1)	50,000	300,000	600,000	1,000,000	4,200.00	3,525.58	3,071.25	2,871.35
Electric Turbocompound (High 2)	50,000	300,000	600,000	1,000,000	4,200.00	3,452.54	3,007.63	2,811.86
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	35,000.00	29,379.81	25,593.75	23,927.88

HEV (High 2)	50,000	300,000	600,000	1,000,000	35,000.00	28,771.19	25,063.56	23,432.20
Diesel APU	50,000	300,000	600,000	1,000,000	10,000.00	9,187.77	8,723.74	8,584.53
Battery APU	50,000	300,000	600,000	1,000,000	6,400.00	5,880.17	5,583.19	5,494.10
Fuel Fired Heater	50,000	300,000	600,000	1,000,000	1,200.00	1,102.53	1,046.85	1,030.14
Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Air Compressor Improvements	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Shore Power	50,000	300,000	600,000	1,000,000	1,050.00	1,002.62	972.39	957.28
Aero: Trailer (Side) skirt (4 to 6 m)	25,000	150,000	300,000	700,000	550.00	525.18	509.35	498.79
Aero: Boat tail	25,000	150,000	300,000	500,000	1,200.00	1,145.85	1,111.31	1,094.03
Aero: Complete trailer skirt (7 to 9 m)	50,000	300,000	600,000	1,000,000	925.00	883.26	856.63	843.32
Aero: Full tractor skirt (over axles)	25,000	150,000	300,000	500,000	1,750.00	1,671.04	1,620.66	1,595.46
Aero: Gap filler	25,000	150,000	300,000	500,000	825.00	787.78	764.02	752.15
Aero on regional haul	25,000	150,000	300,000	500,000	1,150.00	1,098.11	1,065.00	1,048.45
Improved Transmissions	50,000	300,000	600,000	1,000,000	1,800.00	1,653.80	1,570.27	1,545.22
AMT vs. Manual	50,000	300,000	600,000	1,000,000	4,000.00	3,675.11	3,489.50	3,433.81
Dual Clutch Automatic (High 1)	50,000	300,000	600,000	1,000,000	10,350.00	8,688.03	7,568.44	7,075.82
Dual Clutch Automatic (High 2)	50,000	300,000	600,000	1,000,000	10,350.00	8,508.05	7,411.65	6,929.24
Low Rolling Resistance Tires (per tire)	3,000,000	18,000,000	36,000,000	60,000,000	40.50	38.67	37.51	36.92
Single Wide Tires (per tire & wheel)	300,000	1,800,000	3,600,000	6,000,000	141.00	134.64	130.58	128.55
Automatic Tire Pressure Control	50,000	300,000	600,000	1,000,000	1,142.50	1,090.95	1,058.06	1,041.61
Weight Reduction (2,000 pounds)	300,000	1,800,000	3,600,000	6,000,000	12,000.00	11,458.55	11,113.06	10,940.32
6X2 Tractors or Clutched 6X4	300,000	1,800,000	3,600,000	6,000,000	1,100.00	1,050.37	1,018.70	1,002.86
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

Abbreviations

A/C	Air conditioner
AMT	Automated manual transmission
APU	Auxiliary power unit
ATI	Automated tire inflation
BMEP	Brake mean effective pressure
C_d	Drag coefficient
C_{rr}	Rolling resistance coefficient
CARB	California Air Resources Board
D	Diesel
DOT	Department of Transportation
ECM	Engine control module
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EV	Electric vehicle
G	Gasoline
GDI	Gasoline direct injection
GHG	Greenhouse gas
HD	Heavy-duty
HEV	Hybrid Electric Vehicle
ICF	Indirect Cost Factor
LRR	Low rolling resistance
MD	Medium-duty
mpg	Miles per gallon
MY	Model year
n/a	Not applicable
NA	Naturally aspirated
NAS	National Academy of Sciences
NHTSA	National Highway Traffic Safety Administration
NNI	No net increase
O&M	Operation and maintenance

OEM	Original equipment manufacturer
OHC	Overhead camshaft
OHV	Overhead valve
PFI	Port fuel injection
RPM	Revolutions per minute
SCR	Selective catalytic reduction
SwRI	Southwest Research Institute
TBD	To be determined
VMT	Vehicle miles traveled
VVA	Variable valve actuation
VVL	Variable valve lift
VVT	Variable valve timing

1 Introduction

This report accompanies the work performed by Southwest Research Institute (SwRI) in collaboration with the U.S. Department of Transportation (DOT) and the National Highway Traffic Safety Administration (NHTSA) on fuel efficiency and emissions reduction technologies. Technologies are evaluated for medium-duty (MD) and heavy-duty (HD) fuel vehicles for model years (MY) 2019 and beyond. Based on the list of technologies and configurations identified by SwRI, this report examines the costs of implementation in constant 2011 U.S. dollars, in the areas of: 1) incremental retail prices and 2) life cycle cost elements.

Incremental retail prices are evaluated relative to the prices of the specific baseline technologies that would otherwise be used in the vehicles if the fuel efficiency and emissions reduction technologies were not implemented (prices are assumed to remain unchanged in the absence of new regulations). These prices include the technology components as well as their installation and incorporation in the vehicle. Incremental retail prices account for all costs associated with the manufacturers and suppliers' production and sale of the technologies to the retail purchaser.

The life cycle cost element portion of the assessment examines the costs of using the technologies during the vehicles' lifetimes. In addition to the initial purchase costs of the technologies, the technologies' effects on fuel consumption, brake maintenance, major overhaul intervals, vehicle life, and other operations and maintenance (O&M) costs are quantified. Life cycle cost elements reported here are intended to inform a broader life cycle analysis that takes into account additional factors such as fuel expenses.

This report provides details of the costing methodology and findings and is organized as follows. First, Section 2 describes the fuel efficiency and emissions reduction technologies, including their vehicle applications and technology content. Next, Section 3 presents the incremental retail prices for the individual technologies with their corresponding cost curves by manufacturing volume. Finally, building off of these incremental prices, Section 4 presents the life cycle cost elements of using the technologies in the various vehicle applications.

2 Fuel Efficiency and Emissions Reduction Technologies

Specific fuel efficiency and emissions reductions technologies for engines and vehicles were selected and modeled by SwRI. The technologies were selected by NHTSA and SwRI with input from EPA, California Air Resources Board (CARB), and others. The costs corresponding to each of these technologies are estimated in this report. The technologies are divided into three applications: Class 2b&3, Vocational, and Line Haul. The Class 2b&3 application encompasses the light heavy-duty vehicles, operating with either gasoline or diesel engines, while at the other end of the spectrum, the Line Haul application encompasses the heaviest Class 8 diesel vehicles used in long distance duty cycles. The Vocational application spans a range of weight classes and is represented by Class 4 to Class 7 medium heavy-duty vehicles. Vocational also includes straight trucks up through Class 8, such as dump trucks, cement trucks, and refuse trucks (these vehicles were not specifically addressed in this study). At present, vehicles in classes 4 to 7 (such as delivery and bucket trucks) operate primarily with diesel engines, though improving gasoline engine technologies may encourage the increased use of gasoline engines in the Vocational category. Note that in many cases, engines (and therefore incremental prices) are common (or at least very similar) for the classes 2b to 7. Table 1 lists the fuel efficiency and emissions reduction technologies evaluated for each of these applications as specified by SwRI. Note that not all technologies are suitable for all vehicles, and technologies are applied where appropriate.

Table 1. Fuel Efficiency and Emissions Reduction Technologies

Technology	Application					Technology Content
	Class 2b&3 (gasoline)	Class 2b&3 (diesel)	Vocational (gasoline)	Vocational (diesel)	Line Haul	
Engine Technologies:						
Advanced bottoming cycle	N/A	N/A	N/A	N/A	X	For DD15 engine; Steam cycle for 30 kW system
Coolant/Oil Pump	X 2 stage pumps	X variable pumps	X 2 stage pumps	X variable pumps	X variable pumps	For 6.2L V8, ISB, DD15 engines; viscous drive clutch, actuator pin-out on ECM, wiring. 2-stage oil pump for gasoline engines, variable displacement for diesels.
Variable valve actuation (VVA)	X	N/A	X	N/A	X	For 6.2L V8 (OHC), DD15; variable valve lift and timing mechanism similar to BMW Valvetronic, Sturman is an option for diesel

Cylinder deactivation	X	N/A	X	N/A	N/A	For 6.2L V-8 (OHC); systems similar to GM "Displacement on Demand" (pushrod) and Honda 3.5 V-6 cylinder deactivation system (OHC)
Stoichiometric gasoline direct injection (GDI)	X	N/A	X	N/A	N/A	For 6.2L V-8 (OHC); 150 to 200 bar GDI fuel system to replace PFI (assume PM filter)
Lean burn GDI with selective catalytic reduction (SCR)	X	N/A	X	N/A	N/A	For 6.2L V-8 (OHC); add SCR system similar to that used on diesel pickup trucks
Stoichiometric GDI + exhaust gas recirculation (EGR)	New control strategy concept, no costs shown	N/A	X	N/A	N/A	For 3.5L V-6; EGR valve, EGR cooler, plumbing, high energy ignition system
Turbocharging & downsizing	X	N/A	X	N/A	X cost limit*	Ford EcoBoost 3.5L V-6 vs. 6.2L PFI V-8, upgrade is higher cylinder pressure capability. *For 5-cylinder vs. 6-cylinder DD15 in Line Haul, Tetra Tech expects engine downsizing to be zero incremental cost if OEM has portfolio of alternative engine sizes.*
Engine down speeding	X	N/A	X	N/A	X cost limit*	High BMEP 3.5 V-6 with EGR vs. current version, with 8-speed auto vs. 6 speed (gasoline); high BMEP version of DD15 compared to current, with 10 speed AMT vs. 16-18 speed (diesel); reduced cruise RPM, requires transmission technology

Low friction engine oil	X	X	X	X	X	For 6.2L V8, ISB 6.7L, DD15; low friction oil vs. non-synthetic current product; priced per volume for full engine capacity
Engine friction reduction	X	X	X	X	X	For 6.2L V8, ISB 6.7L, DD15; improve low-tension piston rings, roller cam followers, crankshaft design and bearings, and piston/cylinder surface treatments.
Stop/start	X	X	X	X	N/A	For 6.2L V8, ISB 6.7L; more capable vehicle battery and starter, control system development
Improved SCR conversion	*N/A*	*X*	*N/A*	*X*	*X*	*Tetra Tech expects future SCR improvements to occur continuously at zero incremental cost.*
Reduced aftertreatment backpressure	N/A	N/A	N/A	N/A	X	For DD15; Increase catalyst volume by 50% to reduce backpressure
Turbo efficiency improvement	*X*	*X*	*X*	*X*	*X*	*Tetra Tech expects turbo efficiency improvement to be zero incremental cost.*
Air handling improvements	N/A	N/A	N/A	N/A	X	For DD15; larger, reduced restriction charge air cooler – 50% reduction
Mechanical turbo-compound	N/A	N/A	N/A	N/A	X	For DD15; turbocompound system hardware, including gear train
Electric turbo-compound	N/A	N/A	N/A	N/A	X	For DD15; system with drive for electric motor/generator (include 20 kW generator)
Vehicle & Trailer Technologies:						

Hybrid Electric Vehicle	X		X		X	Parallel hybrid-electric powertrain, integrated starter-alternator technology with idle off, and regenerative braking capability
Automatic engine shutdown	*N/A*	*N/A*	*X*	*X*	*X*	*Tetra Tech expects automatic engine shutdown to be zero incremental cost.*
Diesel auxiliary power unit (APU)	N/A	N/A	N/A	N/A	X	For DD15; existing market system
Battery APU	N/A	N/A	N/A	N/A	X	For DD15; existing market system
Fuel fired heater	N/A	N/A	N/A	N/A	X	For DD15; existing market system
Air conditioner (A/C) system improvements	X		X		X	Vehicle dependent, not engine dependent; Higher efficiency compressor, separate electric condenser fan to avoid use of engine-driven fan.
A/C reduced reheat	*New control strategy concept, no costs shown*		*New control strategy concept, no costs shown*		*New control strategy, no costs shown*	*Cabin and intake air humidity sensors, controls. Control Strategy and no Hardware Cost.*
Cab insulation to reduce A/C	X		X		X	Vehicle dependent, not engine dependent; Infrared suppression glass treatment, 50% increase in cab thermal insulation
Air compressor improvements	N/A	N/A	N/A	N/A	X clutched/ variable pumps	Not engine dependent; Clutch similar to A/C compressor clutch, pinout on ECM, wiring
Shore power	N/A	N/A	N/A	N/A	X	For DD15; existing market system

Aero Bin III (not priced as a group)	N/A	N/A	N/A	N/A	X	For DD15; tractor features are baseline 2019, trailer (side) skirt (4 to 6 m) (priced separately)
	N/A	N/A	N/A	N/A	X	For DD15; tractor features are baseline 2019, boat tail (priced separately)
Aero Bin IV and V (not priced as a group)	N/A	N/A	N/A	N/A	X	For DD15; complete trailer skirt (7 to 9 m) (priced separately)
	N/A	N/A	N/A	N/A	X	For DD15; complete tractor skirt (over axles) (priced separately)
	N/A	N/A	N/A	N/A	X	For DD15; gap filler (priced separately)
Include trailer C_d and C_{rr} in rule	N/A	N/A	N/A	N/A	X	For DD15; compare SmartWay spec trailer to standard spec
Aero on regional haul	N/A	N/A	N/A	N/A	X	For DD15/ DD12; aero day cab tractor vs. standard (air dam, tank skirts, cab top shield, gap reducer), trailer skirts
Class 2b&3 improved aerodynamics	X		N/A		N/A	Not engine dependent; active grill shutters, belly pan under engine, belly pan under complete chassis, wheel well skirts
Improved transmissions	X	X	X	X	X	For 6.2L V8, ISB, DD15; ZF 8-speed vs. current Aisin 6-speed (Class 2b&3); 8 speed automatic vs. current Allison 2000 5/6 speed (Vocational); 16 - 18 speed AMT vs. current 10 speed (Line Haul); more gears, higher ratio spread, shift points

Automated manual transmission (AMT)	N/A		X		X	Not engine dependent; compare Eaton Ultrashift HV model FO-6406 B vs. manual equivalent (Vocational); Eaton Ultrashift AMT FO-16E301C-LAS vs. manual equivalent (Line Haul)
Dual clutch automatic	N/A		X		X	Not engine dependent; 10 speed DCT vs. current 6 speed automatic (Vocational); 16-18 speed DCT vs. current 10 speed manual (Line Haul)
Low rolling resistance (LRR) tires	X		X		X	Not engine dependent; lower C_{rr} tires; priced per tire
Single wide tires	N/A	N/A	N/A	N/A	X	For DD15; compare low C_{rr} wide base single wheels and tires to current SmartWay approved duals; priced per tire & wheel
Automated tire inflation (ATI)	N/A		X		X	Automated Tire Inflation systems continually monitor and adjust the level of pressurized air in tires.
Weight reduction	X		X		X	500 pounds for Class2b/3, 1,000 pounds for Vocational, 2,000 pounds for long haul tractor/trailer
6x2 tractors	N/A	N/A	N/A	N/A	X	For DD15; compare standard 6x4 setup with a 6x2 with air suspension that allows weight to be shifted to the one drive axle in low mu conditions.
Chassis friction reduction & improved lube	X		X		X	Not engine dependent; synthetic lube vs. standard, most efficient axles vs. standard

Speed limiters	*N/A*	*N/A*	*X*	*X*	*X*	For DD15. *Tetra Tech expects speed limiters to be zero incremental cost.*

* Customization Cost Limit - $600 million to develop a new engine (estimated cost of a new engine product line including engineering costs was not analyzed for this report)

3 Incremental Retail Prices

The methodology used here for determining incremental retail prices relies on a thorough literature review (peer reviewed or other highly credible sources available at the time of the literature search) for all target technologies to identify ranges of price points. The data reported here draw heavily upon the most recent peer reviewed National Research Council studies of medium- and heavy-duty vehicle technologies, in which OEMs agreed to provide detailed cost information during site visits and interviews.[9,10] From published studies and data, prices of fuel efficiency and emissions reduction technologies are reported as incremental retail prices. In cases where single technologies are combined into a technology package, the price of the package is defined as the sum of the prices of the components (this is a conservative estimate since there may be price reductions from combining technologies).

The ranges of values found in the literature are scaled to project incremental prices using manufacturing volume-dependent cost curves. The cost curves are calculated from two components:

- Direct costs, which encompass materials, labor, and other relatively fixed costs of technology manufacture
- Indirect costs, which are divided into production overhead (warranty, R&D/engineering, and depreciation and amortization), corporate overhead, selling and dealer support (distribution, marketing, dealer support, and dealer discount), and net income to the manufacturer

Indirect costs are derived from direct costs using an adjusted multiplier. This multiplier contains two main factors (indirect cost factors and manufacturing process improvements) that determine the final incremental price of the technology to the purchaser over increasing production volume. The first main factor is derived from research conducted for the U.S. Environmental Protection Agency (EPA) and reflects manufacturer costs that are difficult to allocate to specific production activities, such as R&D, corporate operations, dealer support, and marketing.[11,12,13] Taking into account the complexity of the technology, this type of cost

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[9] National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.

[10] National Research Council, "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report," The National Academies Press Pre-Publication copy, 2014

[11] Rogozhin, A., M. Gallaher, W. McManus. "Automotive Industry Retail Price Equivalent and Indirect Cost Multipliers." Prepared by RTI International and Transportation Research Institute, University of Michigan for the U.S. Environmental Protection Agency. February 2009.

[12] Rogozhin, A., M. Gallaher, A. Lentz, W. McManus. "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers." Prepared by RTI International and Transportation Research Institute, University of Michigan for the U.S. Environmental Protection Agency. July 2010.

reduction results from short- and long-term indirect cost factors, as shown in Table 2. The time based short- and long- term indirect cost factors are used to estimate the decrease in costs as the cumulative manufacturing volume increases over time. The indirect cost factors account for differences in the technical complexity of the required vehicle modifications and adjust for increasing production volumes as new technologies become assimilated into the manufacturing process. The indirect costs portion of the incremental price is further broken out into four elements: production overhead, corporate overhead, selling and dealer support, and net income. The relative contributions of each of these elements to the total indirect cost are based on research by Argonne National Laboratory for the U.S. Department of Energy that examined and modified Argonne National Laboratory's incremental cost components of implementing new vehicle technologies.[14,15] Table 3 shows the complexity levels for the technology considered in this report.

Table 2. Indirect Cost Factors

Low Technology Complexity		Medium Technology Complexity		High 1 Technology Complexity		High 2 Technology Complexity	
Short-Term	Long-Term	Short-Term	Long-Term	Short-Term	Long-Term	Short-Term	Long-Term
1.24	1.19	1.39	1.29	1.56	1.35	1.77	1.50

Table 3. Technology Complexity Levels

Technology	Technology Complexity
Engine Technologies	
Advanced Bottoming Cycle	High 1/**High 2**
Coolant/Oil Pump	Medium
Variable Valve Actuation	**High 1**/High 2
Cylinder Deactivation	Medium
Stoichiometric GDI	Medium
Lean Burn GDI w/ SCR	Medium

[13] U.S. Environmental Protection Agency, "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA report # EPA-420-R-12-901, August 2012

[14] Cuenca, R.M., L.L. Gaines, A.D. Vyas. "Evaluation of Electric Vehicle Production and Operating Costs." Prepared by Argonne National Laboratory for the U.S. Department of Energy. ANL/ESD-41. November 1999.

[15] Vyas, A., D. Santini, R. Cuenca. "Comparison of Indirect Cost Multipliers for Vehicle Manufacturing." Prepared by Argonne National Laboratory for the U.S. Department of Energy. April 2000.

Stoichiometric GDI + EGR	Medium
Turbocharging & Downsizing	Medium
Engine Downspeeding	Medium
Low Friction Engine Oil	Low
Engine Friction Reduction	Low
Stop / start	Medium
Reduced Aftertreatment Backpressure	Low
Air handling Improvement	Medium
Mechanical Turbocompound	Medium
Electric Turbocompound	**High 1**/High 2
Vehicle & Trailer Technologies	
Hybrid Electric Vehicle	**High 1**/High 2
Diesel APU	Medium
Battery APU	Medium
Fuel Fired Heater	Medium
Air Conditioner System Improvements	Medium
Cab Insulation to Reduce A/C	Low
Air Compressor Improvements	Medium
Fan Power Demand Reduction	Medium
Thermal Storage for A/C	Medium
Shore Power	Low
Aero: Trailer (Side) skirt (4 to 6 m)	Low
Aero: Boat tail	Low
Aero: Complete trailer skirt (7 to 9 m)	Low
Aero: Full tractor skirt	Low
Aero: Gap filler	Low
Aero on regional haul	Low
Improved 2b & 3 Aerodynamics	Low
Improved Transmissions	Medium

AMT vs. Manual	Medium
Dual Clutch Automatic	**High 1**/High 2
Low Rolling Resistance Tires	Low
Single Wide Tires	Low
Automatic Tire Pressure Control	Low
Weight Reduction	Low
6X2 Tractors or Clutched 6X4	Low
Chassis friction reduction & improved lube	Low

The second main factor of the adjusted multiplier reflects improvements in the manufacturing process that take place as the technology matures (newness of the technology as it applies to the manufacturing process). As described by the Center for Automotive Research, manufacturing process efficiencies that are learned over time are captured in this type of cost reduction and are expressed as an annual percent improvement from the previous year (Table 4).[16] Advanced Electronics and electronic control systems are the newest technology to be incorporated into the manufacturing process. Electrical Machines (such as motor, generator, gears, and electrical accessories) are more mature than Advanced Electronics in the manufacturing process. Developing Technologies are mature technologies in the manufacturing process but are still developing (such as mass reduction materials). Advanced Electronics are assumed to be associated with the highest technology complexity with Developing Technologies associated with the lowest technology complexity (leaving Electrical Machines with medium technology complexity).

Table 4. Manufacturing Process Improvements

Advanced Electronics	Electrical Machines	Developing Technologies
3%	1%	0.5%

The indirect cost factors and the manufacturing process improvements (newness) then are multiplied together to derive the adjusted multipliers that make up the volume-dependent technology cost curves for each of the identified technologies. From the cost curves, incremental prices at different manufacturing volumes can be calculated. NHTSA requested the analysis to be presented in terms of volume for their modeling analysis work. The agencies' modeling analyses use "learning" for the purposes of reducing technology costs which resulted

[16] Center for Automotive Research. "The U.S. Automotive Market and Industry in 2025." June 2011.

from efficiency improvements that occurred as production volumes increased, or with incremental process and design revisions that occurred over a period of time (years). Thus the models use two types of learning: volume-based learning, which reduces costs for newly available, low-volume technologies expected to undergo significant production volume increases during the rulemaking period; and time-based learning, which reduced the costs for established, readily available technologies currently in high-volume production, over the course of a multi-year contract. Since the Phase 2 GHG and fuel efficiency standards will potentially drive adoption of advanced technologies that are newly available and low-volume, the incremental technology price are presented in terms of volume to facilitate a volume-based learning approach.

As production runs are successful, in terms of cost reductions from continuous improvements and paying off capital expenditures, profits for the manufacturer are expected to increase. In other words, production overhead is expected to decrease and net income is expected to increase over time and with increasing manufacturing volume (in the idealized case of successful production runs). In addition, because cost curves are different for different technology complexity levels, the relative contributions of the cost elements are expected to differ as well. This report primarily draws upon reported incremental retail prices (which may have been based upon varying indirect cost factor estimates) of published studies and data. A teardown analysis was not performed in this report to determine the breakout between the direct and indirect cost elements. To estimate the cost element breakouts in the incremental price, the relative cost contributions for truck manufacturers in RTI's 2010 heavy duty truck report were used.[17] Table 5, Table 6, Table 7, and Table 8 show the estimated cost breakouts applied to the total incremental price used in this analysis. As shown, the relative net income increases with increasing technology complexity, reflecting the manufacturers' business case for investing in the production of more complex technologies. The current analysis doesn't attempt to identify pre-production prices of experimental or very low volume production runs. The estimated volume for individual technologies is an attempt to identify the North American volume of a production assembly line (no assumptions of global volumes were made). This will vary by type of technology and vehicle class. 50,000 units was a baseline initial amount agreed upon as reasonable after discussions between Tetra Tech and SwRI. Adjustments were made for items that are produced in lower volume, like side skirts, and those at higher volume, like quarts of oil and tires.

Table 5. Relative Cost Contributions for Low Technology Complexity

Cost Element	Share of Incremental Price		
	50,000 Units	300,000 Units	600,000 Units

[17] Rogozhin, A., M. Gallaher, A. Lentz, W. McManus. "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers." Prepared by RTI International and Transportation Research Institute, University of Michigan for the U.S. Environmental Protection Agency. July 2010.

Vehicle manufacturing (direct)	87%	89%	91%
Production overhead	6%	4%	3%
Corporate overhead	2%	1%	1%
Selling and dealer support	1%	1%	1%
Net income	4%	4%	5%

Table 6. Relative Cost Contributions for Medium Technology Complexity

Cost Element	Share of Incremental Price		
	50,000 Units	300,000 Units	600,000 Units
Vehicle manufacturing (direct)	79%	82%	86%
Production overhead	10%	8%	6%
Corporate overhead	2%	2%	2%
Selling and dealer support	5%	3%	2%
Net income	4%	4%	4%

Table 7. Relative Cost Contributions for High 1 Technology Complexity

Cost Element	Share of Incremental Price		
	50,000 Units	300,000 Units	600,000 Units
Vehicle manufacturing (direct)	70%	75%	79%
Production overhead	15%	12%	9%
Corporate overhead	4%	4%	4%
Selling and dealer support	7%	6%	5%
Net income	4%	4%	4%

Table 8. Relative Cost Contributions for High 2 Technology Complexity

Cost Element	Share of Incremental Price		
	50,000 Units	300,000 Units	600,000 Units
Vehicle manufacturing (direct)	64%	69%	73%
Production overhead	21%	18%	15%

Corporate overhead	6%	5%	4%
Selling and dealer support	6%	5%	4%
Net income	3%	3%	4%

Based on the methodology described above, the incremental price curve and price breakouts for each technology in each applicable vehicle category are presented below. Note that the vertical bars in the charts represent the low and high values used to calculate the median, not average, incremental price (values selected were based upon the range of values found and the detail is presented in Appendix A). The regression formulas for all the total incremental price curves (the solid green line) is a best fit polynomial (second order) regression analysis/trend line through the four total incremental price points. All prices are presented on a *cumulative* volume basis across the entire market (time based units/year was a proxy to apply adjustment factors for production volume); no distinctions are made among specific suppliers, factories, or manufacturing lines. It is important to note that because prices are for cumulative volumes, volumes across vehicle classes may be additive. For example, if the same gasoline engine is used in both Class 2b&3 and Vocational vehicles, the industry total volume for a technology on that engine will include volumes from both vehicle categories. As a result, the incremental price of the technology may be lower than the price according the volume in a single vehicle category. Technologies that apply only to a single vehicle category will accumulate volumes more slowly than those technologies that apply to multiple categories (refer to Table 1).

Example using the methodology and application of Indirect Cost Factors (ICF):

a. Range of full retail price is estimated

b. High and low range limits are estimated for calculation (for example, $500 for High range).

c. Initial volume is estimated (for example, 50,000/year)

d. Complexity and Newness of Technology is estimated from Table 2, Table 3, and Table 4 above (for example, Medium complexity and newness of Electrical Machines) [Options are Low/Medium/High Technology Complexity with Developing Technologies/Electrical Machines/Advanced Electronics Newness]

e. With Medium Tech Complexity, the 2012 ICF for short (1 year) and long term (5 year) are 1.39 and 1.29 respectively. A power function formula is used estimate the initial years. For our example, Y=1.39X^(-0.046) where X=year and Y=ICF

f. Using the ICF power function, ICF for years 1 to 5 are calculated. Years after 5, the ICF remain constant. For this example, the ICF at this point in the calculation for the years 1 through 10 are:

Years	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Cumulative Volume	50,000	100,000	150,000	200,000	250,000	300,000	350,000	400,000	450,000	500,000
ICF, Med Tech Complexity	1.39	1.35	1.32	1.30	1.29	1.29	1.29	1.29	1.29	1.29

g. For Newness of technology, a factor of 1 is assumed for years 1 to 5, but for years >5, the Electrical machines newness of 1% reduction for each year after year 5 is used to account for the learning curve/economies-of-scale volumes.

h. For example year 1 has the ICF of 1.39 times the Newness of 1 equals the adjusted ICF multiplier which is 100% of the initial ICF.

i. For example year 5 has the ICF of 1.29 times the Newness of 1 equals the adjusted ICF multiplier which is 92.8% of the initial ICF

j. For example year 6 has the ICF of 1.29 times the Newness of 0.99 (100%-1%) equals the adjusted ICF of 1.28 which is 91.9% of the initial ICF. For this example, the adjusted ICF and % of initial adjusted ICF (Medium Technology Complexity with Electrical Machines Newness) at this point in the calculation for the years 1 through 10 are:

Years	1	2	3	4	5	6	7	8	9	10
Cumulative Volume	50,000	100,000	150,000	200,000	250,000	300,000	350,000	400,000	450,000	500,000
ICF, Med Tech Complexity	1.39	1.35	1.32	1.30	1.29	1.29	1.29	1.29	1.29	1.29
Electrical Machines Newness	100%	100%	100%	100%	100%	99.0%	98.0%	97.0%	96.0%	95.0%
Adjusted ICF	1.39	1.35	1.32	1.30	1.29	1.28	1.26	1.25	1.24	1.23
% of Initial Adjusted ICF	100.0%	96.9%	95.1%	93.8%	92.8%	91.9%	90.9%	90.0%	89.1%	88.2%

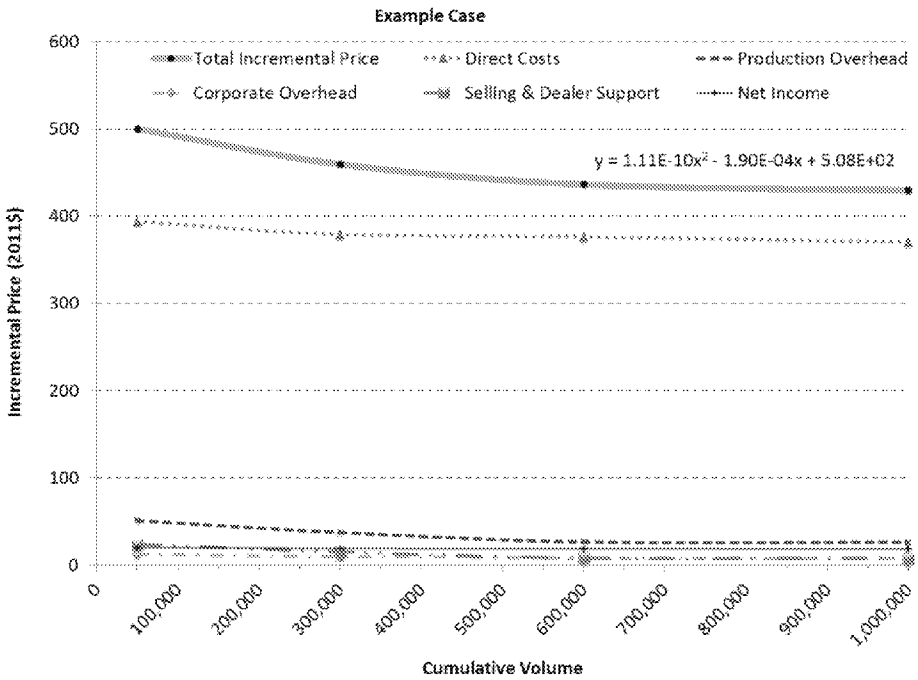
k. The High estimate of $500 (initial price at year 1 and 50,000 units) becomes in year 6 = $459 ($500 times 91.9%) at a cumulative volume of 300,000 (50,000 times 6).

l. This process is done for each year for the high and low ranges out to year 20 (which for our example of 50,000 start volume, has a cumulative volume of 1,000,000 in year 20).

m. The direct/indirect breakouts (direct cost, production overhead, corporate overhead, selling/dealer support, and net income) are applied to the median price based upon the Low/Medium/High Technology and the start/mid/long/end range estimate (Year 1/50,000, Year 6/300,000, Year 12/600,000, Year 20/1,000,000).

n. The 2010 RTI HD Report (for Truck Manufacturers) has the relative cost breakout shown in Table 5, Table 6, Table 7, and Table 8. For our example, we applied the Medium Tech % breakout for 50,000 units to year 1, 300,000 units to Year 6, and 600,000 units to Year 12 to get the data/curve breakouts. This produces the following example breakout table and chart:

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$500.00	$459.39	$436.19	$429.23
Direct Costs	$393.70	$378.91	$376.09	$370.09
Production Overhead	$51.18	$37.34	$26.25	$25.83
Corporate Overhead	$11.81	$9.39	$7.52	$7.40
Selling & Dealer Support	$23.62	$14.81	$7.52	$7.40
Net Income	$19.69	$18.95	$18.80	$18.50



To use the price curves, it is suggested that that the "beginning" production volume and an "ending" production volume for each modeling scenario would need to be identified by the modeler. It's unknown at this time if the modeling scenarios will be by year or by production run on a vehicle (multiple years). Since a supplier typically signs a contract to sell units at $/unit over that time, it is suggested that the average amount between the beginning and ending volumes be used for modeling. It's unlikely that manufacturers are going to buy (or sell) technologies at continually declining $/unit amounts. Additional details of the baseline technologies, prior technologies assumed, supporting data, and references can be found in Appendix A. Descriptions of the gasoline engine technologies, diesel engine technologies, vehicle technologies, and bottoming cycle technology can be found in Appendix A, Appendix B, Appendix C, and Appendix D respectively of an accompanying SwRI report.[18]

Projections of future price contain risk. As the technology matures, it may become more or less expensive, or it may prove unable to achieve the expected benefits. Only limited conclusions can be drawn from the evaluation of the technology price results in this report. These price results will be combined with technology performance results in subsequent analyses to allow calculation of cost/benefit ratios for each technology.

[18] Reinhart, T. (2015). Commercial Medium- and Heavy-Duty (MD/HD) Truck Fuel Efficiency Technology Study – Report #1. Washington, DC: National Highway Traffic Safety Administration.

Table 9. Class 2b&3 Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Coolant/Oil Pump (G)	50,000	300,000	600,000	1,000,000	180.00	165.38	157.03	154.52
Coolant/Oil Pump (D)	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	620.00	520.44	453.38	423.87
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	620.00	509.66	443.98	415.08
Cylinder Deactivation	50,000	300,000	600,000	1,000,000	287.50	264.15	250.81	246.81
Stoichiometric GDI	50,000	300,000	600,000	1,000,000	625.00	574.24	545.23	536.53
Lean Burn GDI w/ SCR	50,000	300,000	600,000	1,000,000	1,930.00	1,773.24	1,683.68	1,656.81
Turbocharging & Downsizing	50,000	300,000	600,000	1,000,000	1,390.00	1,277.10	1,212.60	1,193.25
Engine Downspeeding	50,000	300,000	600,000	1,000,000	2,600.00	2,388.82	2,268.17	2,231.98
Low Friction Engine Oil (G) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	7.50	7.16	6.95	6.84
Low Friction Engine Oil (D) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	14.00	13.37	12.97	12.76
Engine Friction Reduction (G)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Engine Friction Reduction (D)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Stop / start (G)	50,000	300,000	600,000	1,000,000	700.00	643.14	610.66	600.92
Stop / start (D)	50,000	300,000	600,000	1,000,000	1,500.00	1,378.17	1,308.56	1,287.68
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	19,500.00	16,368.75	14,259.38	13,331.25
HEV (High 2)	50,000	300,000	600,000	1,000,000	19,500.00	16,029.66	13,963.98	13,055.08
Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Improved 2b & 3 Aerodynamics	50,000	300,000	600,000	1,000,000	280.00	267.37	259.30	255.27
Improved Transmissions (G)	50,000	300,000	600,000	1,000,000	480.00	441.01	418.74	412.06
Improved Transmissions (D)	50,000	300,000	600,000	1,000,000	875.00	803.93	763.33	751.15

Low Rolling Resistance Tires (per tire)	5,000,000	30,000,000	60,000,000	100,000,000	16.00	15.28	14.82	14.59
Weight Reduction (500 pounds)	300,000	1,800,000	3,600,000	6,000,000	2,000.00	1,909.76	1,852.18	1,823.39
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

Table 10. Vocational Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Coolant/Oil Pump (G)	50,000	300,000	600,000	1,000,000	180.00	165.38	157.03	154.52
Coolant/Oil Pump (D)	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	635.00	533.03	464.34	434.12
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	635.00	521.99	454.72	425.13
Cylinder Deactivation	50,000	300,000	600,000	1,000,000	287.50	264.15	250.81	246.81
Stoichiometric GDI	50,000	300,000	600,000	1,000,000	625.00	574.24	545.23	536.53
Lean Burn GDI w/ SCR	50,000	300,000	600,000	1,000,000	1,930.00	1,773.24	1,683.68	1,656.81
Stoichiometric GDI + EGR	50,000	300,000	600,000	1,000,000	1,430.00	1,313.85	1,247.49	1,227.59
Turbocharging & Downsizing	50,000	300,000	600,000	1,000,000	1,390.00	1,277.10	1,212.60	1,193.25
Engine Downspeeding	50,000	300,000	600,000	1,000,000	2,600.00	2,388.82	2,268.17	2,231.98
Low Friction Engine Oil (G) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	7.50	7.16	6.95	6.84
Low Friction Engine Oil (D) (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	14.00	13.37	12.97	12.76
Engine Friction Reduction (G)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Engine Friction Reduction (D)	50,000	300,000	600,000	1,000,000	228.00	217.71	211.15	207.87
Stop / start (G)	50,000	300,000	600,000	1,000,000	700.00	643.14	610.66	600.92
Stop / start (D)	50,000	300,000	600,000	1,000,000	1,500.00	1,378.17	1,308.56	1,287.68
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	32,000.00	26,861.54	23,400.00	21,876.92
HEV (High 2)	50,000	300,000	600,000	1,000,000	32,000.00	26,305.08	22,915.25	21,423.73

Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Improved Transmissions (G)	50,000	300,000	600,000	1,000,000	750.00	689.08	654.28	643.84
Improved Transmissions (D)	50,000	300,000	600,000	1,000,000	1,325.00	1,217.38	1,155.90	1,137.45
AMT vs. Manual	50,000	300,000	600,000	1,000,000	1,050.00	964.72	915.99	901.38
Dual Clutch Automatic (High 1)	50,000	300,000	600,000	1,000,000	2,700.00	2,266.44	1,974.38	1,845.87
Dual Clutch Automatic (High 2)	50,000	300,000	600,000	1,000,000	2,700.00	2,219.49	1,933.47	1,807.63
Low Rolling Resistance Tires (per tire)	700,000	4,200,000	8,400,000	14,000,000	30.50	29.12	28.25	27.81
Automatic Tire Pressure Control	50,000	300,000	600,000	1,000,000	800.00	763.90	740.87	729.35
Weight Reduction (1,000 pounds)	300,000	1,800,000	3,600,000	6,000,000	6,000.00	5,729.27	5,556.53	5,470.16
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

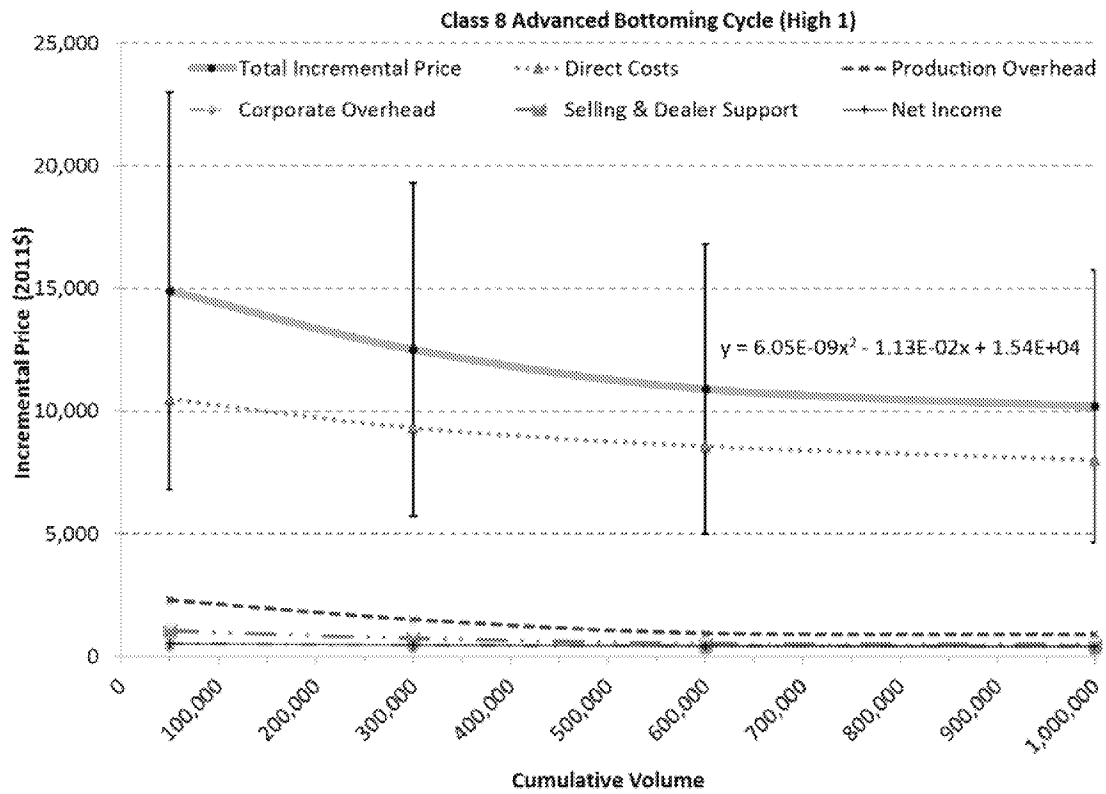
Table 11. Line Haul Summary of Volumes and Total Incremental Price

Technology	Vol. 1	Vol. 2	Vol. 3	Vol. 4	Price 1	Price 2	Price 3	Price 4
Engine Technologies								
Advanced Bottoming Cycle (High 1)	50,000	300,000	600,000	1,000,000	14,900.00	12,507.40	10,895.63	10,186.44
Advanced Bottoming Cycle (High 2)	50,000	300,000	600,000	1,000,000	14,900.00	12,248.31	10,669.92	9,975.42
Coolant/Oil Pump	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Variable Valve Actuation (High 1)	50,000	300,000	600,000	1,000,000	525.00	440.70	383.91	358.92
Variable Valve Actuation (High 2)	50,000	300,000	600,000	1,000,000	525.00	431.57	375.95	351.48
Low Friction Engine Oil (per vehicle)	300,000	1,800,000	3,600,000	6,000,000	102.50	97.88	94.92	93.45
Engine Friction Reduction	50,000	300,000	600,000	1,000,000	282.00	269.28	261.16	257.10
Reduced Aftertreatment Backpressure	50,000	300,000	600,000	1,000,000	727.50	694.67	673.73	663.26

Air handling Improvement	50,000	300,000	600,000	1,000,000	1,125.00	1,033.62	981.42	965.76
Mechanical Turbocompound	50,000	300,000	600,000	1,000,000	2,500.00	2,296.94	2,180.94	2,146.13
Electric Turbocompound (High 1)	50,000	300,000	600,000	1,000,000	4,200.00	3,525.58	3,071.25	2,871.35
Electric Turbocompound (High 2)	50,000	300,000	600,000	1,000,000	4,200.00	3,452.54	3,007.63	2,811.86
Vehicle & Trailer Technologies								
HEV (High 1)	50,000	300,000	600,000	1,000,000	35,000.00	29,379.81	25,593.75	23,927.88
HEV (High 2)	50,000	300,000	600,000	1,000,000	35,000.00	28,771.19	25,063.56	23,432.20
Diesel APU	50,000	300,000	600,000	1,000,000	10,000.00	9,187.77	8,723.74	8,584.53
Battery APU	50,000	300,000	600,000	1,000,000	6,400.00	5,880.17	5,583.19	5,494.10
Fuel Fired Heater	50,000	300,000	600,000	1,000,000	1,200.00	1,102.53	1,046.85	1,030.14
Air Conditioner System Improvements	50,000	300,000	600,000	1,000,000	317.50	291.71	276.98	272.56
Cab Insulation to Reduce A/C	50,000	300,000	600,000	1,000,000	375.00	358.08	347.28	341.89
Air Compressor Improvements	50,000	300,000	600,000	1,000,000	350.00	321.57	305.33	300.46
Shore Power	50,000	300,000	600,000	1,000,000	1,050.00	1,002.62	972.39	957.28
Aero: Trailer (Side) skirt (4 to 6 m)	25,000	150,000	300,000	700,000	550.00	525.18	509.35	498.79
Aero: Boat tail	25,000	150,000	300,000	500,000	1,200.00	1,145.85	1,111.31	1,094.03
Aero: Complete trailer skirt (7 to 9 m)	50,000	300,000	600,000	1,000,000	925.00	883.26	856.63	843.32
Aero: Full tractor skirt (over axles)	25,000	150,000	300,000	500,000	1,750.00	1,671.04	1,620.66	1,595.46
Aero: Gap filler	25,000	150,000	300,000	500,000	825.00	787.78	764.02	752.15
Aero on regional haul	25,000	150,000	300,000	500,000	1,150.00	1,098.11	1,065.00	1,048.45
Improved Transmissions	50,000	300,000	600,000	1,000,000	1,800.00	1,653.80	1,570.27	1,545.22
AMT vs. Manual	50,000	300,000	600,000	1,000,000	4,000.00	3,675.11	3,489.50	3,433.81
Dual Clutch Automatic (High 1)	50,000	300,000	600,000	1,000,000	10,350.00	8,688.03	7,568.44	7,075.82
Dual Clutch Automatic (High 2)	50,000	300,000	600,000	1,000,000	10,350.00	8,508.05	7,411.65	6,929.24

Low Rolling Resistance Tires (per tire)	3,000,000	18,000,000	36,000,000	60,000,000	40.50	38.67	37.51	36.92
Single Wide Tires (per tire & wheel)	300,000	1,800,000	3,600,000	6,000,000	141.00	134.64	130.58	128.55
Automatic Tire Pressure Control	50,000	300,000	600,000	1,000,000	1,142.50	1,090.95	1,058.06	1,041.61
Weight Reduction (2,000 pounds)	300,000	1,800,000	3,600,000	6,000,000	12,000.00	11,458.55	11,113.06	10,940.32
6X2 Tractors or Clutched 6X4	300,000	1,800,000	3,600,000	6,000,000	1,100.00	1,050.37	1,018.70	1,002.86
Chassis friction reduction & improved lube	50,000	300,000	600,000	1,000,000	250.00	238.72	231.52	227.92

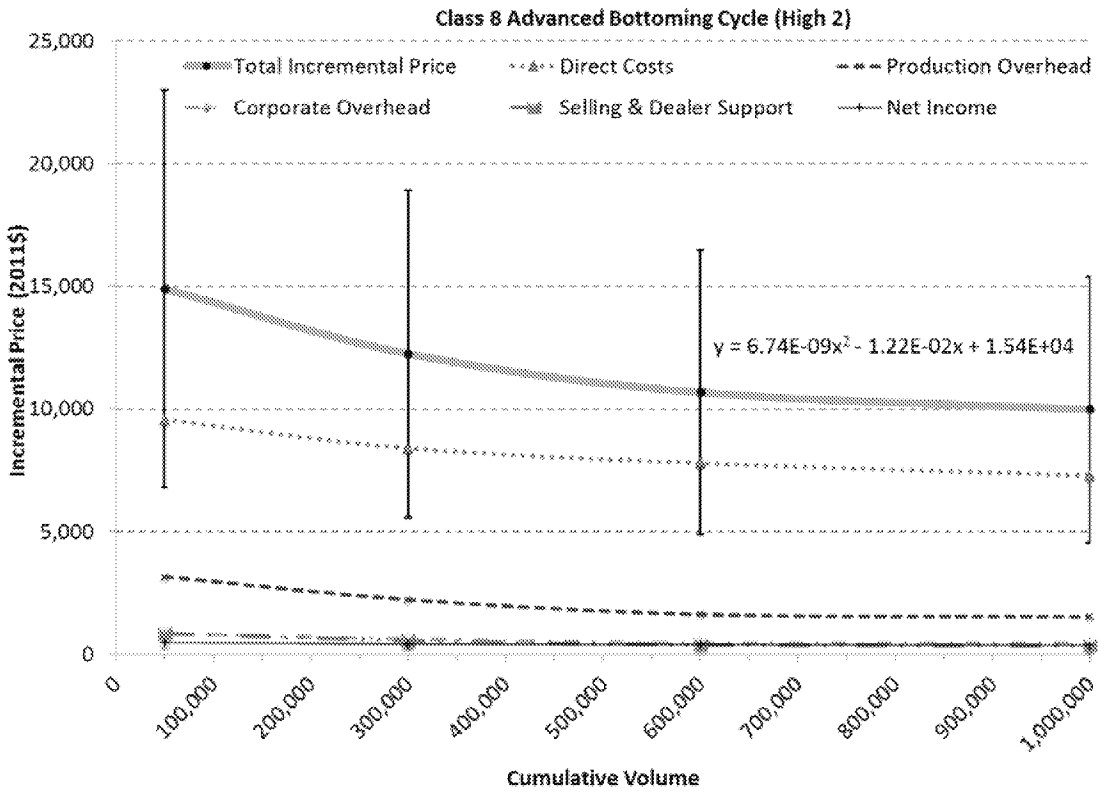
Advanced Bottoming Cycle



Class 8 Advanced Bottoming Cycle (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$14,900.00	$12,507.40	$10,895.63	$10,186.44
Direct Costs	$10,492.96	$9,328.19	$8,579.23	$8,020.82
Production Overhead	$2,308.45	$1,510.54	$943.72	$882.29
Corporate Overhead	$524.65	$466.41	$428.96	$401.04
Selling & Dealer Support	$1,049.30	$735.85	$514.75	$481.25
Net Income	$524.65	$466.41	$428.96	$401.04

Figure 1. Incremental Price and Breakouts for Line Haul Advanced Bottoming Cycle (High 1)

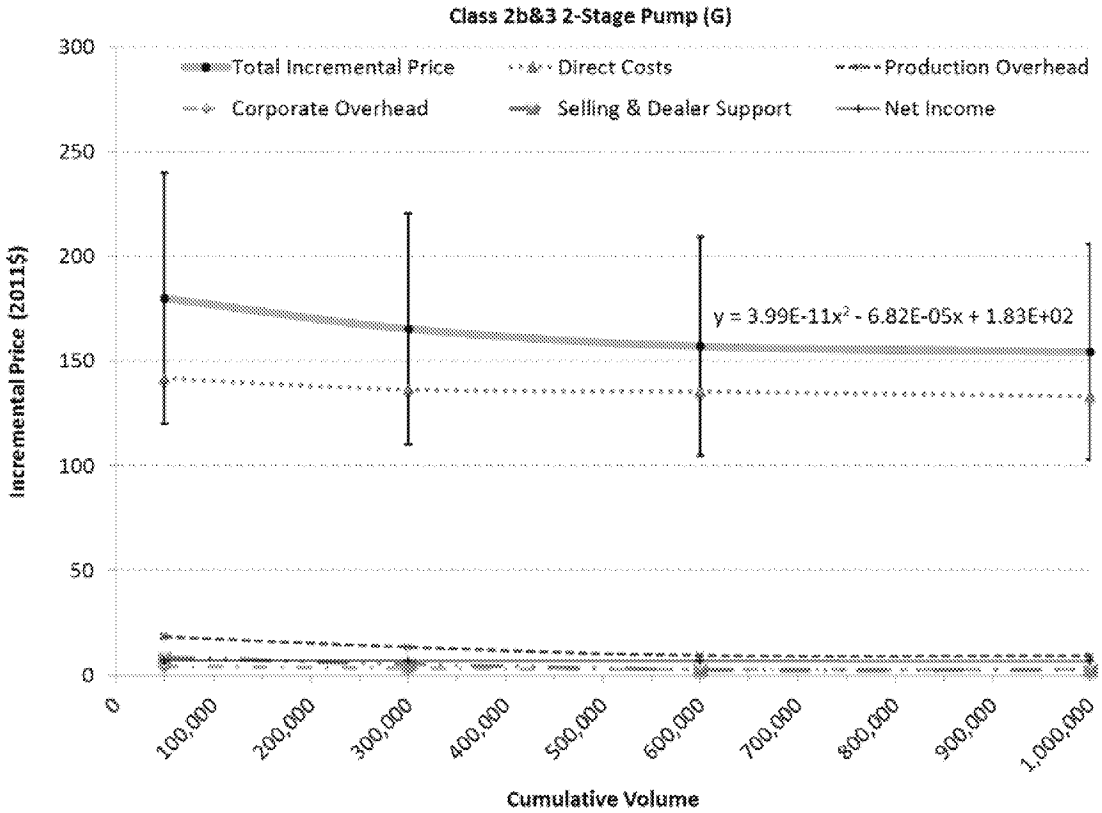


Class 8 Advanced Bottoming Cycle (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$14,900.00	$12,248.31	$10,669.92	$9,975.42
Direct Costs	$9,551.28	$8,402.46	$7,799.65	$7,291.98
Production Overhead	$3,151.92	$2,226.65	$1,622.33	$1,516.73
Corporate Overhead	$859.62	$621.92	$467.98	$437.52
Selling & Dealer Support	$859.62	$577.15	$389.98	$364.60
Net Income	$477.56	$420.12	$389.98	$364.60

Figure 2. Incremental Price and Breakouts for Line Haul Advanced Bottoming Cycle (High 2)

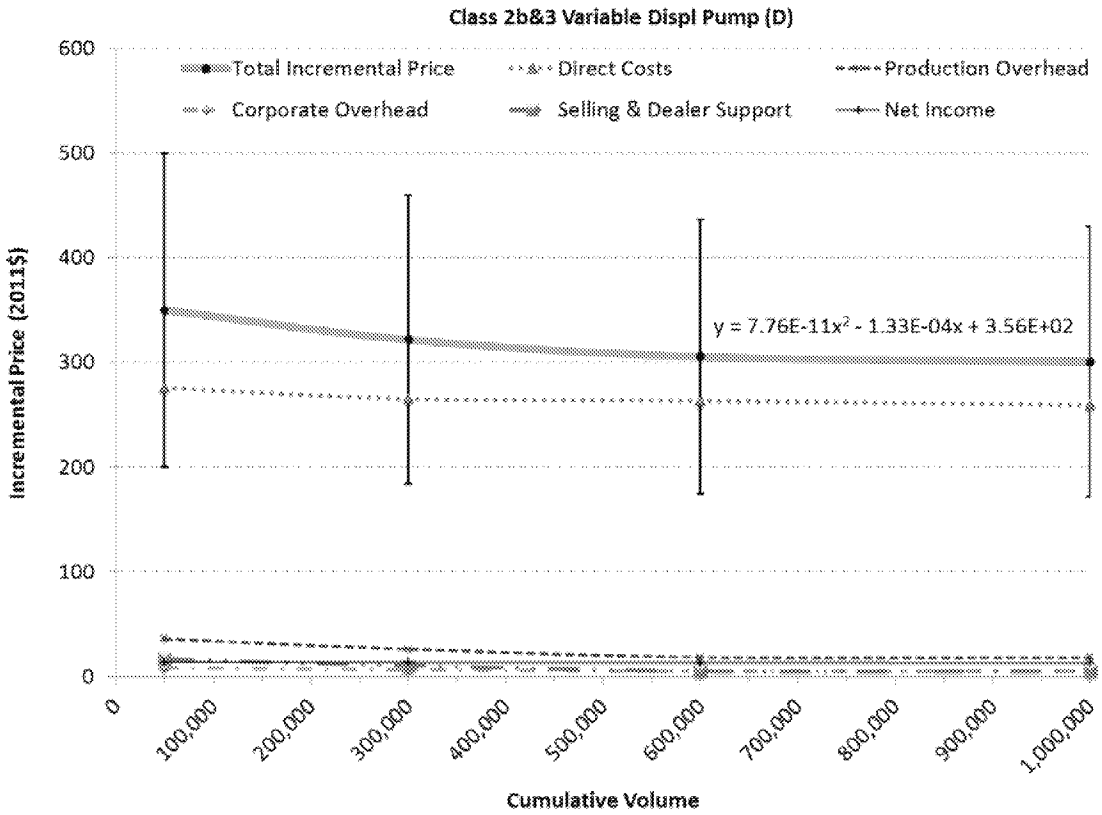
Coolant/Oil Pump



Class 2b&3 2-Stage Pump (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$180.00	$165.38	$157.03	$154.52
Direct Costs	$141.73	$136.41	$135.39	$133.23
Production Overhead	$18.43	$13.44	$9.45	$9.30
Corporate Overhead	$4.25	$3.38	$2.71	$2.66
Selling & Dealer Support	$8.50	$5.33	$2.71	$2.66
Net Income	$7.09	$6.82	$6.77	$6.66

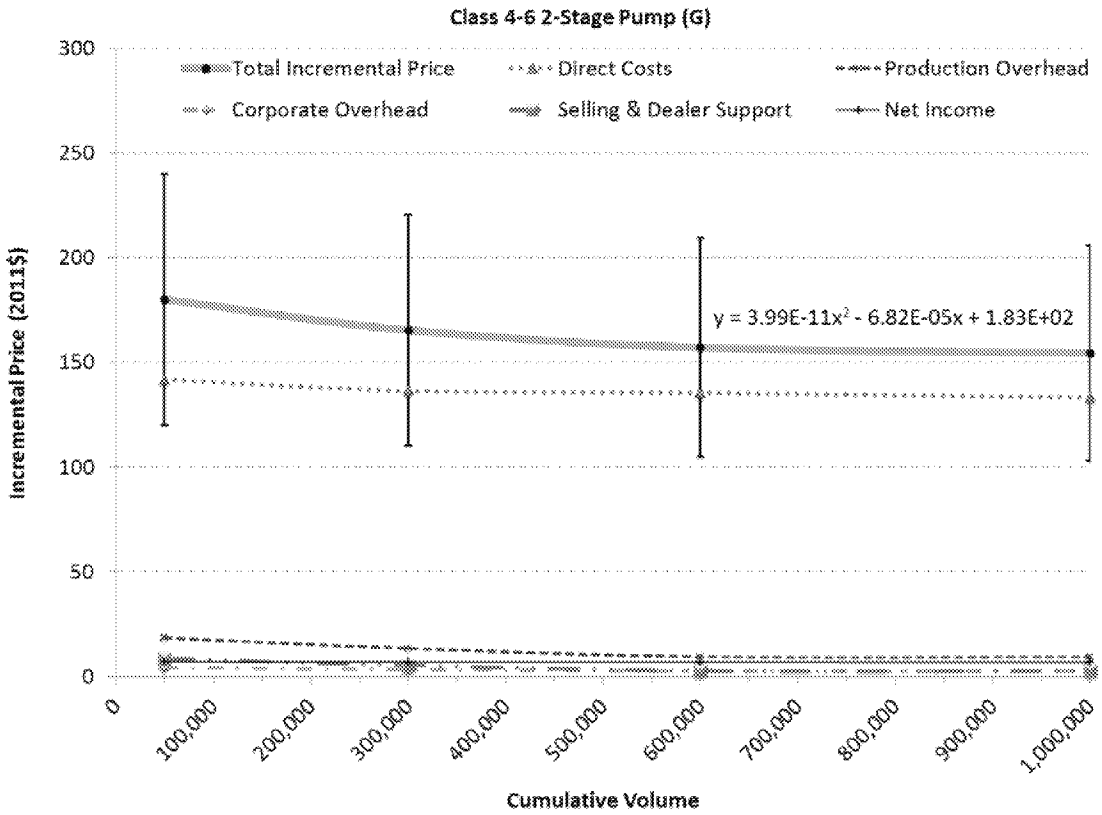
Figure 3. Incremental Price and Breakouts for Class 2b&3 (Gasoline) 2-Stage Pump (Coolant/Oil)



Class 2b&3 Variable Displ Pump (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$350.00	$321.57	$305.33	$300.46
Direct Costs	$275.59	$265.24	$263.26	$259.06
Production Overhead	$35.83	$26.13	$18.38	$18.08
Corporate Overhead	$8.27	$6.57	$5.27	$5.18
Selling & Dealer Support	$16.54	$10.37	$5.27	$5.18
Net Income	$13.78	$13.26	$13.16	$12.95

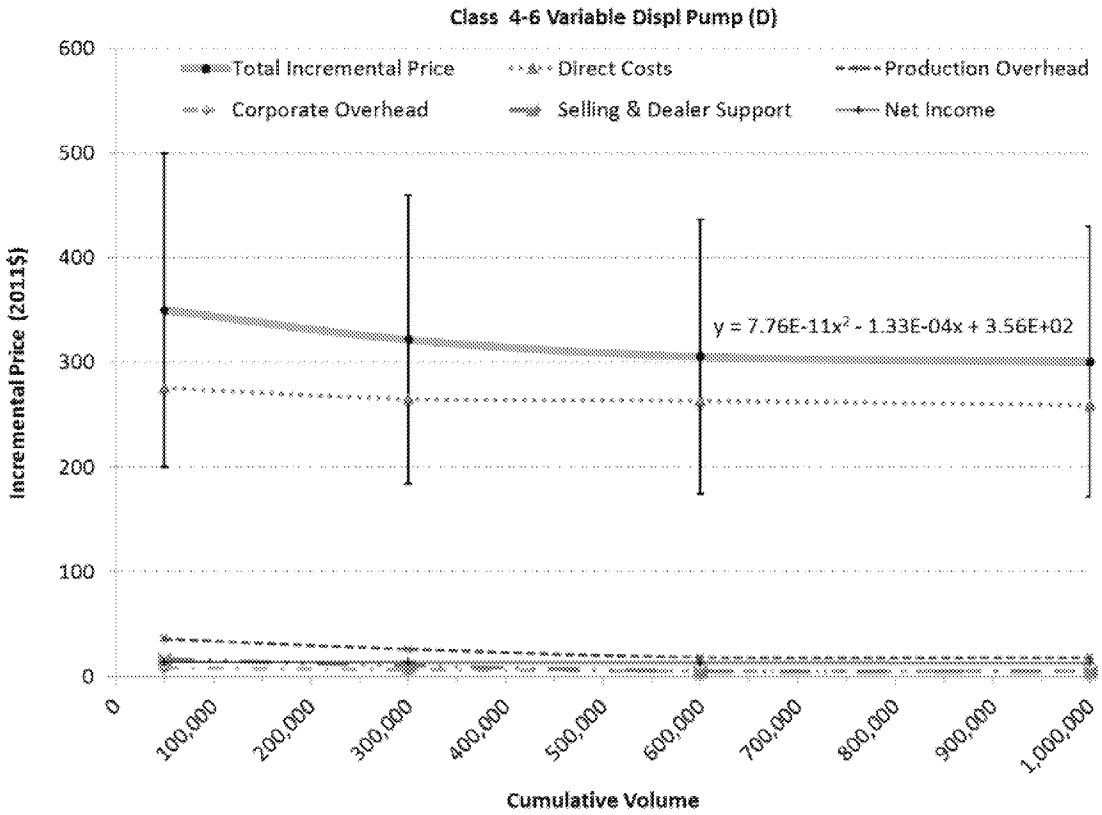
Figure 4. Incremental Price and Breakouts for Class 2b&3 (Diesel) Variable Displacement Pump (Coolant/Oil)



Class 4-6 2-Stage Pump (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$180.00	$165.38	$157.03	$154.52
Direct Costs	$141.73	$136.41	$135.39	$133.23
Production Overhead	$18.43	$13.44	$9.45	$9.30
Corporate Overhead	$4.25	$3.38	$2.71	$2.66
Selling & Dealer Support	$8.50	$5.33	$2.71	$2.66
Net Income	$7.09	$6.82	$6.77	$6.66

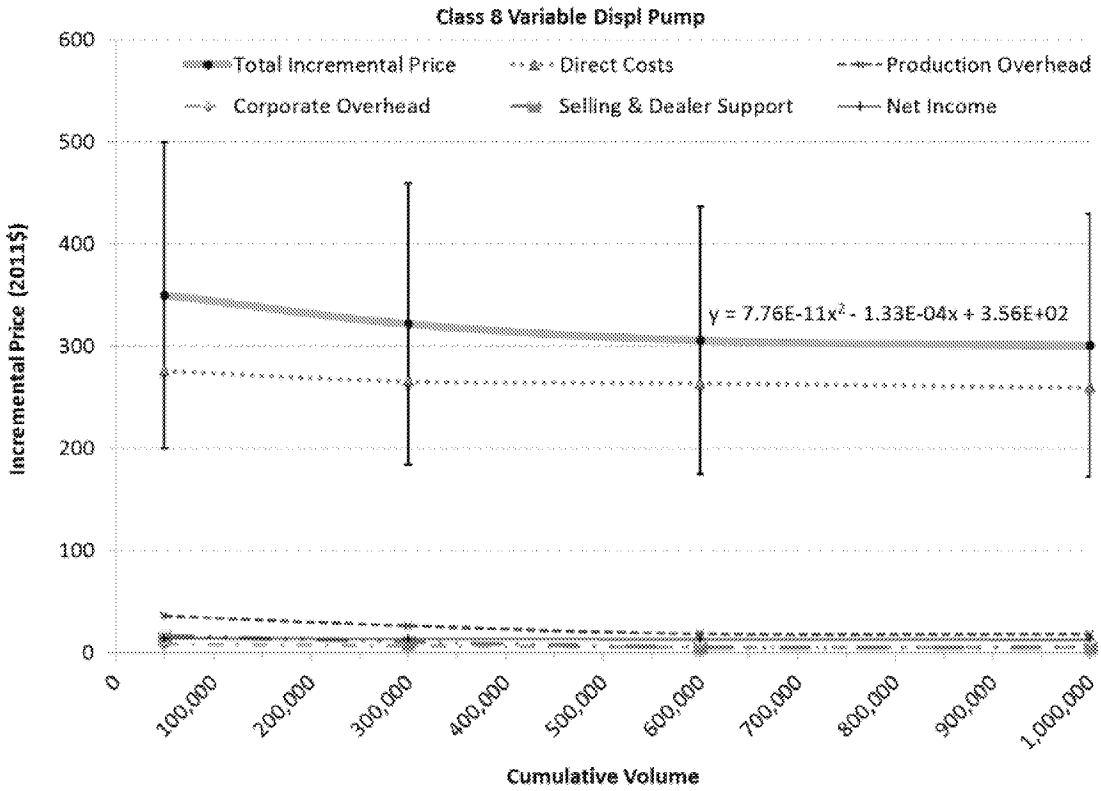
Figure 5. Incremental Price and Breakouts for Vocational (Gasoline) 2-Stage Pump (Coolant/Oil)



Class 4-6 Variable Displ Pump (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$350.00	$321.57	$305.33	$300.46
Direct Costs	$275.59	$265.24	$263.26	$259.06
Production Overhead	$35.83	$26.13	$18.38	$18.08
Corporate Overhead	$8.27	$6.57	$5.27	$5.18
Selling & Dealer Support	$16.54	$10.37	$5.27	$5.18
Net Income	$13.78	$13.26	$13.16	$12.95

Figure 6. Incremental Price and Breakouts for Vocational (Diesel) Variable Displacement Pump (Coolant/Oil)

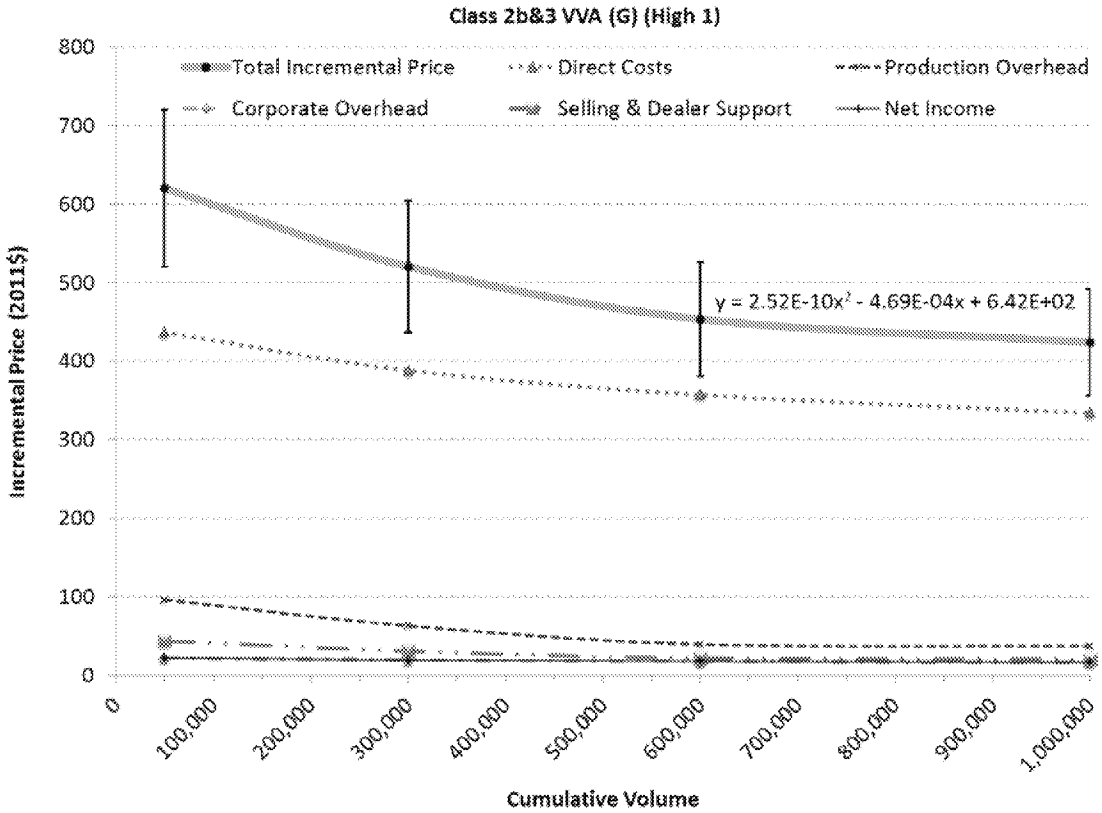


Class 8 Variable Displ Pump

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$350.00	$321.57	$305.33	$300.46
Direct Costs	$275.59	$265.24	$263.26	$259.06
Production Overhead	$35.83	$26.13	$18.38	$18.08
Corporate Overhead	$8.27	$6.57	$5.27	$5.18
Selling & Dealer Support	$16.54	$10.37	$5.27	$5.18
Net Income	$13.78	$13.26	$13.16	$12.95

Figure 7. Incremental Price and Breakouts for Line Haul Variable Displacement Pump (Coolant/Oil)

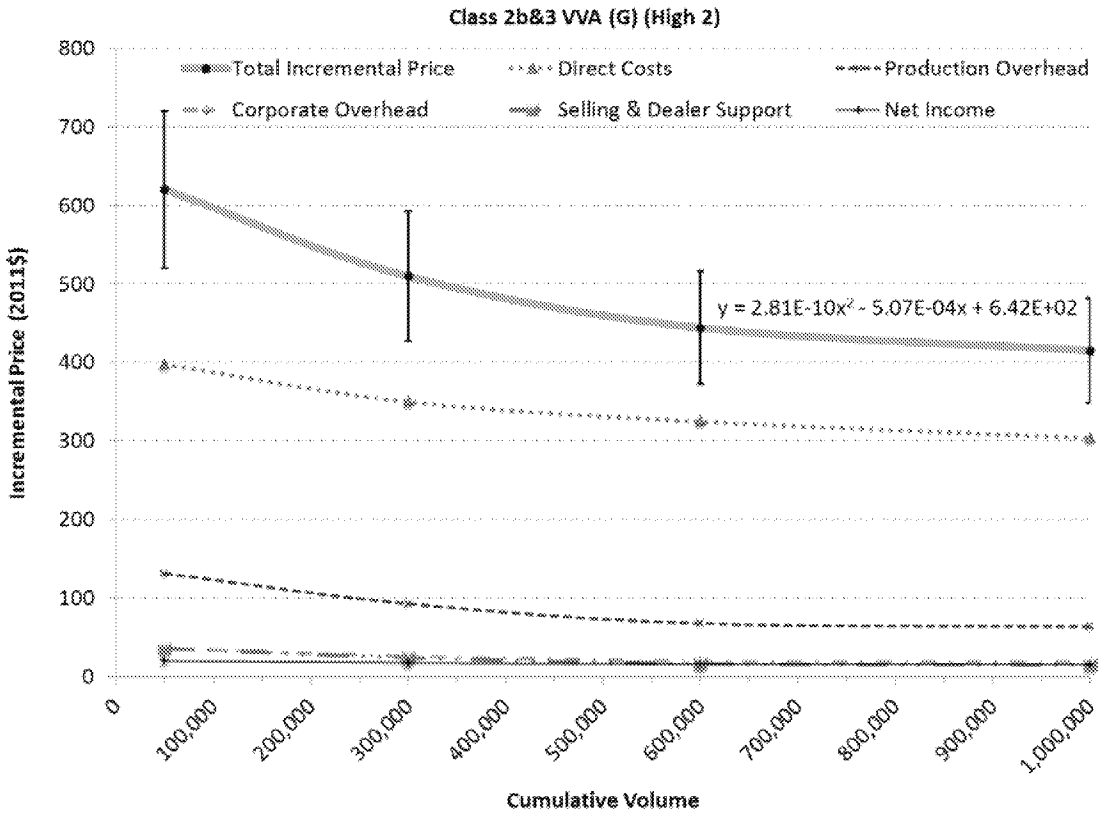
Variable Valve Actuation (priced per vehicle)



Class 2b&3 VVA (G) (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$620.00	$520.44	$453.38	$423.87
Direct Costs	$436.62	$388.15	$356.99	$333.75
Production Overhead	$96.06	$62.85	$39.27	$36.71
Corporate Overhead	$21.83	$19.41	$17.85	$16.69
Selling & Dealer Support	$43.66	$30.62	$21.42	$20.03
Net Income	$21.83	$19.41	$17.85	$16.69

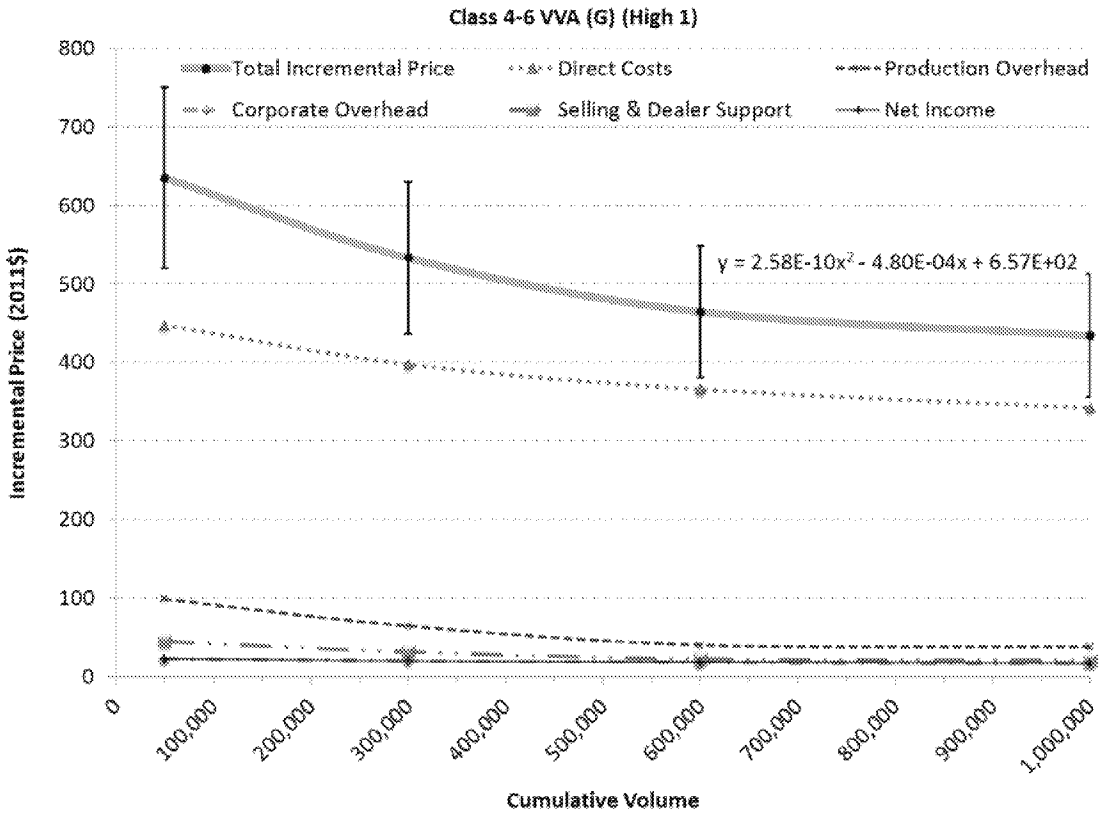
Figure 8. Incremental Price and Breakouts for Class 2b&3 (Gasoline) VVA (High 1 Complexity)



Class 2b&3 VVA (G) (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$620.00	$509.66	$443.98	$415.08
Direct Costs	$397.44	$349.63	$324.55	$303.42
Production Overhead	$131.15	$92.65	$67.51	$63.11
Corporate Overhead	$35.77	$25.88	$19.47	$18.21
Selling & Dealer Support	$35.77	$24.02	$16.23	$15.17
Net Income	$19.87	$17.48	$16.23	$15.17

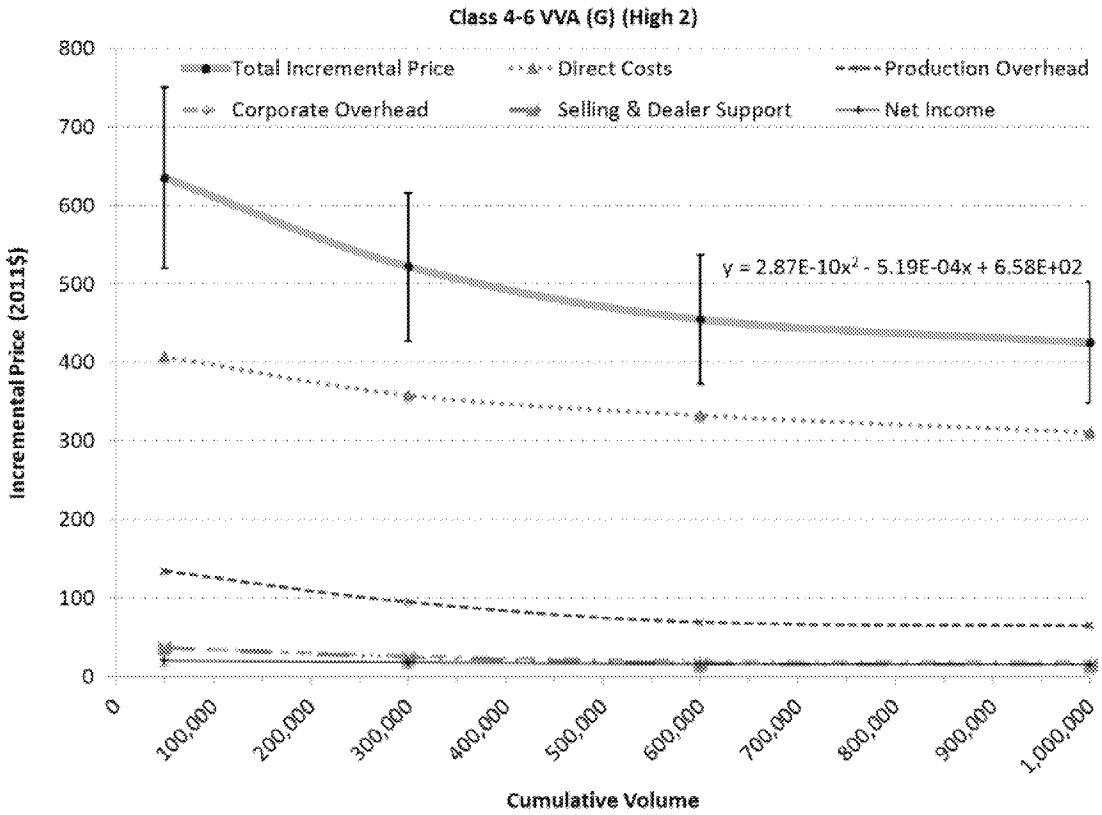
Figure 9. Incremental Price and Breakouts for Class 2b&3 (Gasoline) VVA (High 2 Complexity)



Class 4-6 VVA (G) (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$635.00	$533.03	$464.34	$434.12
Direct Costs	$447.18	$397.54	$365.63	$341.83
Production Overhead	$98.38	$64.38	$40.22	$37.60
Corporate Overhead	$22.36	$19.88	$18.28	$17.09
Selling & Dealer Support	$44.72	$31.36	$21.94	$20.51
Net Income	$22.36	$19.88	$18.28	$17.09

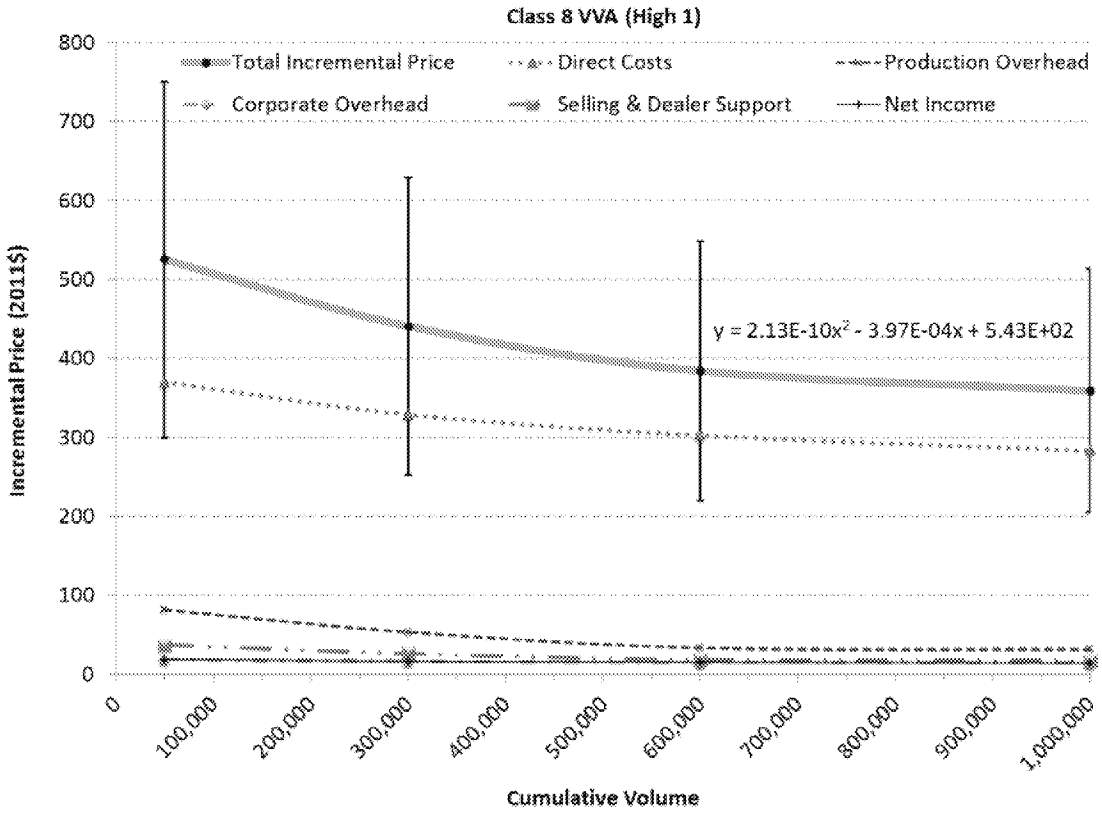
Figure 10. Incremental Price and Breakouts for Vocational (Gasoline) VVA (High 1 Complexity)



Class 4-6 VVA (G) (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$635.00	$521.99	$454.72	$425.13
Direct Costs	$407.05	$358.09	$332.40	$310.77
Production Overhead	$134.33	$94.89	$69.14	$64.64
Corporate Overhead	$36.63	$26.50	$19.94	$18.65
Selling & Dealer Support	$36.63	$24.60	$16.62	$15.54
Net Income	$20.35	$17.90	$16.62	$15.54

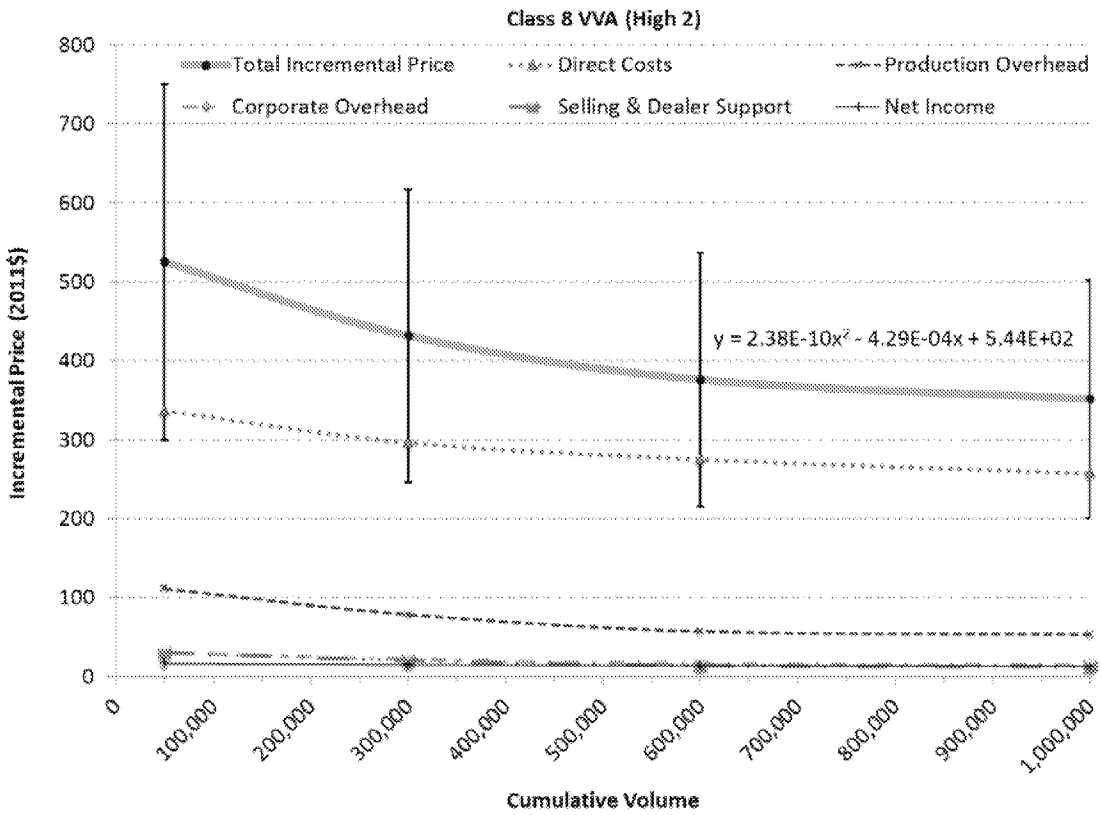
Figure 11. Incremental Price and Breakouts for Vocational (Gasoline) VVA (High 2 Complexity)



Class 8 VVA (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$525.00	$440.70	$383.91	$358.92
Direct Costs	$369.72	$328.68	$302.29	$282.61
Production Overhead	$81.34	$53.22	$33.25	$31.09
Corporate Overhead	$18.49	$16.43	$15.11	$14.13
Selling & Dealer Support	$36.97	$25.93	$18.14	$16.96
Net Income	$18.49	$16.43	$15.11	$14.13

Figure 12. Incremental Price and Breakouts for Line Haul VVA (High 1 Complexity)

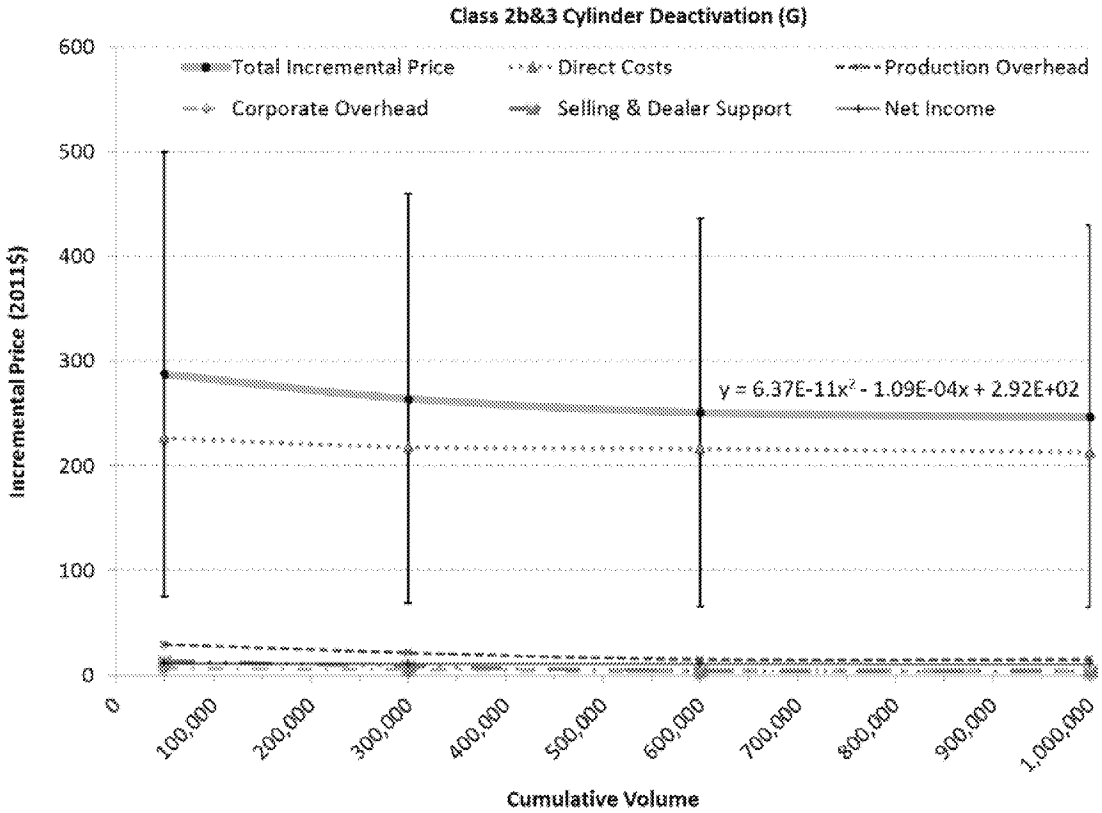


Class 8 VVA (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$525.00	$431.57	$375.95	$351.48
Direct Costs	$336.54	$296.06	$274.82	$256.93
Production Overhead	$111.06	$78.46	$57.16	$53.44
Corporate Overhead	$30.29	$21.91	$16.49	$15.42
Selling & Dealer Support	$30.29	$20.34	$13.74	$12.85
Net Income	$16.83	$14.80	$13.74	$12.85

Figure 13. Incremental Price and Breakouts for Line Haul VVA (High 2 Complexity)

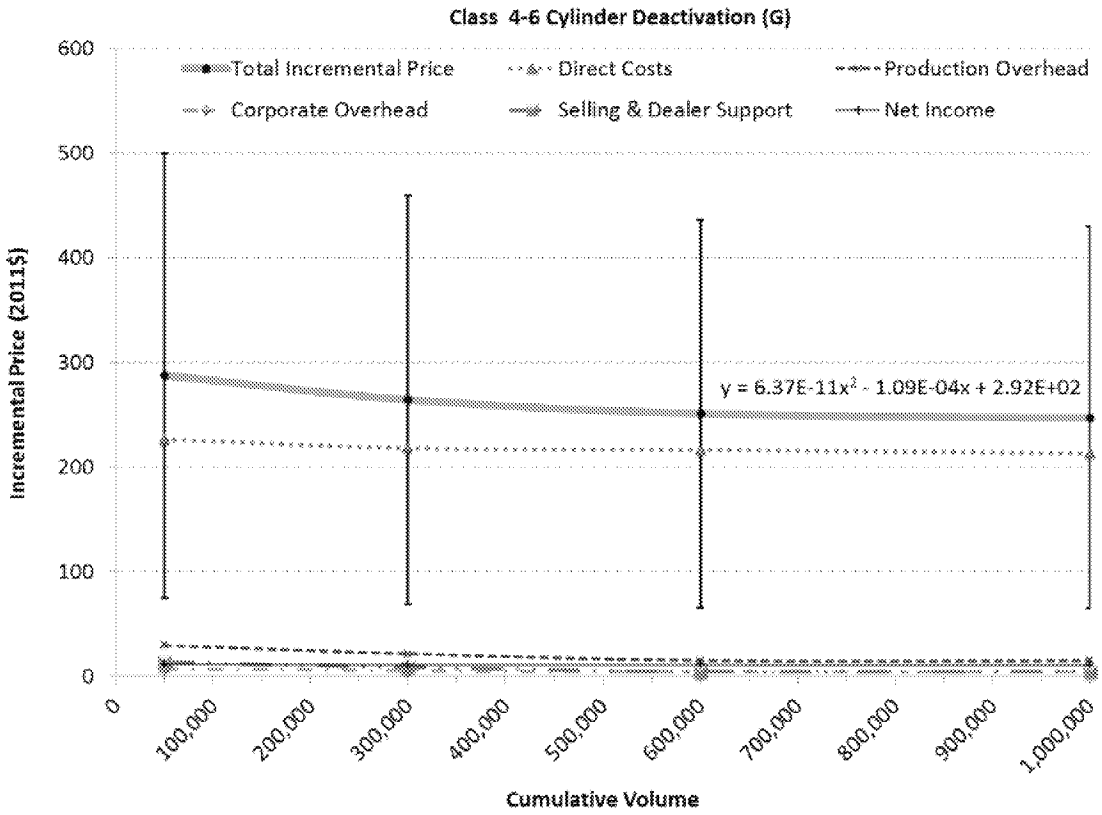
Cylinder Deactivation



Class 2b&3 Cylinder Deactivation (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$287.50	$264.15	$250.81	$246.81
Direct Costs	$226.38	$217.87	$216.25	$212.80
Production Overhead	$29.43	$21.47	$15.09	$14.85
Corporate Overhead	$6.79	$5.40	$4.33	$4.26
Selling & Dealer Support	$13.58	$8.52	$4.33	$4.26
Net Income	$11.32	$10.89	$10.81	$10.64

Figure 14. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Cylinder Deactivation

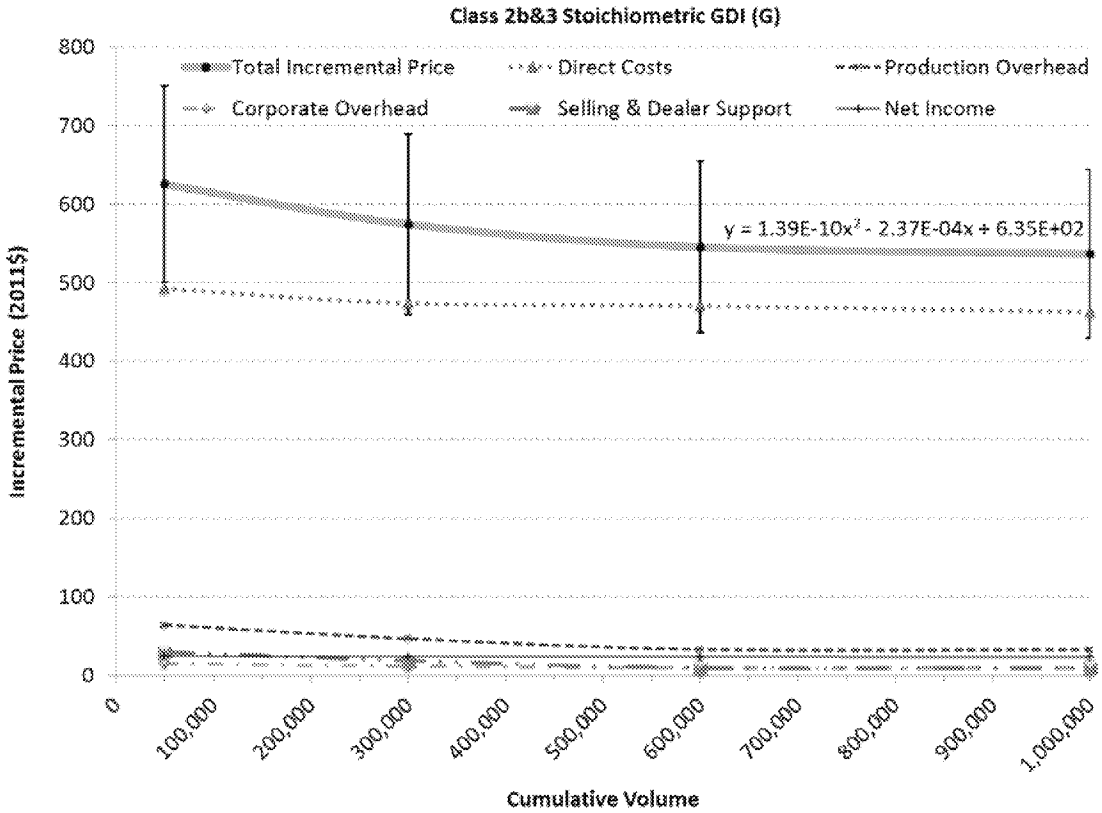


Class 4-6 Cylinder Deactivation (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$287.50	$264.15	$250.81	$246.81
Direct Costs	$226.38	$217.87	$216.25	$212.80
Production Overhead	$29.43	$21.47	$15.09	$14.85
Corporate Overhead	$6.79	$5.40	$4.33	$4.26
Selling & Dealer Support	$13.58	$8.52	$4.33	$4.26
Net Income	$11.32	$10.89	$10.81	$10.64

Figure 15. Incremental Price and Breakouts for Vocational (Gasoline) Cylinder Deactivation

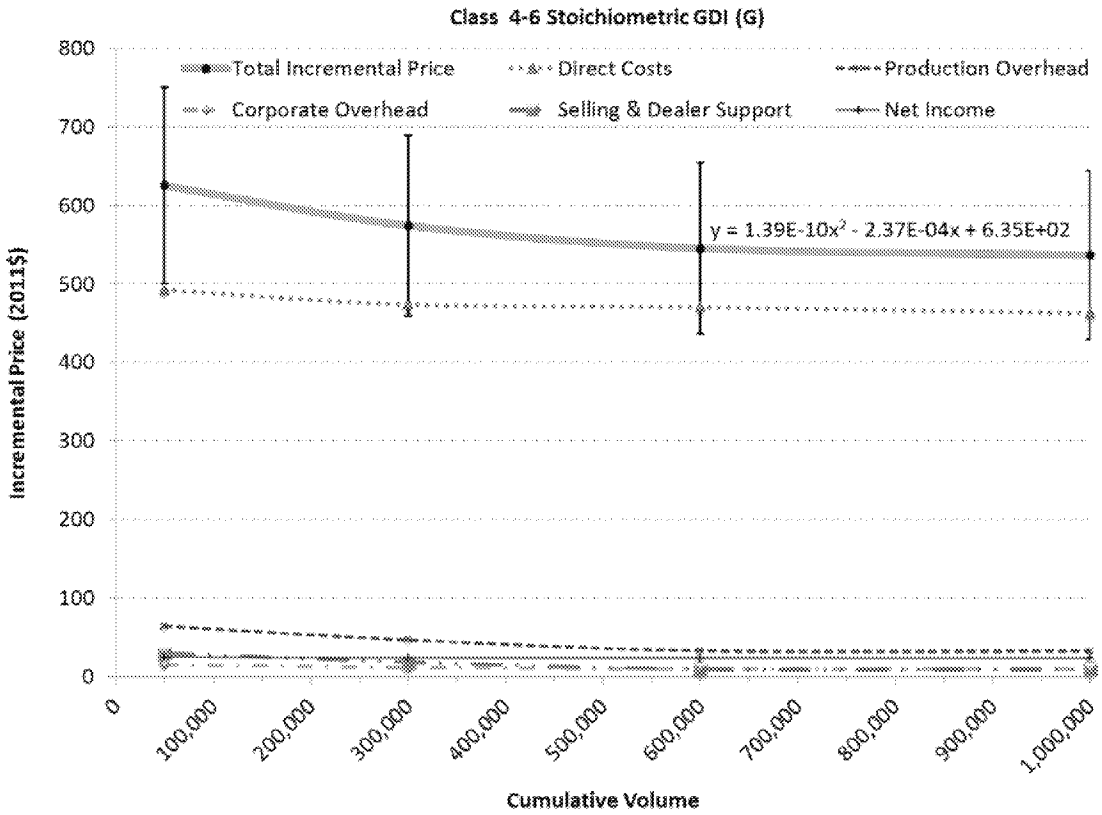
Stoichiometric GDI



Class 2b&3 Stoichiometric GDI (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$625.00	$574.24	$545.23	$536.53
Direct Costs	$492.13	$473.64	$470.11	$462.61
Production Overhead	$63.98	$46.67	$32.81	$32.29
Corporate Overhead	$14.76	$11.73	$9.40	$9.25
Selling & Dealer Support	$29.53	$18.52	$9.40	$9.25
Net Income	$24.61	$23.68	$23.51	$23.13

Figure 16. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Stoichiometric GDI

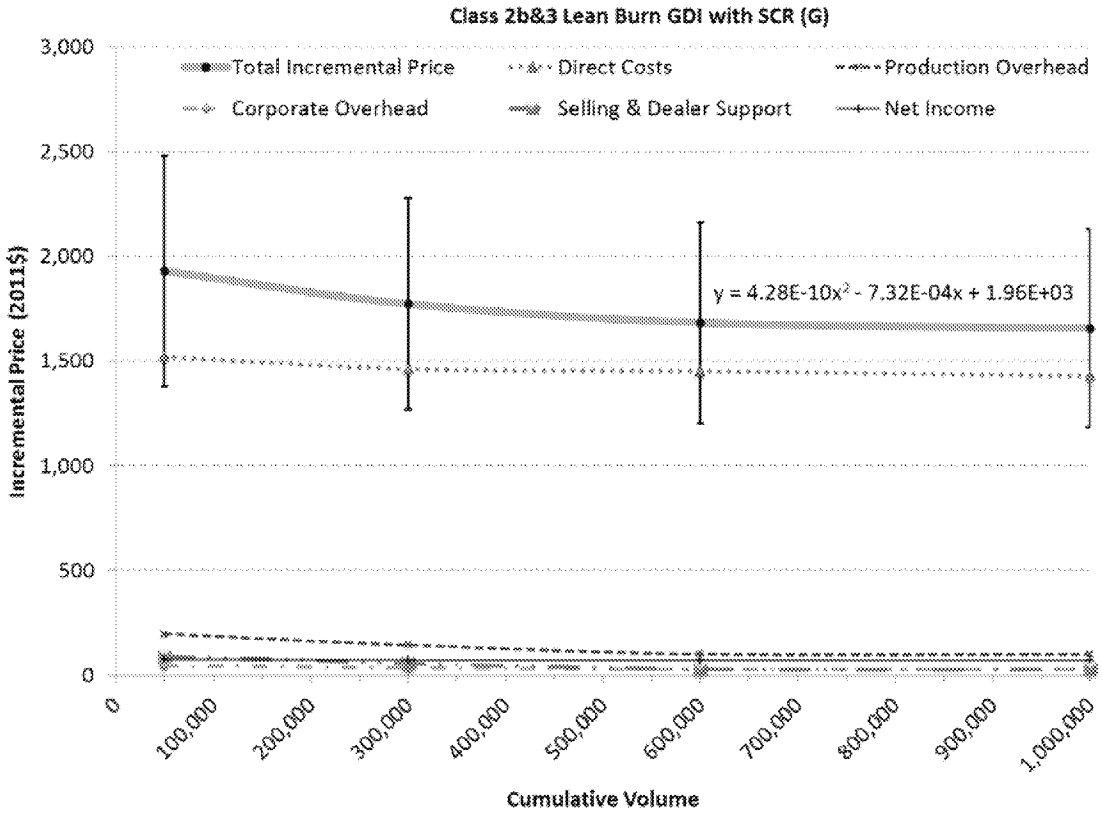


Class 4-6 Stoichiometric GDI (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$625.00	$574.24	$545.23	$536.53
Direct Costs	$492.13	$473.64	$470.11	$462.61
Production Overhead	$63.98	$46.67	$32.81	$32.29
Corporate Overhead	$14.76	$11.73	$9.40	$9.25
Selling & Dealer Support	$29.53	$18.52	$9.40	$9.25
Net Income	$24.61	$23.68	$23.51	$23.13

Figure 17. Incremental Price and Breakouts for Vocational (Gasoline) Stoichiometric GDI

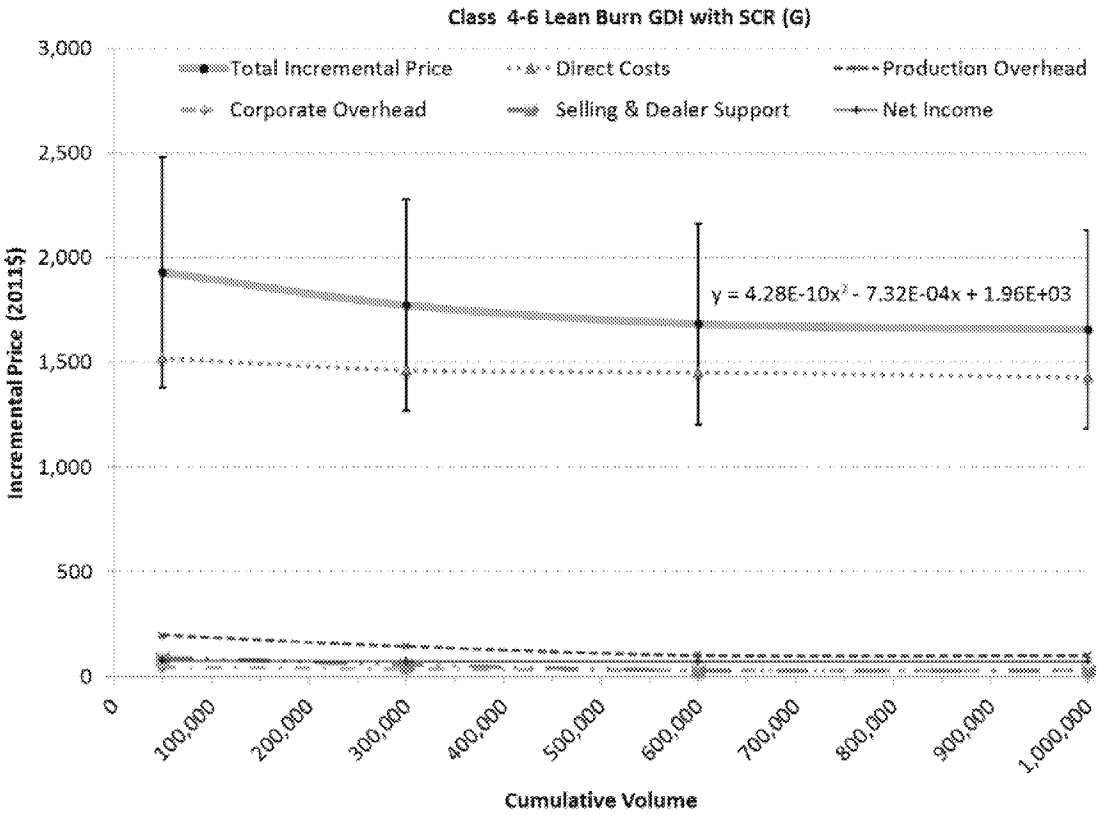
Lean Burn GDI with SCR



Class 2b&3 Lean Burn GDI with SCR (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,930.00	$1,773.24	$1,683.68	$1,656.81
Direct Costs	$1,519.69	$1,462.59	$1,451.70	$1,428.53
Production Overhead	$197.56	$144.12	$101.33	$99.71
Corporate Overhead	$45.59	$36.23	$29.03	$28.57
Selling & Dealer Support	$91.18	$57.18	$29.03	$28.57
Net Income	$75.98	$73.13	$72.59	$71.43

Figure 18. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Lean Burn GDI with SCR



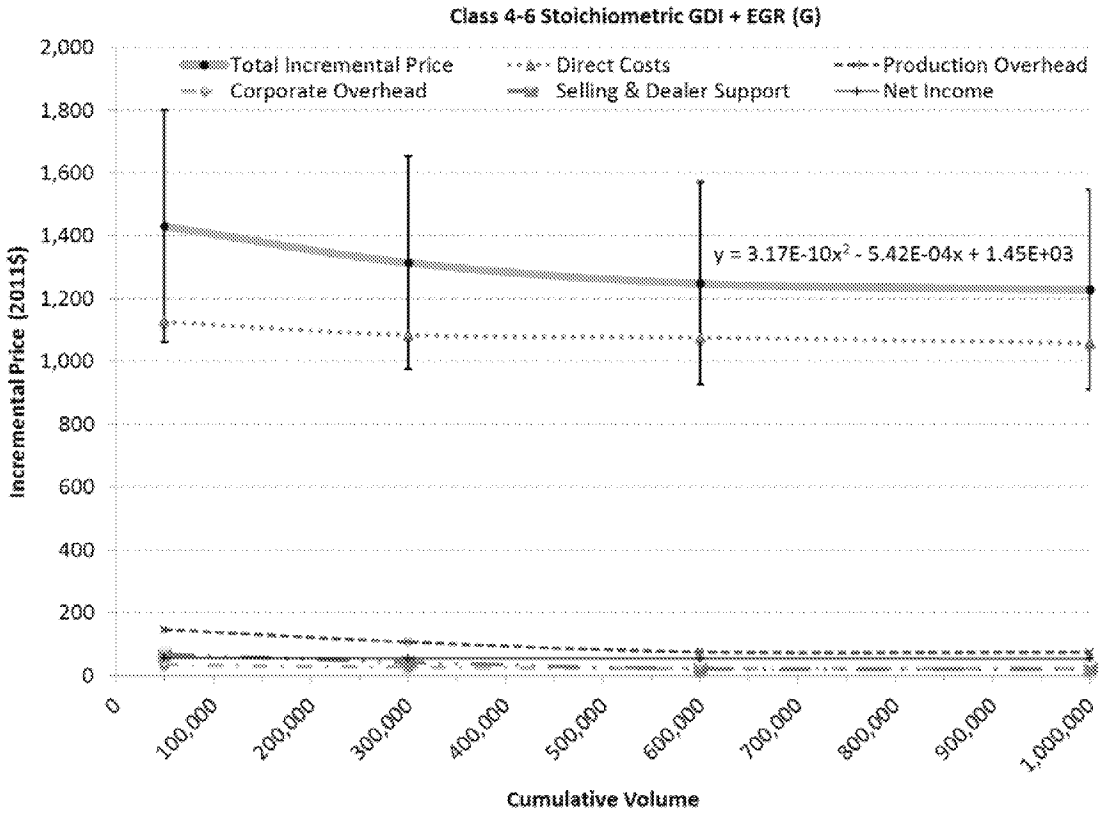
Class 4-6 Lean Burn GDI with SCR (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,930.00	$1,773.24	$1,683.68	$1,656.81
Direct Costs	$1,519.69	$1,462.59	$1,451.70	$1,428.53
Production Overhead	$197.56	$144.12	$101.33	$99.71
Corporate Overhead	$45.59	$36.23	$29.03	$28.57
Selling & Dealer Support	$91.18	$57.18	$29.03	$28.57
Net Income	$75.98	$73.13	$72.59	$71.43

Figure 19. Incremental Price and Breakouts for Vocational (Gasoline) Lean Burn GDI with SCR

Stoichiometric GDI+EGR

New control strategy concept for Class 2b&3. No costing performed.

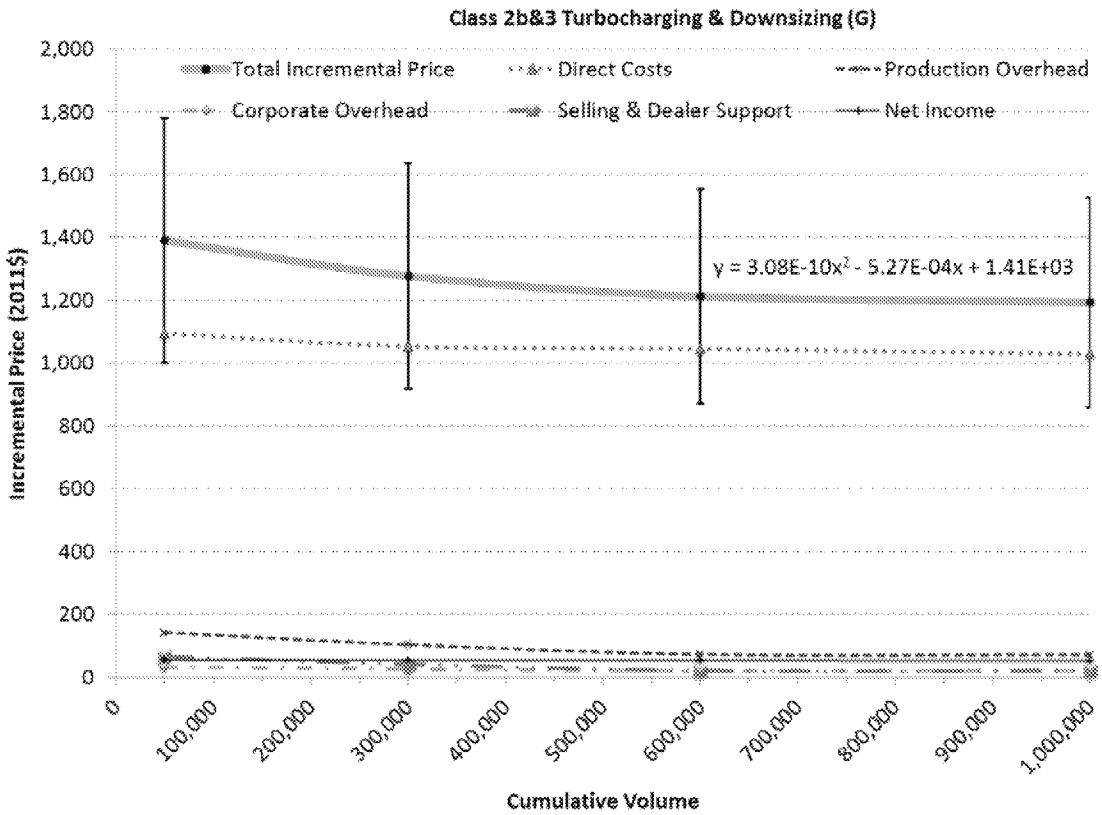


Class 4-6 Stoichiometric GDI + EGR (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,430.00	$1,313.85	$1,247.49	$1,227.59
Direct Costs	$1,125.98	$1,083.68	$1,075.61	$1,058.45
Production Overhead	$146.38	$106.78	$75.08	$73.88
Corporate Overhead	$33.78	$26.85	$21.51	$21.17
Selling & Dealer Support	$67.56	$42.36	$21.51	$21.17
Net Income	$56.30	$54.18	$53.78	$52.92

Figure 20. Incremental Price and Breakouts for Vocational (Gasoline) Stoichiometric GDI+EGR

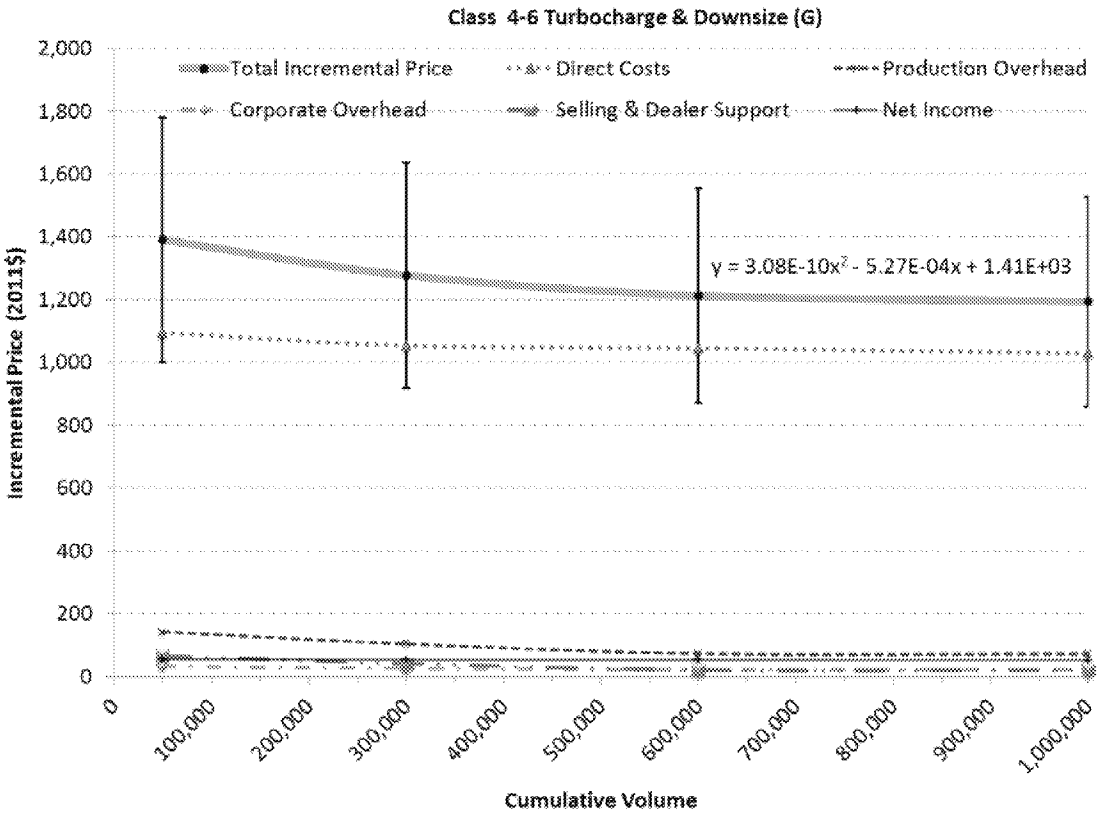
Turbocharging & Downsizing



Class 2b&3 Turbocharging & Downsizing (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,390.00	$1,277.10	$1,212.60	$1,193.25
Direct Costs	$1,094.49	$1,053.36	$1,045.53	$1,028.84
Production Overhead	$142.28	$103.79	$72.98	$71.81
Corporate Overhead	$32.83	$26.10	$20.91	$20.58
Selling & Dealer Support	$65.67	$41.18	$20.91	$20.58
Net Income	$54.72	$52.67	$52.28	$51.44

Figure 21. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Turbocharging & Downsizing



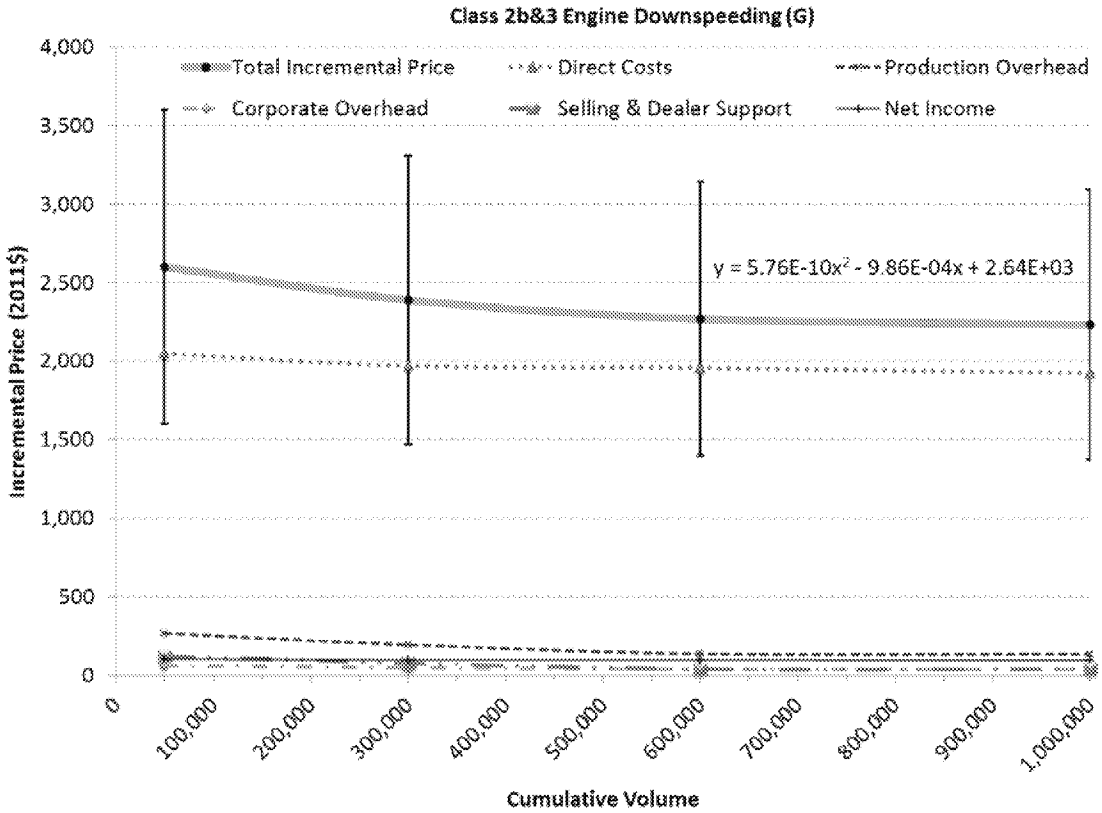
Class 4-6 Turbocharge & Downsize (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,390.00	$1,277.10	$1,212.60	$1,193.25
Direct Costs	$1,094.49	$1,053.36	$1,045.53	$1,028.84
Production Overhead	$142.28	$103.79	$72.98	$71.81
Corporate Overhead	$32.83	$26.10	$20.91	$20.58
Selling & Dealer Support	$65.67	$41.18	$20.91	$20.58
Net Income	$54.72	$52.67	$52.28	$51.44

Figure 22. Incremental Price and Breakouts for Vocational (Gasoline) Turbocharging & Downsizing

No Class 8 costing performed.

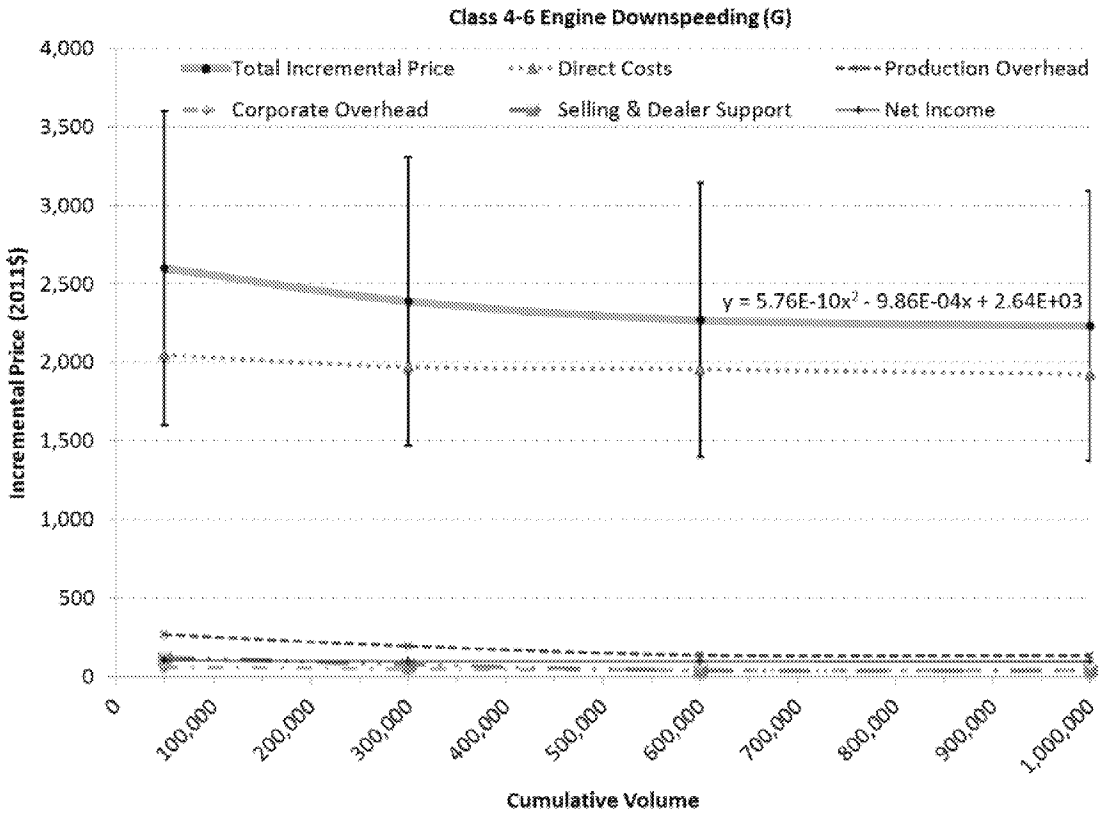
Engine Downspeeding



Class 2b&3 Engine Downspeeding (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$2,600.00	$2,388.82	$2,268.17	$2,231.98
Direct Costs	$2,047.24	$1,970.32	$1,955.66	$1,924.45
Production Overhead	$266.14	$194.15	$136.50	$134.33
Corporate Overhead	$61.42	$48.81	$39.11	$38.49
Selling & Dealer Support	$122.83	$77.03	$39.11	$38.49
Net Income	$102.36	$98.52	$97.78	$96.22

Figure 23. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Engine Downspeeding



Class 4-6 Engine Downspeeding (G)

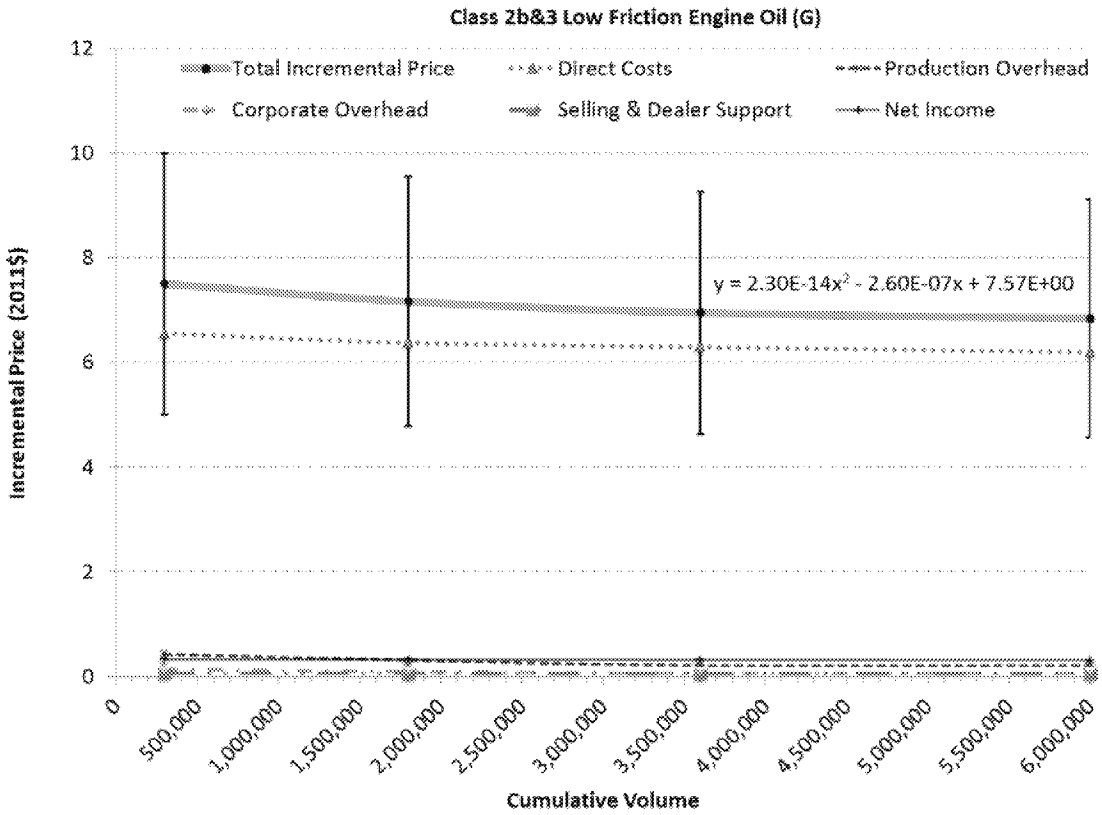
Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$2,600.00	$2,388.82	$2,268.17	$2,231.98
Direct Costs	$2,047.24	$1,970.32	$1,955.66	$1,924.45
Production Overhead	$266.14	$194.15	$136.50	$134.33
Corporate Overhead	$61.42	$48.81	$39.11	$38.49
Selling & Dealer Support	$122.83	$77.03	$39.11	$38.49
Net Income	$102.36	$98.52	$97.78	$96.22

Figure 24. Incremental Price and Breakouts for Vocational (Gasoline) Engine Downspeeding

No Class 8 costing performed.

Low Friction Engine Oil (priced per vehicle)

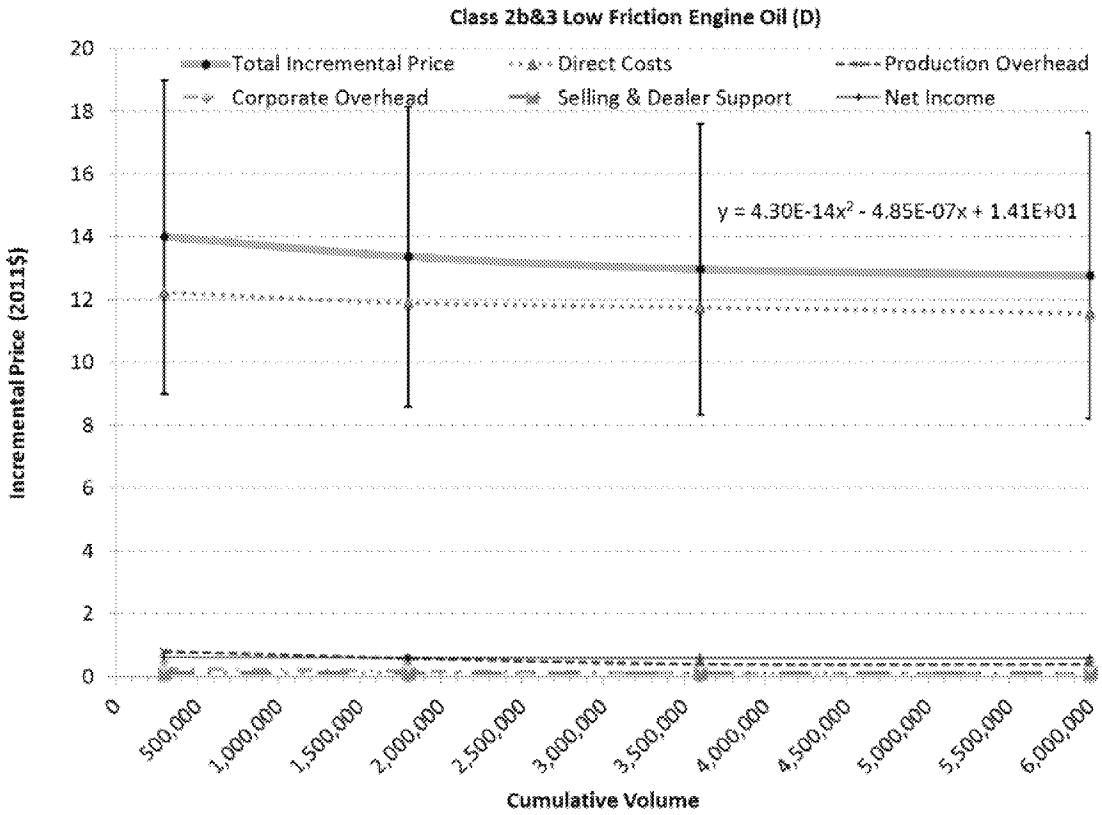
Assumed 7 quarts oil capacity for Class 2b&3 and Vocational gasoline vehicles. Assumed 13 quarts oil capacity for Class 2b&3 and Vocational diesel vehicles. Assumed 47 quarts for Line Haul.



Class 2b&3 Low Friction Engine Oil (G)

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$7.50	$7.16	$6.95	$6.84
Direct Costs	$6.55	$6.37	$6.29	$6.19
Production Overhead	$0.42	$0.31	$0.21	$0.21
Corporate Overhead	$0.13	$0.09	$0.06	$0.06
Selling & Dealer Support	$0.07	$0.06	$0.06	$0.06
Net Income	$0.33	$0.32	$0.31	$0.31

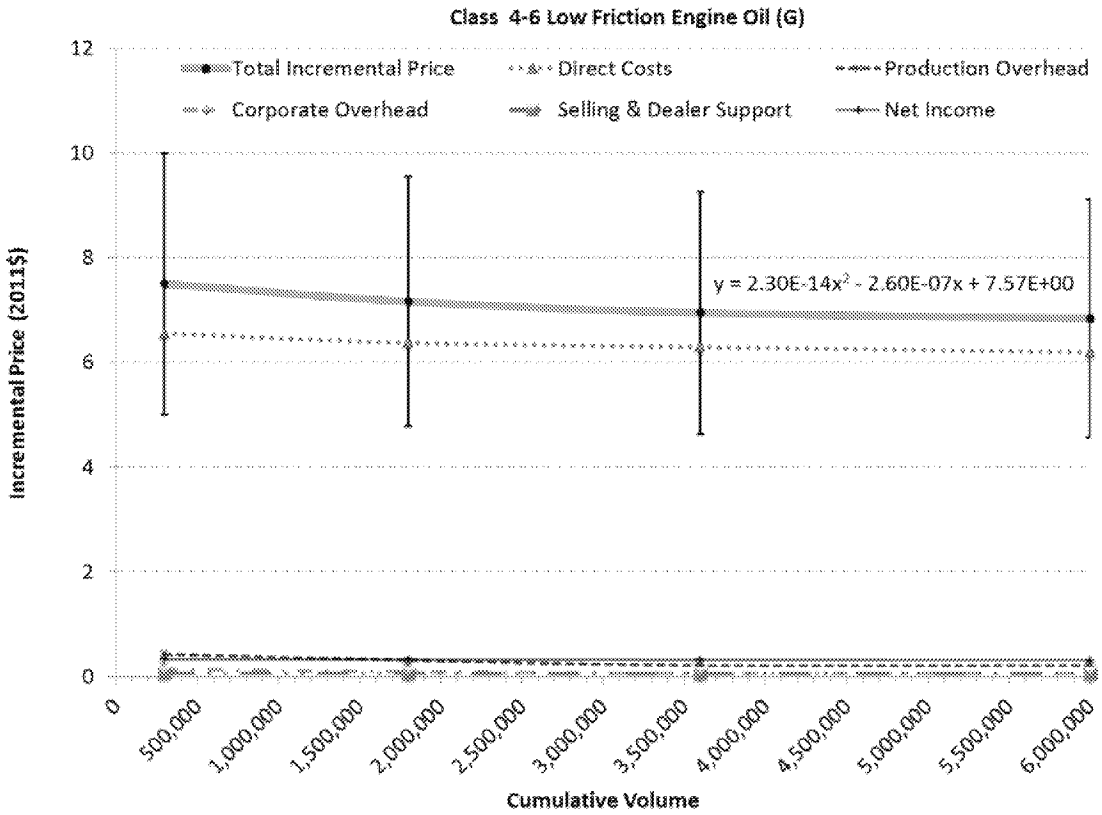
Figure 25. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Low Friction Engine Oil



Class 2b&3 Low Friction Engine Oil (D)

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$14.00	$13.37	$12.97	$12.76
Direct Costs	$12.23	$11.89	$11.75	$11.56
Production Overhead	$0.79	$0.58	$0.40	$0.39
Corporate Overhead	$0.24	$0.18	$0.12	$0.12
Selling & Dealer Support	$0.12	$0.12	$0.12	$0.12
Net Income	$0.61	$0.59	$0.59	$0.58

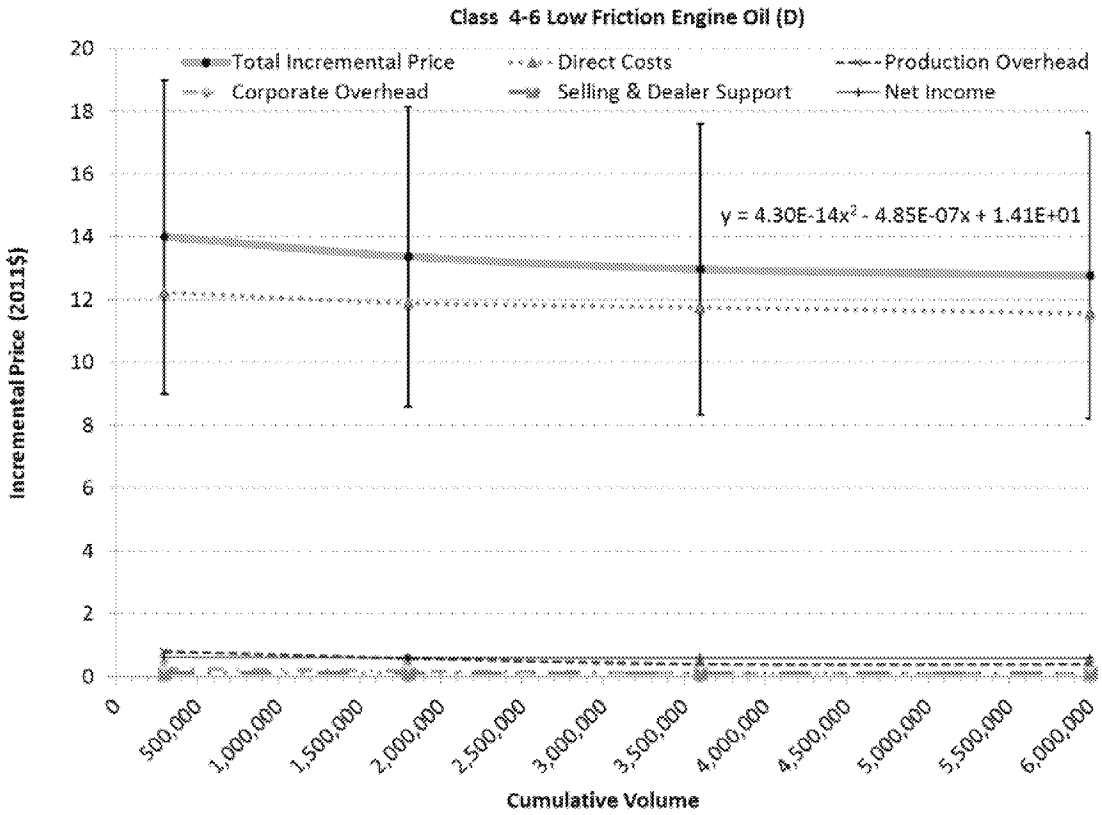
Figure 26. Incremental Price and Breakouts for Class 2b&3 (Diesel) Low Friction Engine Oil



Class 4-6 Low Friction Engine Oil (G)

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$7.50	$7.16	$6.95	$6.84
Direct Costs	$6.55	$6.37	$6.29	$6.19
Production Overhead	$0.42	$0.31	$0.21	$0.21
Corporate Overhead	$0.13	$0.09	$0.06	$0.06
Selling & Dealer Support	$0.07	$0.06	$0.06	$0.06
Net Income	$0.33	$0.32	$0.31	$0.31

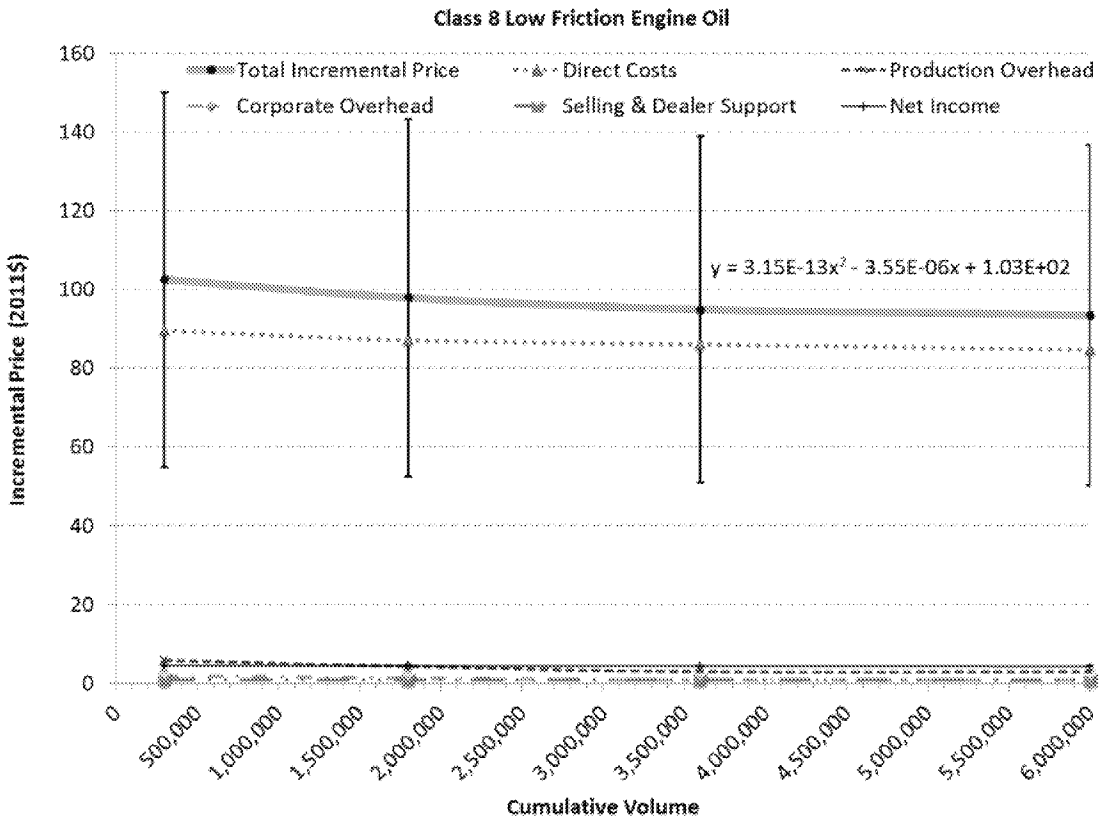
Figure 27. Incremental Price and Breakouts for Vocational (Gasoline) Low Friction Engine Oil



Class 4-6 Low Friction Engine Oil (D)

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$14.00	$13.37	$12.97	$12.76
Direct Costs	$12.23	$11.89	$11.75	$11.56
Production Overhead	$0.79	$0.58	$0.40	$0.39
Corporate Overhead	$0.24	$0.18	$0.12	$0.12
Selling & Dealer Support	$0.12	$0.12	$0.12	$0.12
Net Income	$0.61	$0.59	$0.59	$0.58

Figure 28. Incremental Price and Breakouts for Vocational (Diesel) Low Friction Engine Oil

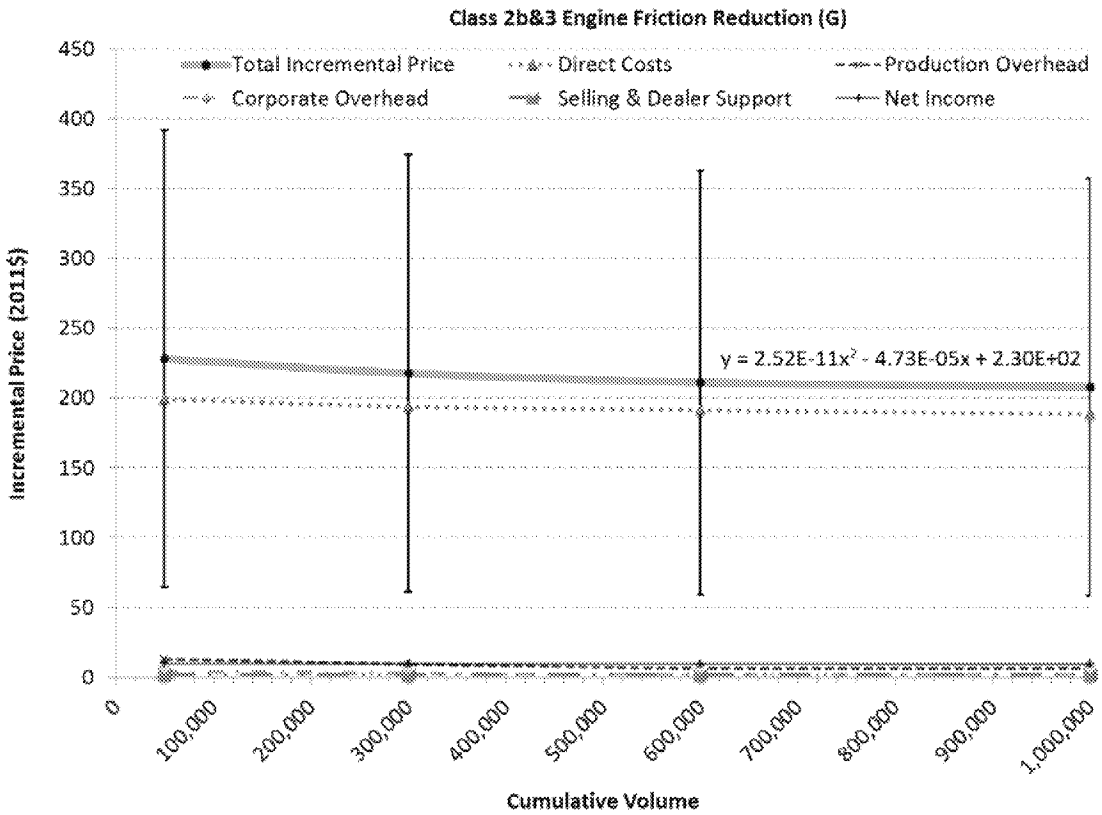


Class 8 Low Friction Engine Oil

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$102.50	$97.88	$94.92	$93.45
Direct Costs	$89.54	$87.08	$86.00	$84.66
Production Overhead	$5.80	$4.27	$2.91	$2.86
Corporate Overhead	$1.79	$1.30	$0.86	$0.85
Selling & Dealer Support	$0.90	$0.87	$0.86	$0.85
Net Income	$4.48	$4.35	$4.30	$4.23

Figure 29. Incremental Price and Breakouts for Line Haul Low Friction Engine Oil

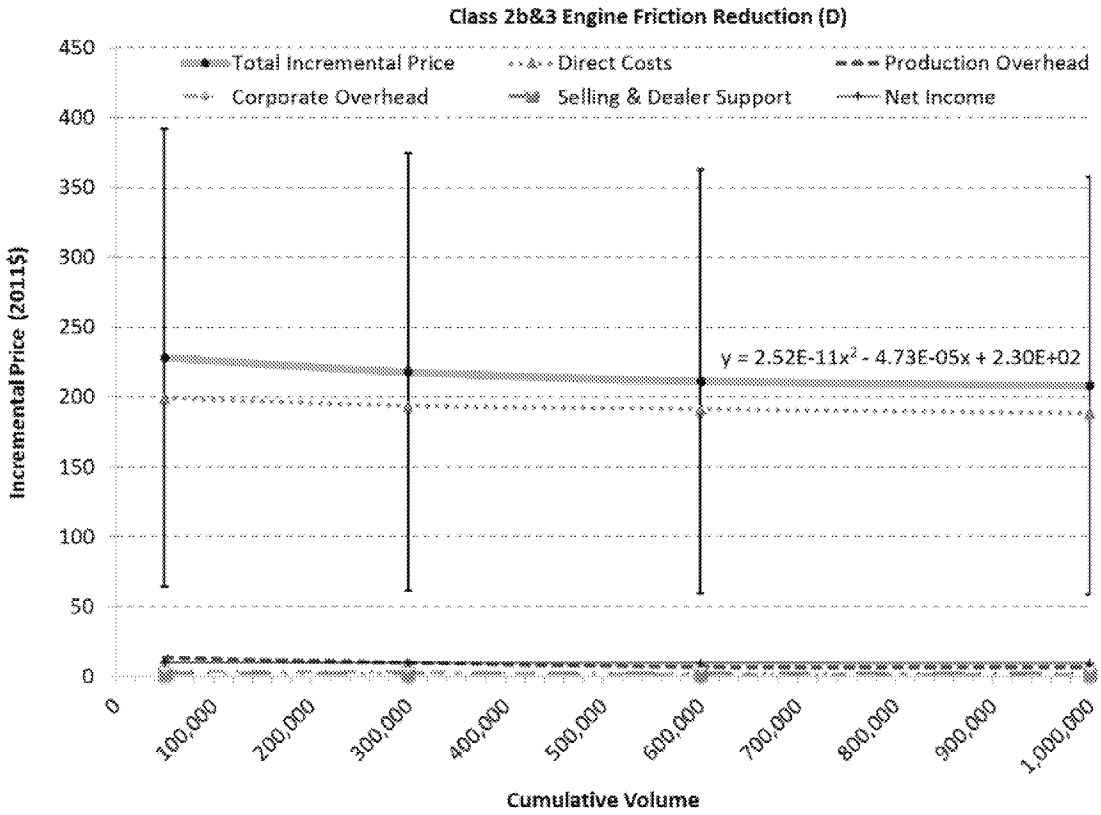
Engine Friction Reduction



Class 2b&3 Engine Friction Reduction (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$228.00	$217.71	$211.15	$207.87
Direct Costs	$199.16	$193.71	$191.29	$188.32
Production Overhead	$12.91	$9.50	$6.47	$6.37
Corporate Overhead	$3.98	$2.89	$1.91	$1.88
Selling & Dealer Support	$1.99	$1.94	$1.91	$1.88
Net Income	$9.96	$9.69	$9.56	$9.42

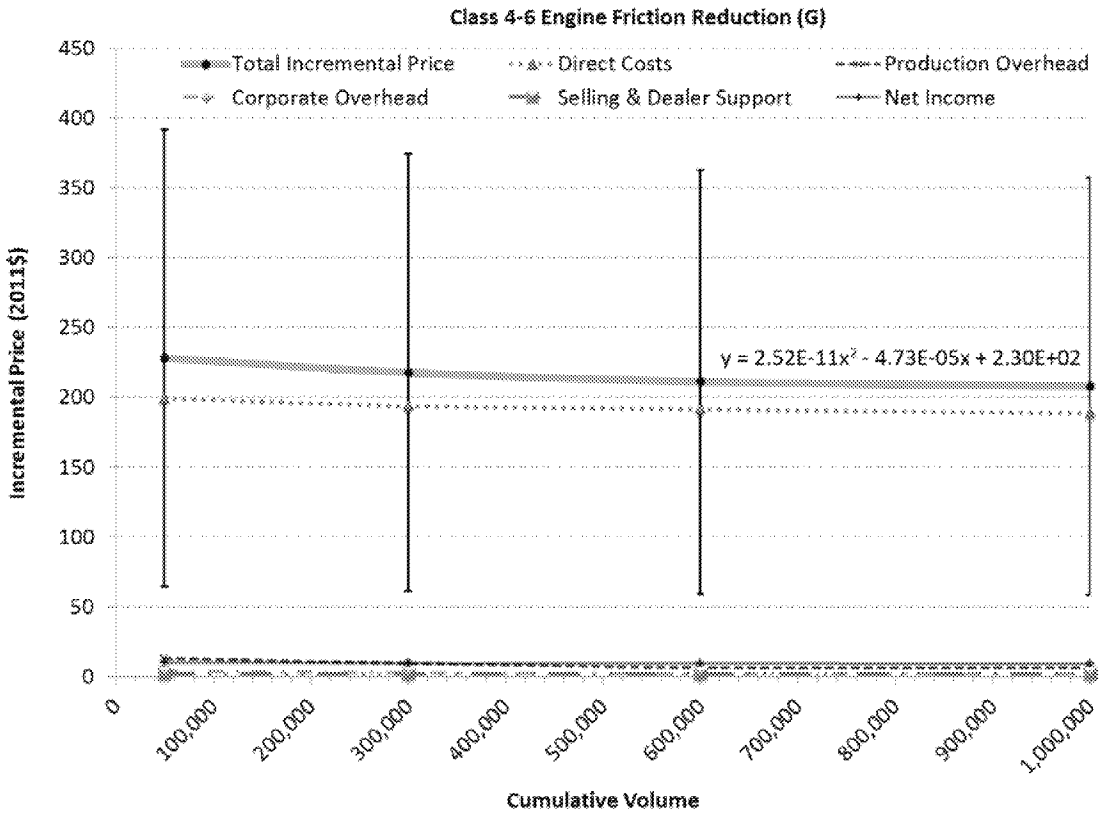
Figure 30. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Engine Friction Reduction



Class 2b&3 Engine Friction Reduction (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$228.00	$217.71	$211.15	$207.87
Direct Costs	$199.16	$193.71	$191.29	$188.32
Production Overhead	$12.91	$9.50	$6.47	$6.37
Corporate Overhead	$3.98	$2.89	$1.91	$1.88
Selling & Dealer Support	$1.99	$1.94	$1.91	$1.88
Net Income	$9.96	$9.69	$9.56	$9.42

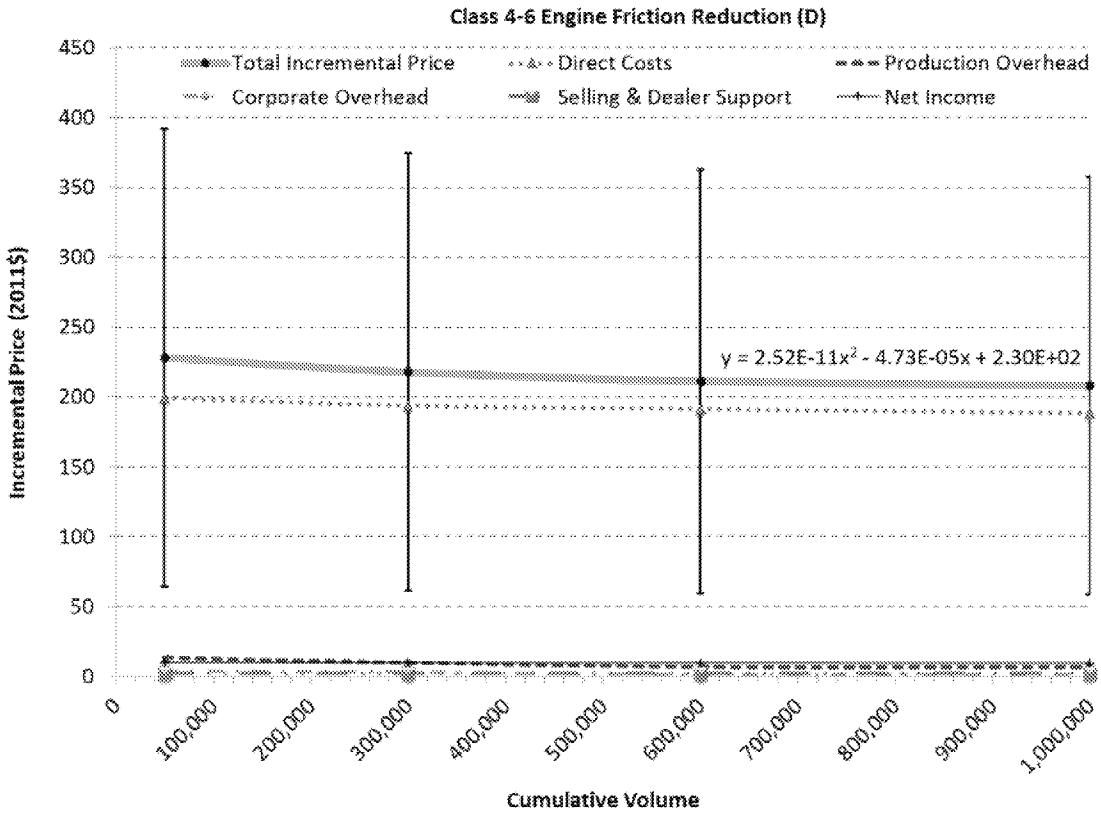
Figure 31. Incremental Price and Breakouts for Class 2b&3 (Diesel) Engine Friction Reduction



Class 4-6 Engine Friction Reduction (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$228.00	$217.71	$211.15	$207.87
Direct Costs	$199.16	$193.71	$191.29	$188.32
Production Overhead	$12.91	$9.50	$6.47	$6.37
Corporate Overhead	$3.98	$2.89	$1.91	$1.88
Selling & Dealer Support	$1.99	$1.94	$1.91	$1.88
Net Income	$9.96	$9.69	$9.56	$9.42

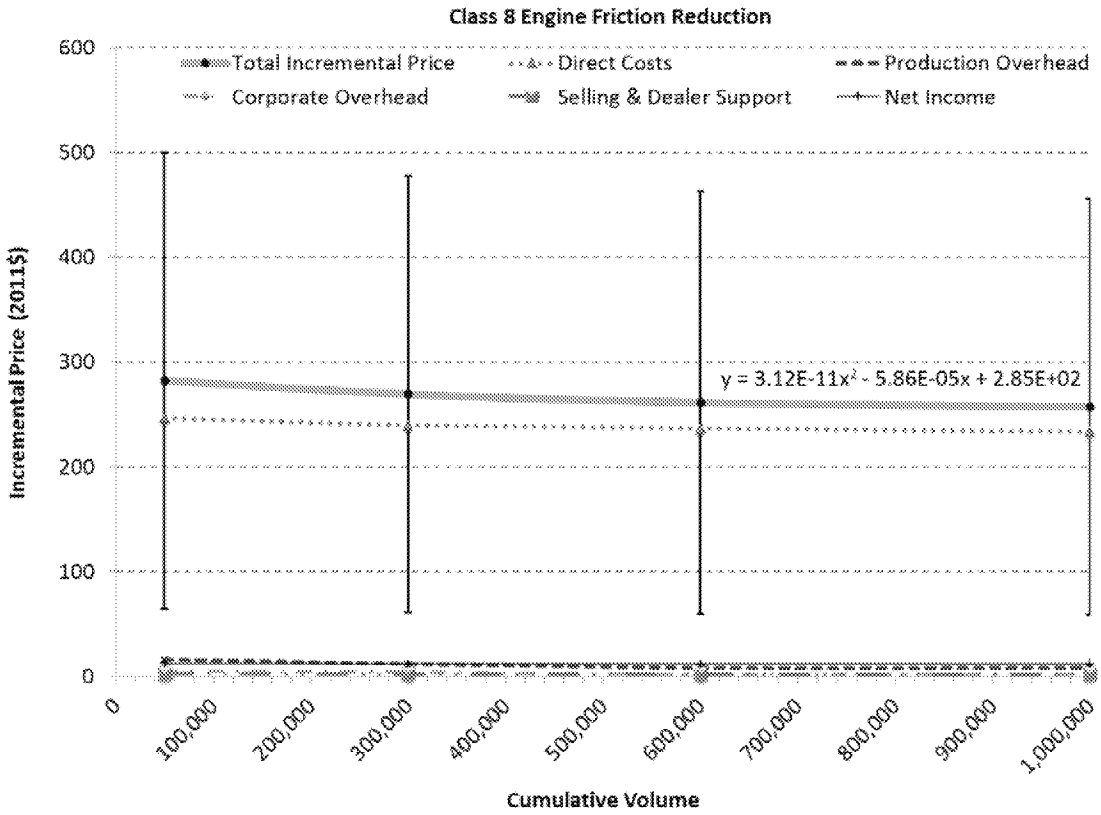
Figure 32. Incremental Price and Breakouts for Vocational (Gasoline) Engine Friction Reduction



Class 4-6 Engine Friction Reduction (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$228.00	$217.71	$211.15	$207.87
Direct Costs	$199.16	$193.71	$191.29	$188.32
Production Overhead	$12.91	$9.50	$6.47	$6.37
Corporate Overhead	$3.98	$2.89	$1.91	$1.88
Selling & Dealer Support	$1.99	$1.94	$1.91	$1.88
Net Income	$9.96	$9.69	$9.56	$9.42

Figure 33. Incremental Price and Breakouts for Vocational (Diesel) Engine Friction Reduction

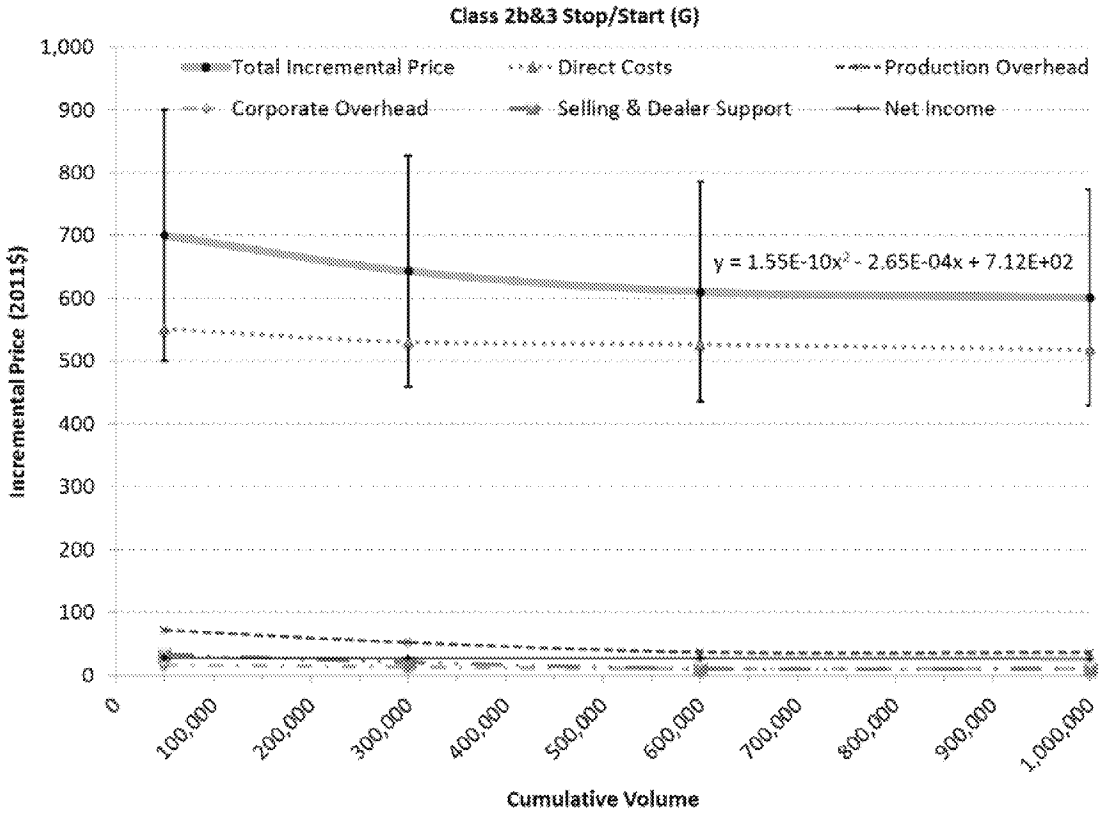


Class 8 Engine Friction Reduction

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$282.00	$269.28	$261.16	$257.10
Direct Costs	$246.33	$239.59	$236.60	$232.92
Production Overhead	$15.96	$11.74	$8.00	$7.87
Corporate Overhead	$4.93	$3.57	$2.37	$2.33
Selling & Dealer Support	$2.46	$2.40	$2.37	$2.33
Net Income	$12.32	$11.98	$11.83	$11.65

Figure 34. Incremental Price and Breakouts for Line Haul Engine Friction Reduction

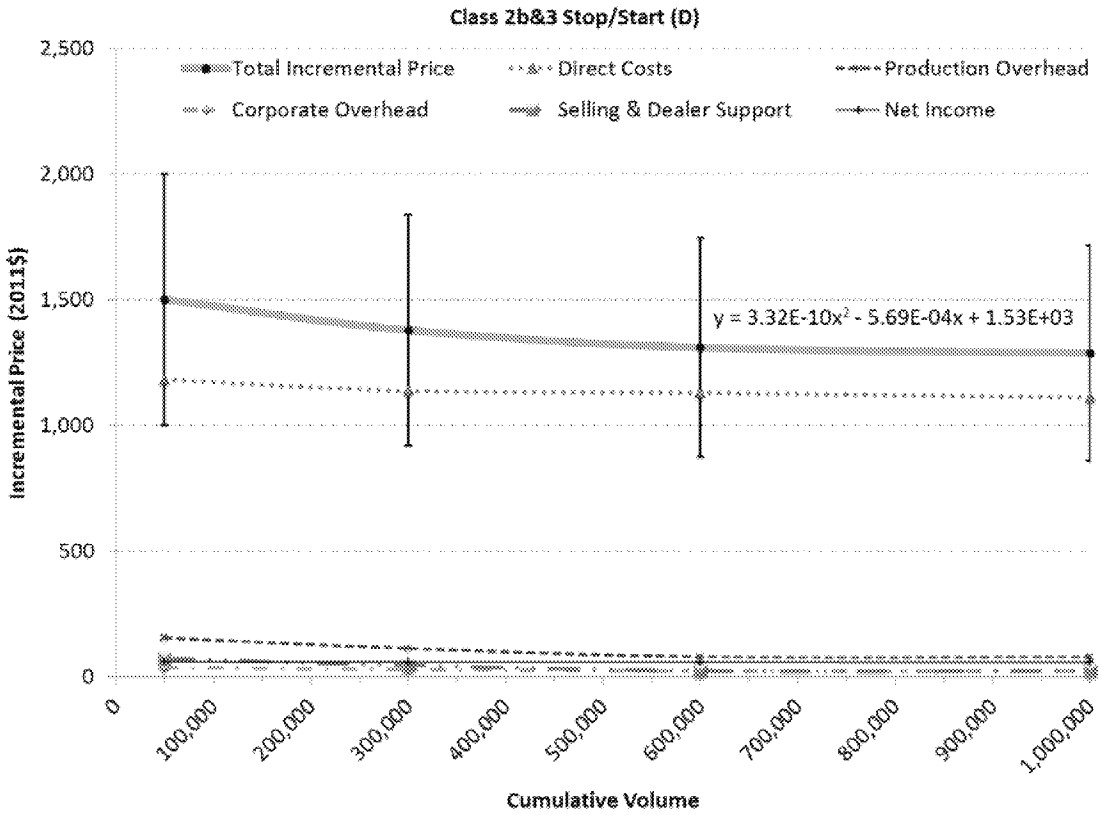
Stop/Start



Class 2b&3 Stop/Start (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$700.00	$643.14	$610.66	$600.92
Direct Costs	$551.18	$530.47	$526.52	$518.12
Production Overhead	$71.65	$52.27	$36.75	$36.16
Corporate Overhead	$16.54	$13.14	$10.53	$10.36
Selling & Dealer Support	$33.07	$20.74	$10.53	$10.36
Net Income	$27.56	$26.52	$26.33	$25.91

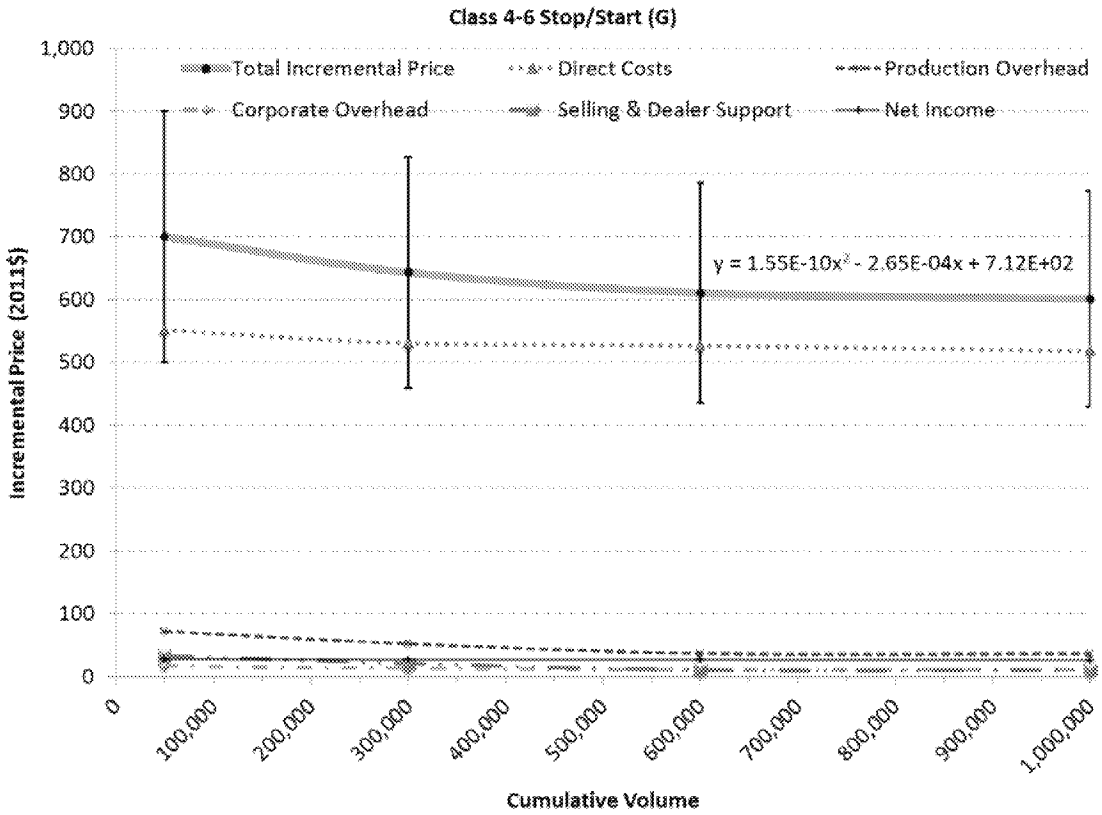
Figure 35. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Stop/Start



Class 2b&3 Stop/Start (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,500.00	$1,378.17	$1,308.56	$1,287.68
Direct Costs	$1,181.10	$1,136.72	$1,128.26	$1,110.26
Production Overhead	$153.54	$112.01	$78.75	$77.50
Corporate Overhead	$35.43	$28.16	$22.57	$22.21
Selling & Dealer Support	$70.87	$44.44	$22.57	$22.21
Net Income	$59.06	$56.84	$56.41	$55.51

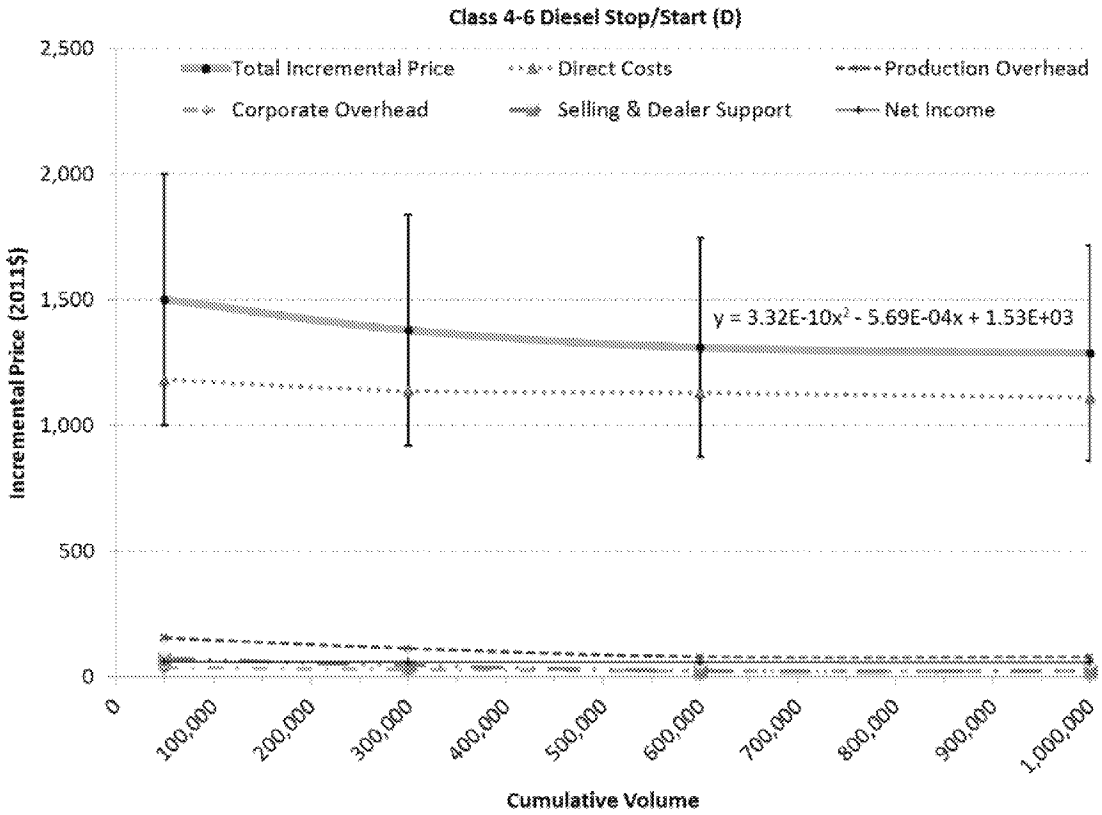
Figure 36. Incremental Price and Breakouts for Class 2b&3 (Diesel) Stop/Start



Class 4-6 Stop/Start (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$700.00	$643.14	$610.66	$600.92
Direct Costs	$551.18	$530.47	$526.52	$518.12
Production Overhead	$71.65	$52.27	$36.75	$36.16
Corporate Overhead	$16.54	$13.14	$10.53	$10.36
Selling & Dealer Support	$33.07	$20.74	$10.53	$10.36
Net Income	$27.56	$26.52	$26.33	$25.91

Figure 37. Incremental Price and Breakouts for Vocational (Gasoline) Stop/Start

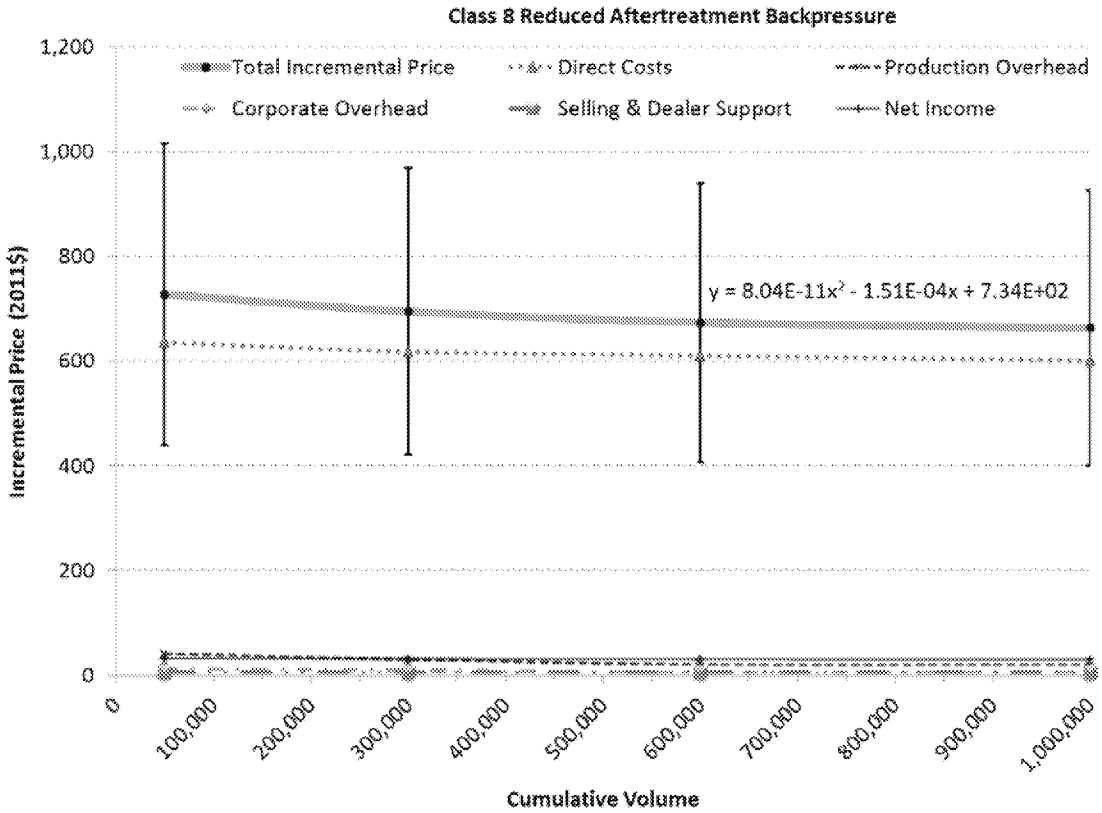


Class 4-6 Diesel Stop/Start (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,500.00	$1,378.17	$1,308.56	$1,287.68
Direct Costs	$1,181.10	$1,136.72	$1,128.26	$1,110.26
Production Overhead	$153.54	$112.01	$78.75	$77.50
Corporate Overhead	$35.43	$28.16	$22.57	$22.21
Selling & Dealer Support	$70.87	$44.44	$22.57	$22.21
Net Income	$59.06	$56.84	$56.41	$55.51

Figure 38. Incremental Price and Breakouts for Vocational (Diesel) Stop/Start

Reduced Aftertreatment Backpressure

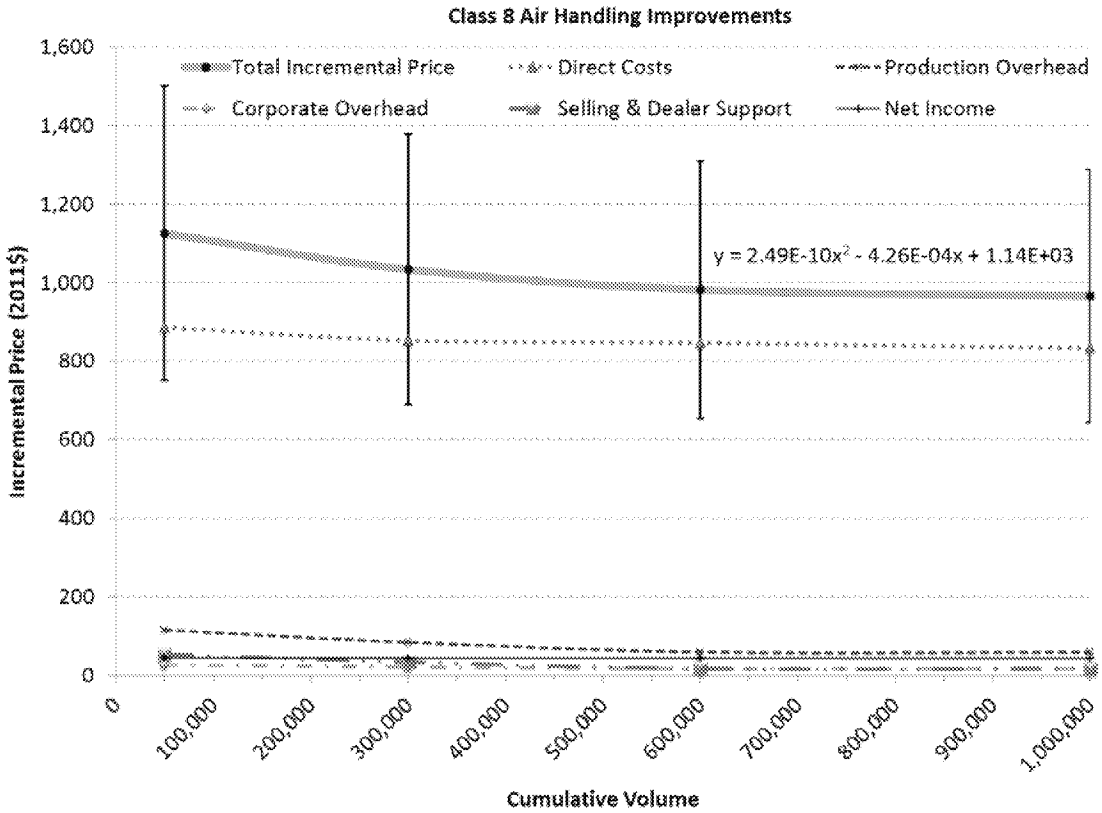


Class 8 Reduced Aftertreatment Backpressure

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$727.50	$694.67	$673.73	$663.26
Direct Costs	$635.48	$618.08	$610.37	$600.89
Production Overhead	$41.18	$30.30	$20.63	$20.31
Corporate Overhead	$12.71	$9.21	$6.10	$6.01
Selling & Dealer Support	$6.35	$6.18	$6.10	$6.01
Net Income	$31.77	$30.90	$30.52	$30.04

Figure 39. Incremental Price and Breakouts for Line Haul Reduced Aftertreatment Backpressure

Air Handling Improvements

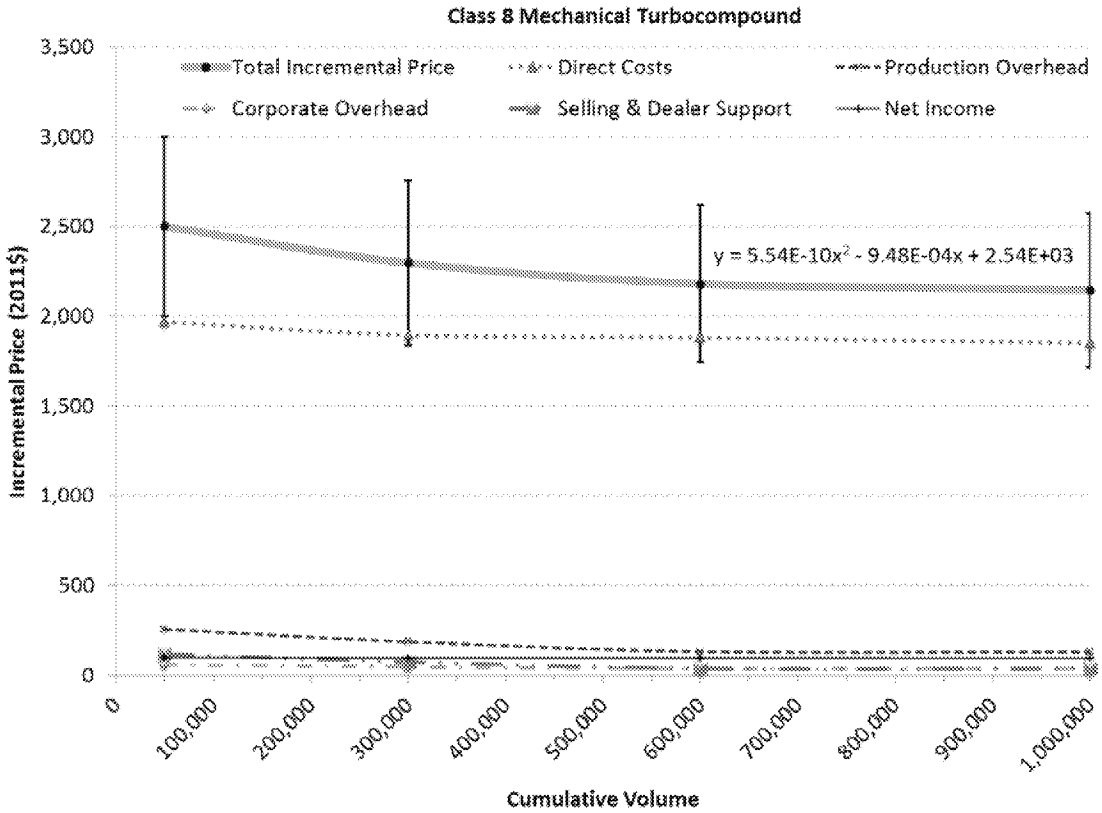


Class 8 Air Handling Improvements

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,125.00	$1,033.62	$981.42	$965.76
Direct Costs	$885.83	$852.54	$846.20	$832.70
Production Overhead	$115.16	$84.01	$59.06	$58.12
Corporate Overhead	$26.57	$21.12	$16.92	$16.65
Selling & Dealer Support	$53.15	$33.33	$16.92	$16.65
Net Income	$44.29	$42.63	$42.31	$41.63

Figure 40. Incremental Price and Breakouts for Line Haul Air Handling Improvements

Mechanical Turbocompound

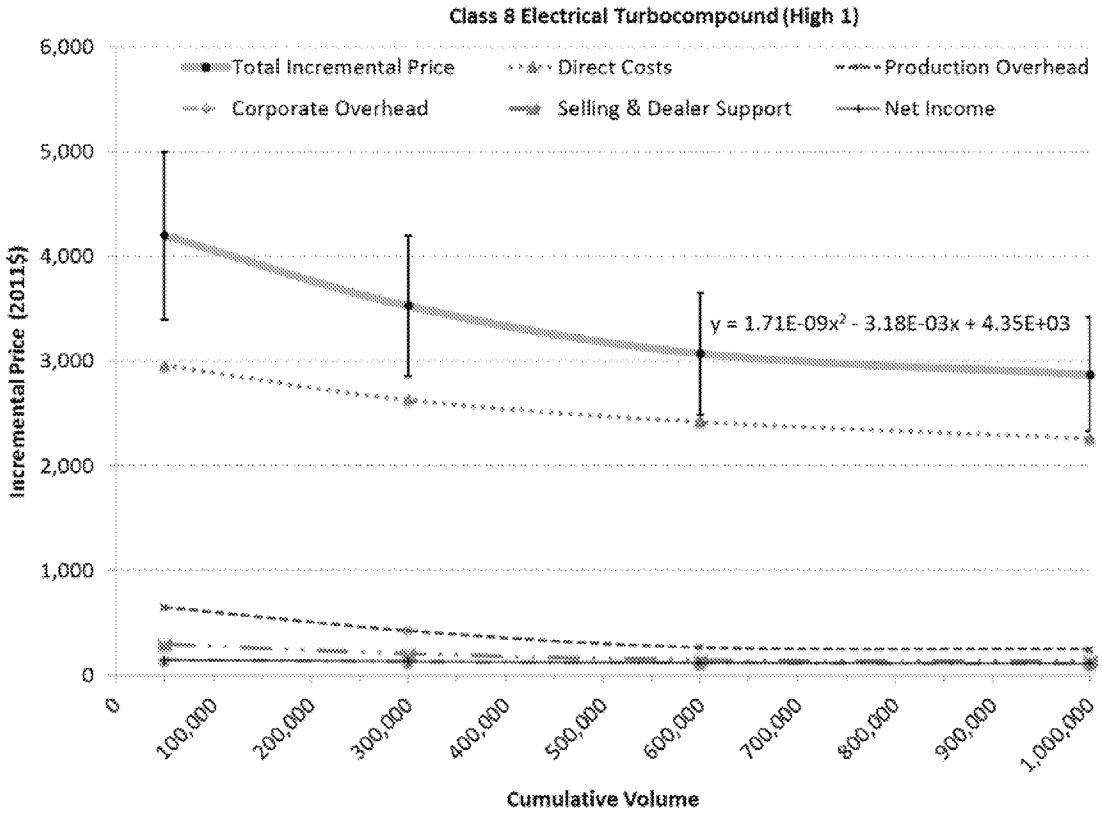


Class 8 Mechanical Turbocompound

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$2,500.00	$2,296.94	$2,180.94	$2,146.13
Direct Costs	$1,968.50	$1,894.54	$1,880.44	$1,850.43
Production Overhead	$255.91	$186.68	$131.25	$129.16
Corporate Overhead	$59.06	$46.93	$37.61	$37.01
Selling & Dealer Support	$118.11	$74.06	$37.61	$37.01
Net Income	$98.43	$94.73	$94.02	$92.52

Figure 41. Incremental Price and Breakouts for Line Haul Mechanical Turbocompound

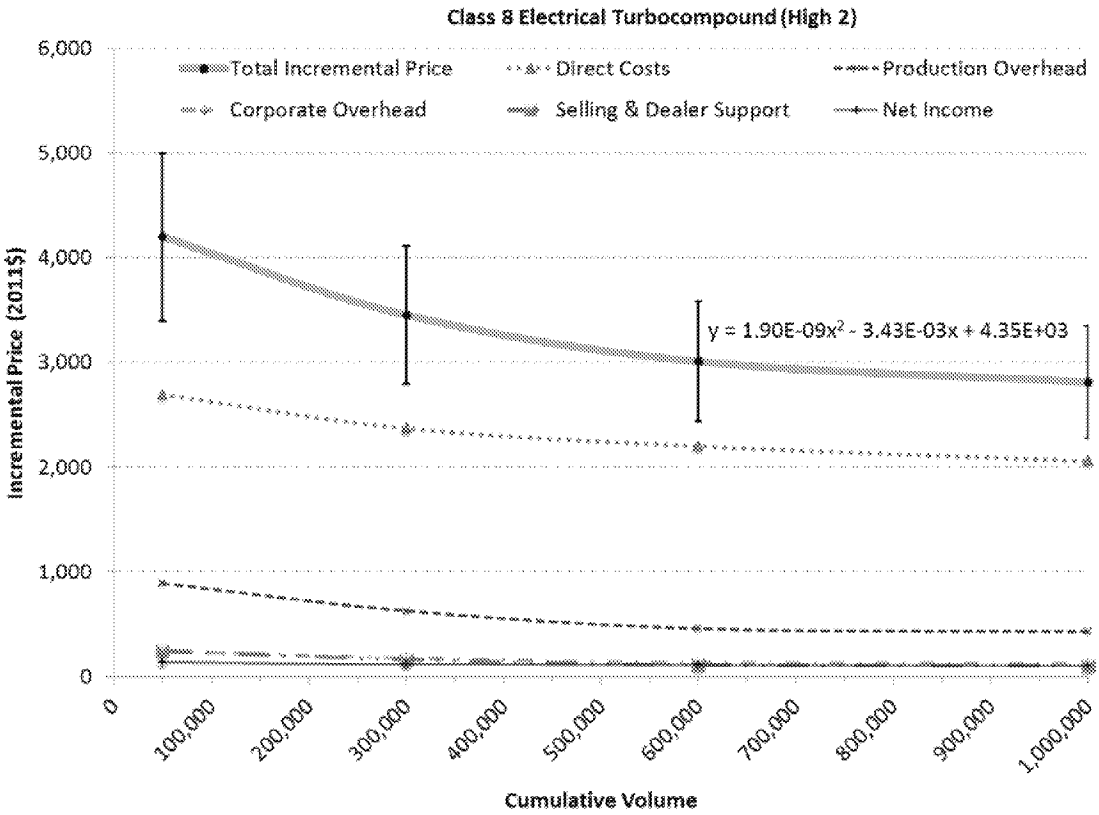
Electric Turbocompound



Class 8 Electrical Turbocompound (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$4,200.00	$3,525.58	$3,071.25	$2,871.35
Direct Costs	$2,957.75	$2,629.42	$2,418.31	$2,260.90
Production Overhead	$650.70	$425.79	$266.01	$248.70
Corporate Overhead	$147.89	$131.47	$120.92	$113.05
Selling & Dealer Support	$295.77	$207.42	$145.10	$135.65
Net Income	$147.89	$131.47	$120.92	$113.05

Figure 42. Incremental Price and Breakouts for Line Haul Electric Turbocompound (High 1 Complexity)

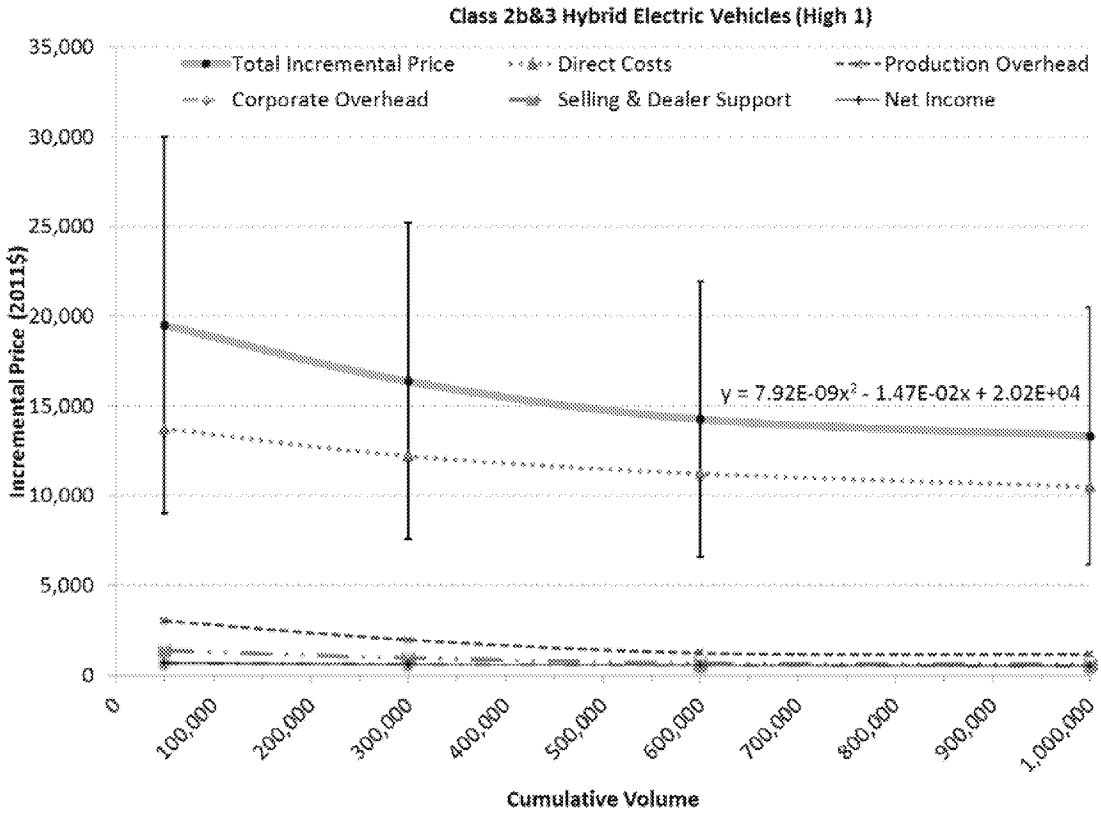


Class 8 Electrical Turbocompound (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$4,200.00	$3,452.54	$3,007.63	$2,811.86
Direct Costs	$2,692.31	$2,368.48	$2,198.56	$2,055.46
Production Overhead	$888.46	$627.65	$457.30	$427.53
Corporate Overhead	$242.31	$175.31	$131.91	$123.33
Selling & Dealer Support	$242.31	$162.69	$109.93	$102.77
Net Income	$134.62	$118.42	$109.93	$102.77

Figure 43. Incremental Price and Breakouts for Line Haul Electric Turbocompound (High 2 Complexity)

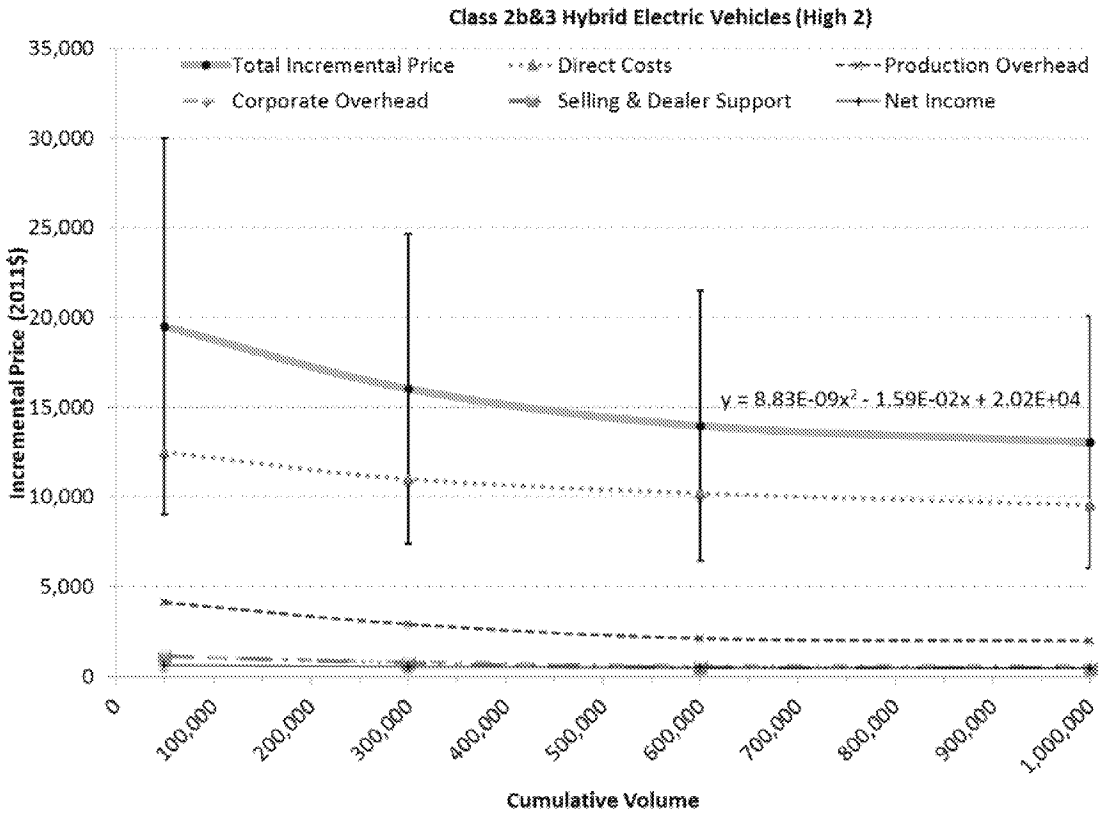
Hybrid Electric Vehicles



Class 2b&3 Hybrid Electric Vehicles (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$19,500.00	$16,368.75	$14,259.38	$13,331.25
Direct Costs	$13,732.39	$12,208.03	$11,227.85	$10,497.05
Production Overhead	$3,021.13	$1,976.88	$1,235.06	$1,154.68
Corporate Overhead	$686.62	$610.40	$561.39	$524.85
Selling & Dealer Support	$1,373.24	$963.03	$673.67	$629.82
Net Income	$686.62	$610.40	$561.39	$524.85

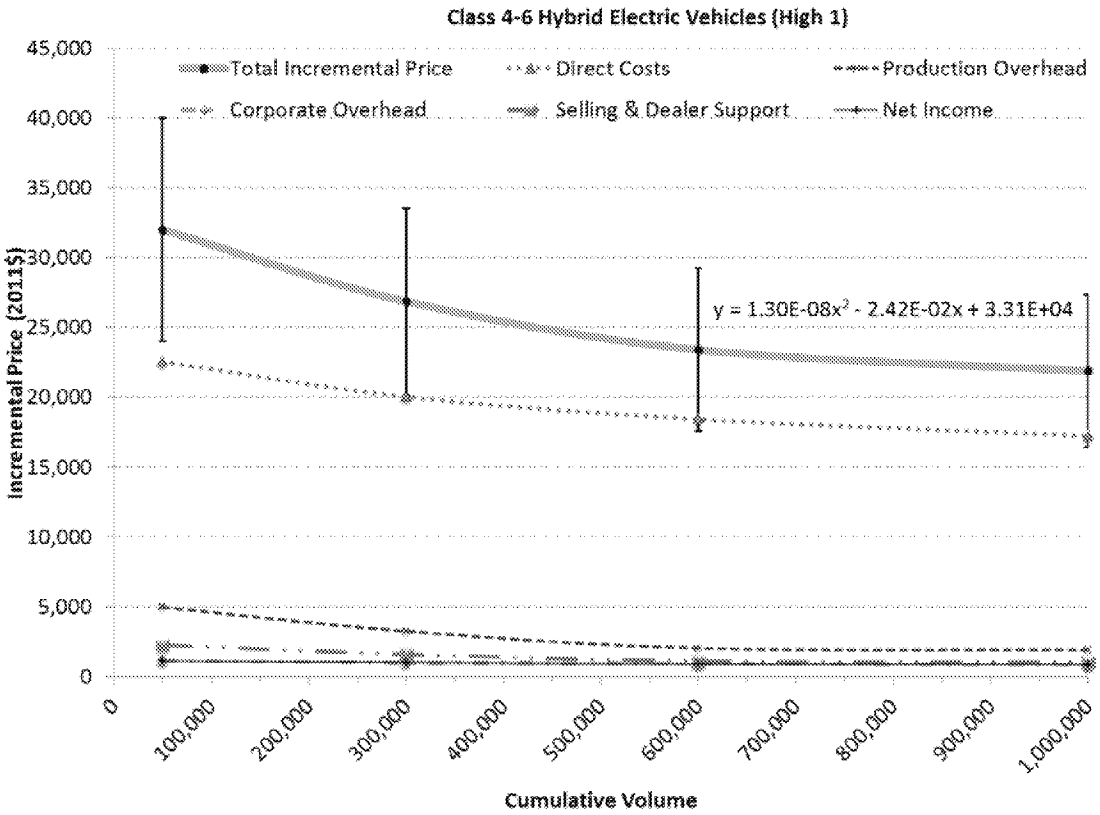
Figure 44. Incremental Price and Breakouts for Class 2b&3 Hybrid Electric Vehicles (High 1)



Class 2b&3 Hybrid Electric Vehicles (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$19,500.00	$16,029.66	$13,963.98	$13,055.08
Direct Costs	$12,500.00	$10,996.51	$10,207.59	$9,543.19
Production Overhead	$4,125.00	$2,914.07	$2,123.18	$1,984.98
Corporate Overhead	$1,125.00	$813.92	$612.46	$572.59
Selling & Dealer Support	$1,125.00	$755.33	$510.38	$477.16
Net Income	$625.00	$549.83	$510.38	$477.16

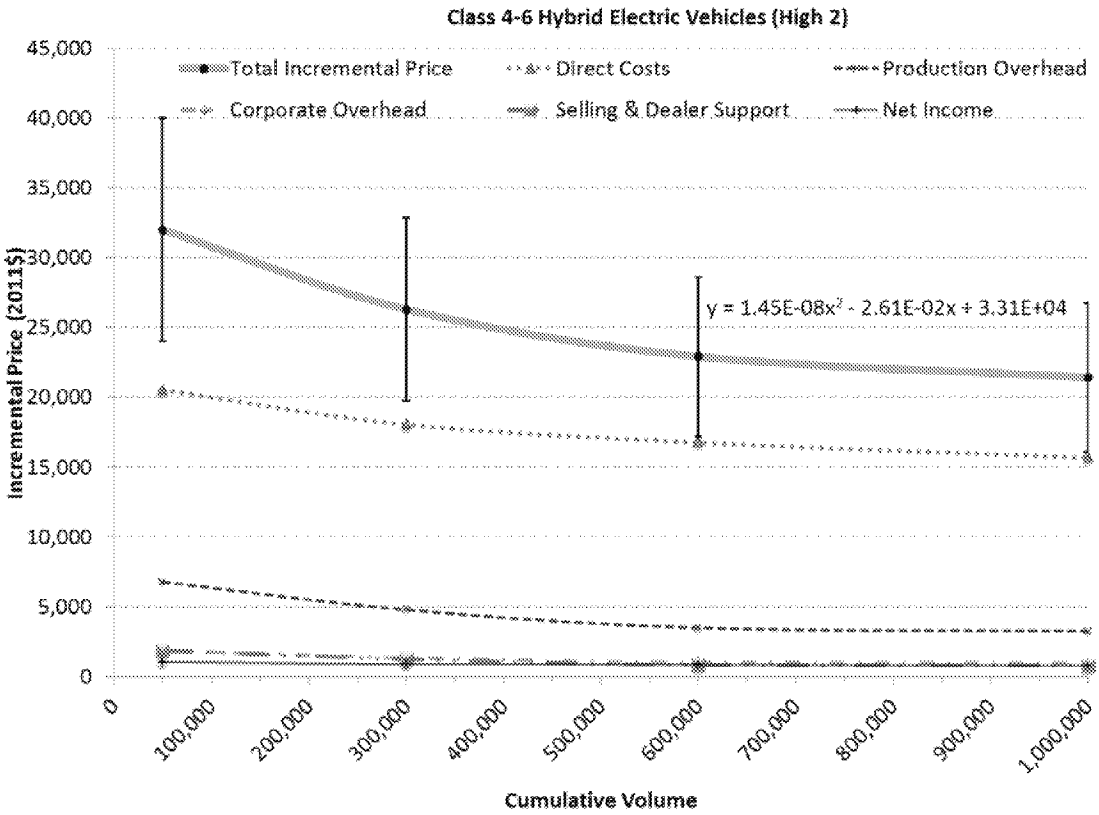
Figure 45. Incremental Price and Breakouts for Class 2b&3 Hybrid Electric Vehicles (High 2)



Class 4-6 Hybrid Electric Vehicles (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$32,000.00	$26,861.54	$23,400.00	$21,876.92
Direct Costs	$22,535.21	$20,033.70	$18,425.20	$17,225.92
Production Overhead	$4,957.75	$3,244.12	$2,026.77	$1,894.85
Corporate Overhead	$1,126.76	$1,001.68	$921.26	$861.30
Selling & Dealer Support	$2,253.52	$1,580.35	$1,105.51	$1,033.56
Net Income	$1,126.76	$1,001.68	$921.26	$861.30

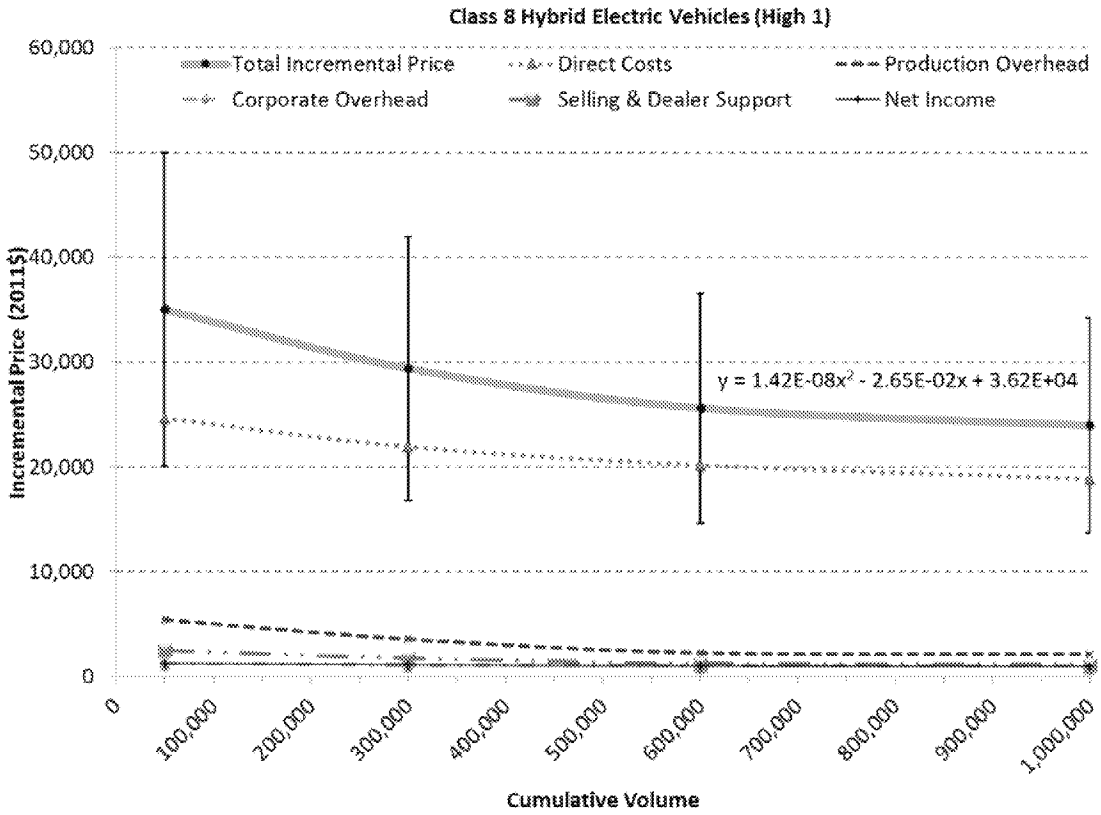
Figure 46. Incremental Price and Breakouts for Vocational Hybrid Electric Vehicles (High 1)



Class 4-6 Hybrid Electric Vehicles (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$32,000.00	$26,305.08	$22,915.25	$21,423.73
Direct Costs	$20,512.82	$18,045.55	$16,750.92	$15,660.62
Production Overhead	$6,769.23	$4,782.07	$3,484.19	$3,257.41
Corporate Overhead	$1,846.15	$1,335.67	$1,005.06	$939.64
Selling & Dealer Support	$1,846.15	$1,239.52	$837.55	$783.03
Net Income	$1,025.64	$902.28	$837.55	$783.03

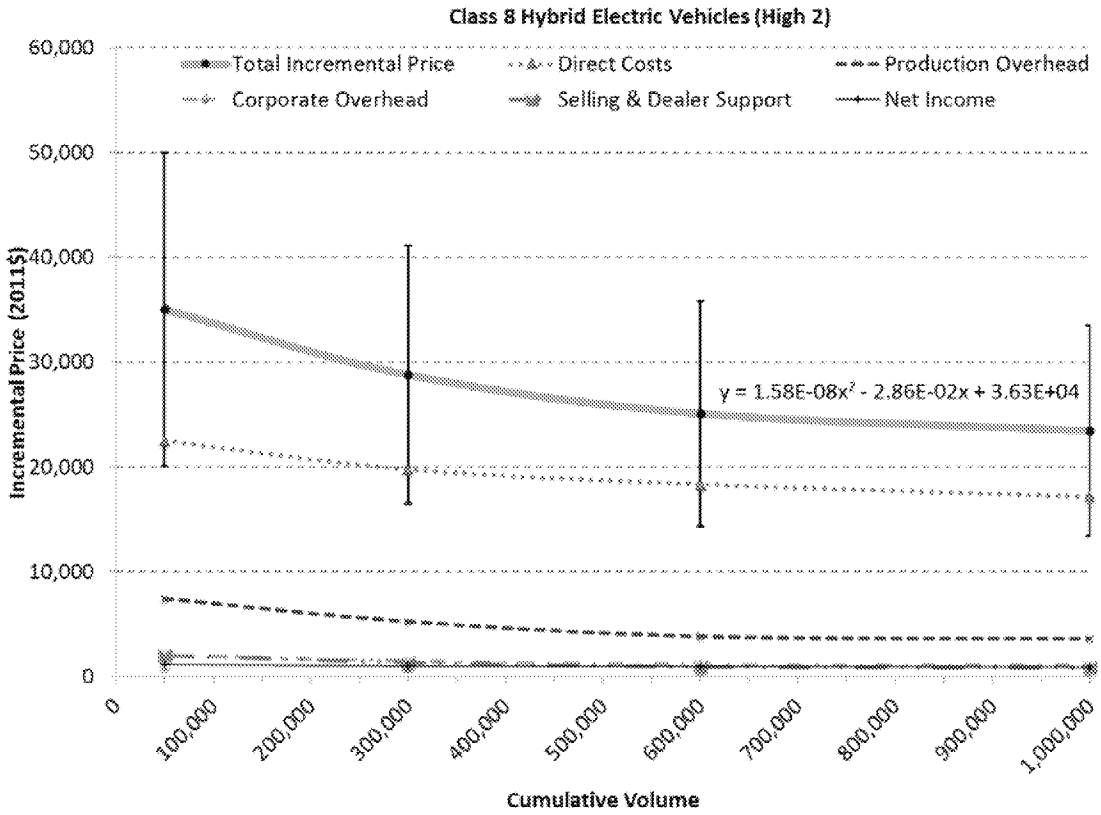
Figure 47. Incremental Price and Breakouts for Vocational Hybrid Electric Vehicles (High 2)



Class 8 Hybrid Electric Vehicles (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$35,000.00	$29,379.81	$25,593.75	$23,927.88
Direct Costs	$24,647.89	$21,911.86	$20,152.56	$18,840.85
Production Overhead	$5,422.54	$3,548.25	$2,216.78	$2,072.49
Corporate Overhead	$1,232.39	$1,095.59	$1,007.63	$942.04
Selling & Dealer Support	$2,464.79	$1,728.51	$1,209.15	$1,130.45
Net Income	$1,232.39	$1,095.59	$1,007.63	$942.04

Figure 48. Incremental Price and Breakouts for Line Haul Hybrid Electric Vehicles (High 1)

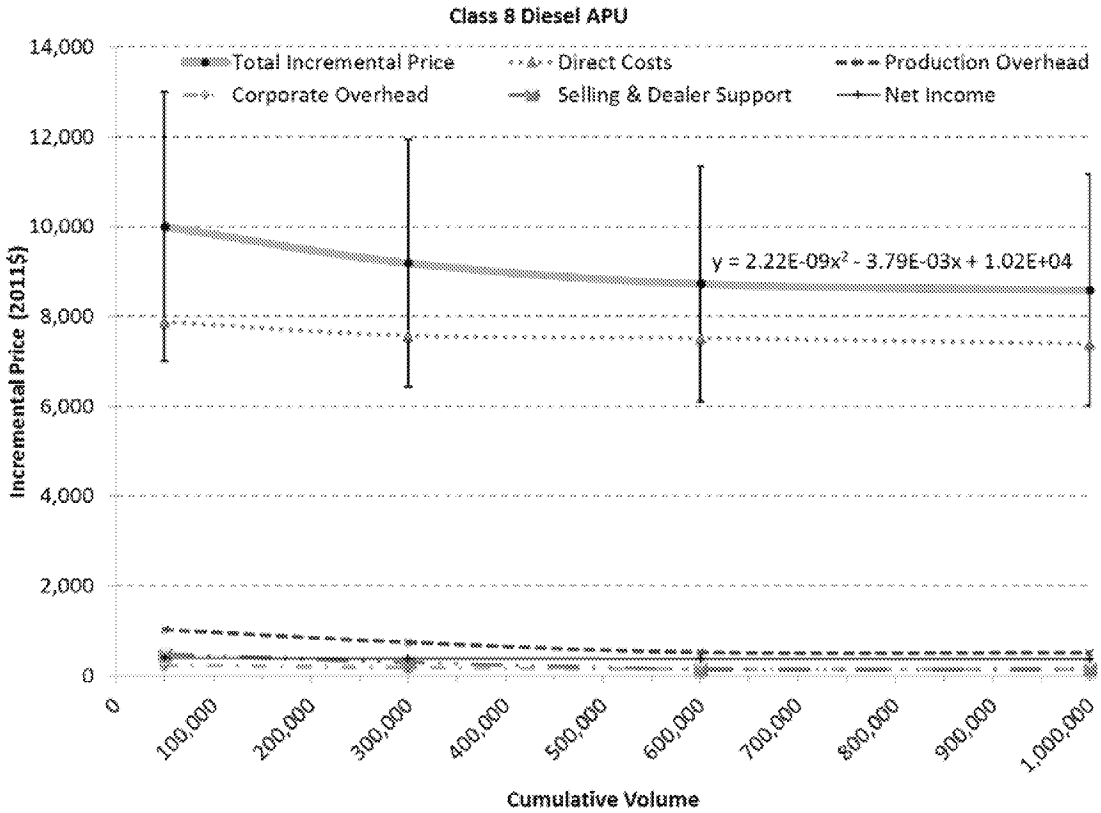


Class 8 Hybrid Electric Vehicles (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$35,000.00	$28,771.19	$25,063.56	$23,432.20
Direct Costs	$22,435.90	$19,737.32	$18,321.32	$17,128.80
Production Overhead	$7,403.85	$5,230.39	$3,810.83	$3,562.79
Corporate Overhead	$2,019.23	$1,460.89	$1,099.28	$1,027.73
Selling & Dealer Support	$2,019.23	$1,355.73	$916.07	$856.44
Net Income	$1,121.79	$986.87	$916.07	$856.44

Figure 49. Incremental Price and Breakouts for Line Haul Hybrid Electric Vehicles (High 2)

Diesel APU (with DPF)

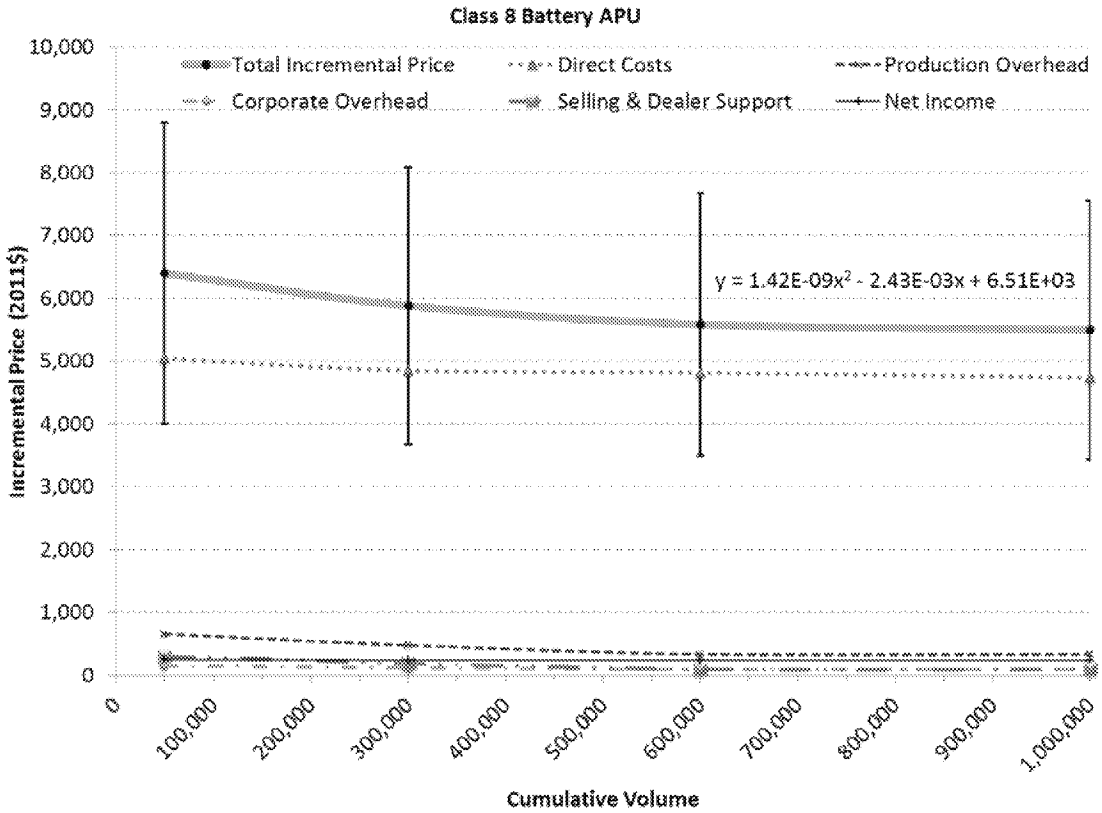


Class 8 Diesel APU

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$10,000.00	$9,187.77	$8,723.74	$8,584.53
Direct Costs	$7,874.02	$7,578.16	$7,521.76	$7,401.74
Production Overhead	$1,023.62	$746.71	$525.02	$516.64
Corporate Overhead	$236.22	$187.74	$150.44	$148.03
Selling & Dealer Support	$472.44	$296.25	$150.44	$148.03
Net Income	$393.70	$378.91	$376.09	$370.09

Figure 50. Incremental Price and Breakouts for Line Haul Diesel APU (w/DPF)

Battery APU

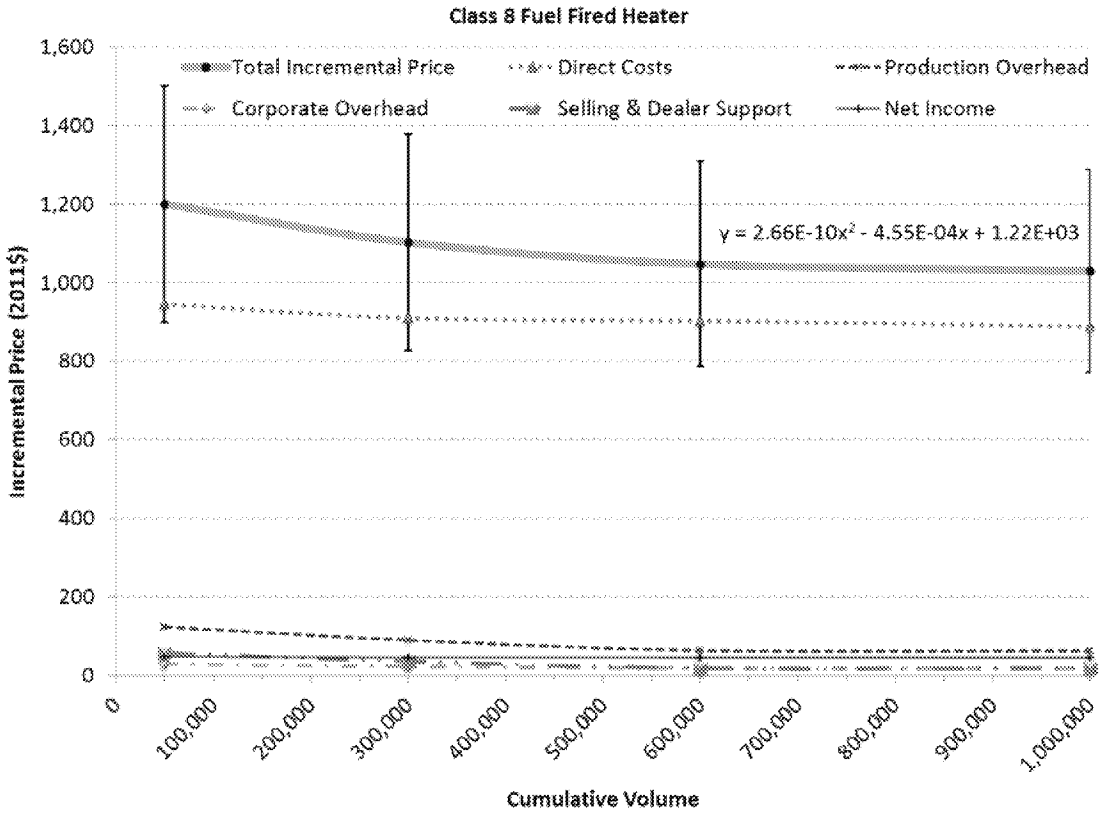


Class 8 Battery APU

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$6,400.00	$5,880.17	$5,583.19	$5,494.10
Direct Costs	$5,039.37	$4,850.02	$4,813.93	$4,737.11
Production Overhead	$655.12	$477.90	$336.01	$330.65
Corporate Overhead	$151.18	$120.15	$96.28	$94.74
Selling & Dealer Support	$302.36	$189.60	$96.28	$94.74
Net Income	$251.97	$242.50	$240.70	$236.86

Figure 51. Incremental Price and Breakouts for Line Haul Battery APU

Fuel Fired Heater

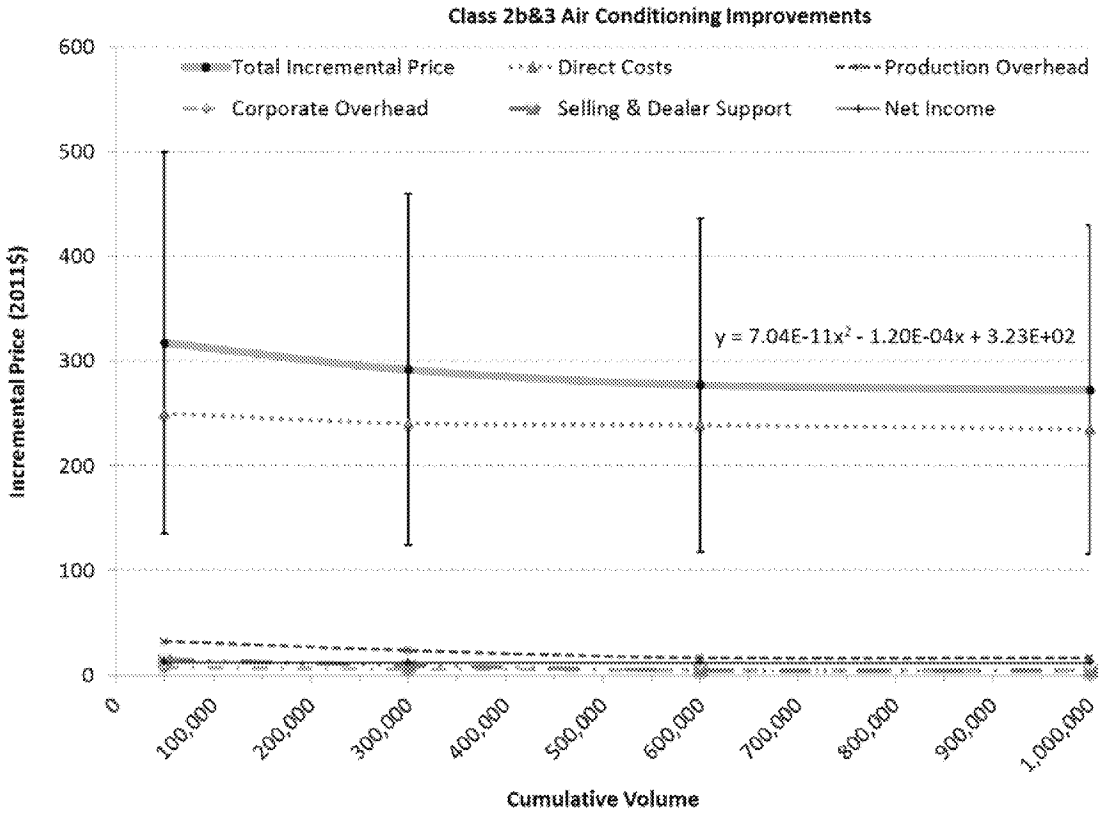


Class 8 Fuel Fired Heater

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,200.00	$1,102.53	$1,046.85	$1,030.14
Direct Costs	$944.88	$909.38	$902.61	$888.21
Production Overhead	$122.83	$89.61	$63.00	$62.00
Corporate Overhead	$28.35	$22.53	$18.05	$17.76
Selling & Dealer Support	$56.69	$35.55	$18.05	$17.76
Net Income	$47.24	$45.47	$45.13	$44.41

Figure 52. Incremental Price and Breakouts for Line Haul Fuel Fired Heater

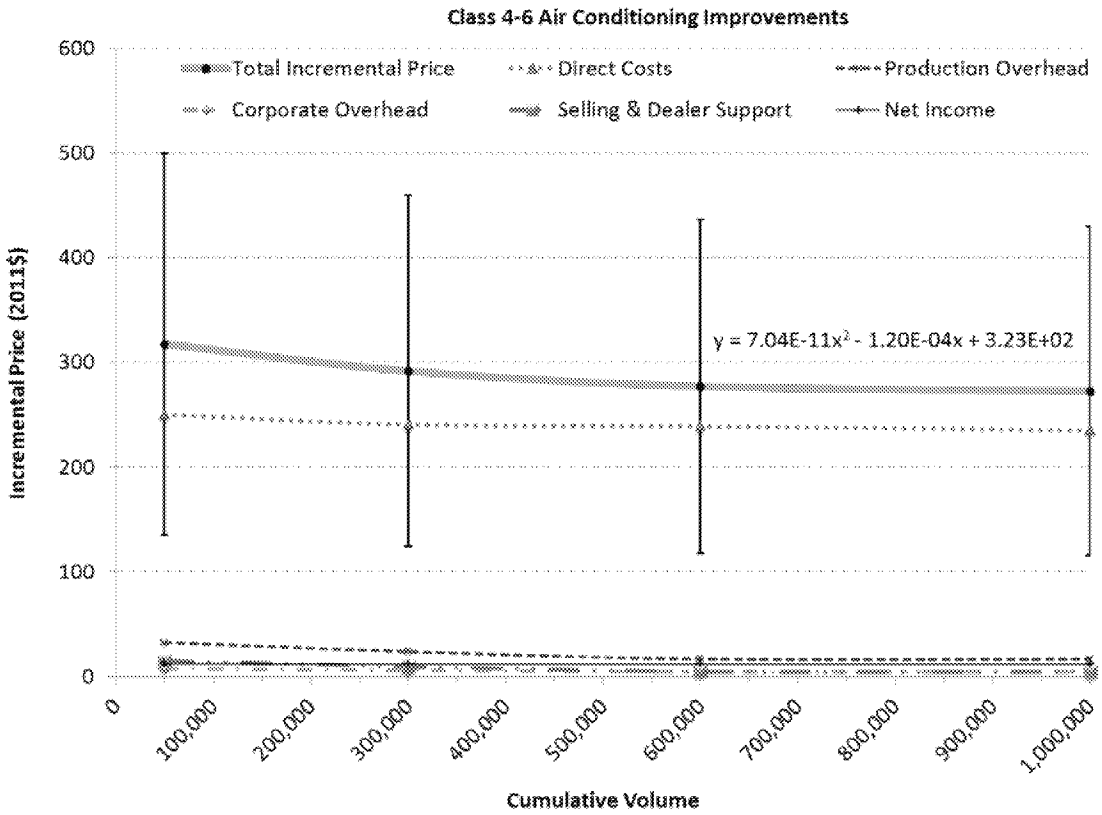
Air Conditioner System Improvements



Class 2b&3 Air Conditioning Improvements

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$317.50	$291.71	$276.98	$272.56
Direct Costs	$250.00	$240.61	$238.82	$235.01
Production Overhead	$32.50	$23.71	$16.67	$16.40
Corporate Overhead	$7.50	$5.96	$4.78	$4.70
Selling & Dealer Support	$15.00	$9.41	$4.78	$4.70
Net Income	$12.50	$12.03	$11.94	$11.75

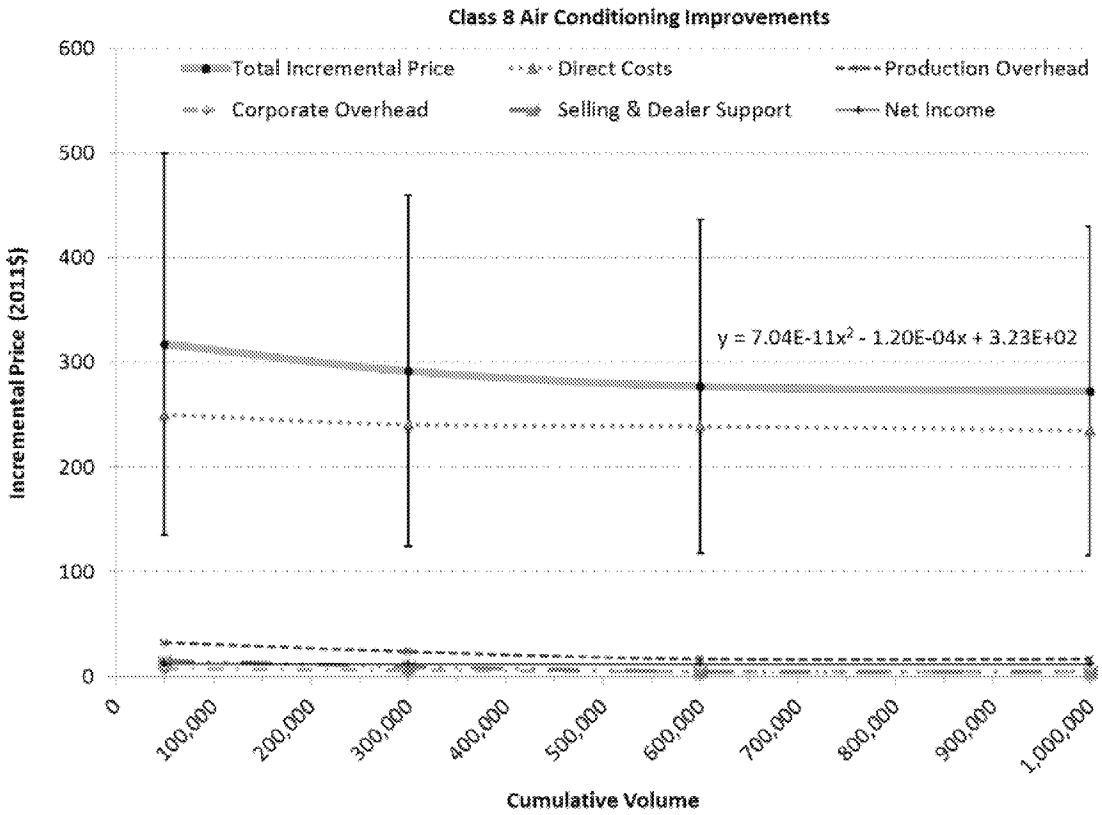
Figure 53. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) A/C System Improvements



Class 4-6 Air Conditioning Improvements

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$317.50	$291.71	$276.98	$272.56
Direct Costs	$250.00	$240.61	$238.82	$235.01
Production Overhead	$32.50	$23.71	$16.67	$16.40
Corporate Overhead	$7.50	$5.96	$4.78	$4.70
Selling & Dealer Support	$15.00	$9.41	$4.78	$4.70
Net Income	$12.50	$12.03	$11.94	$11.75

Figure 54. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) A/C System Improvements

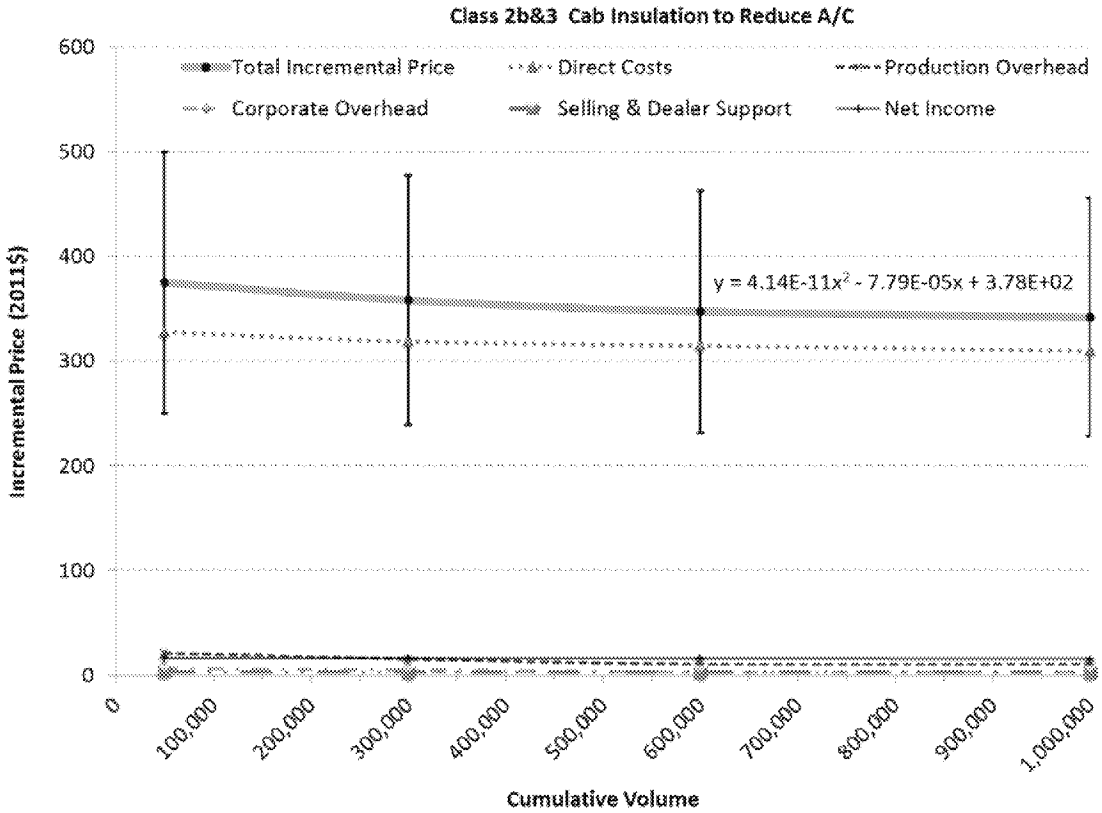


Class 8 Air Conditioning Improvements

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$317.50	$291.71	$276.98	$272.56
Direct Costs	$250.00	$240.61	$238.82	$235.01
Production Overhead	$32.50	$23.71	$16.67	$16.40
Corporate Overhead	$7.50	$5.96	$4.78	$4.70
Selling & Dealer Support	$15.00	$9.41	$4.78	$4.70
Net Income	$12.50	$12.03	$11.94	$11.75

Figure 55. Incremental Price and Breakouts for Line Haul A/C System Improvements

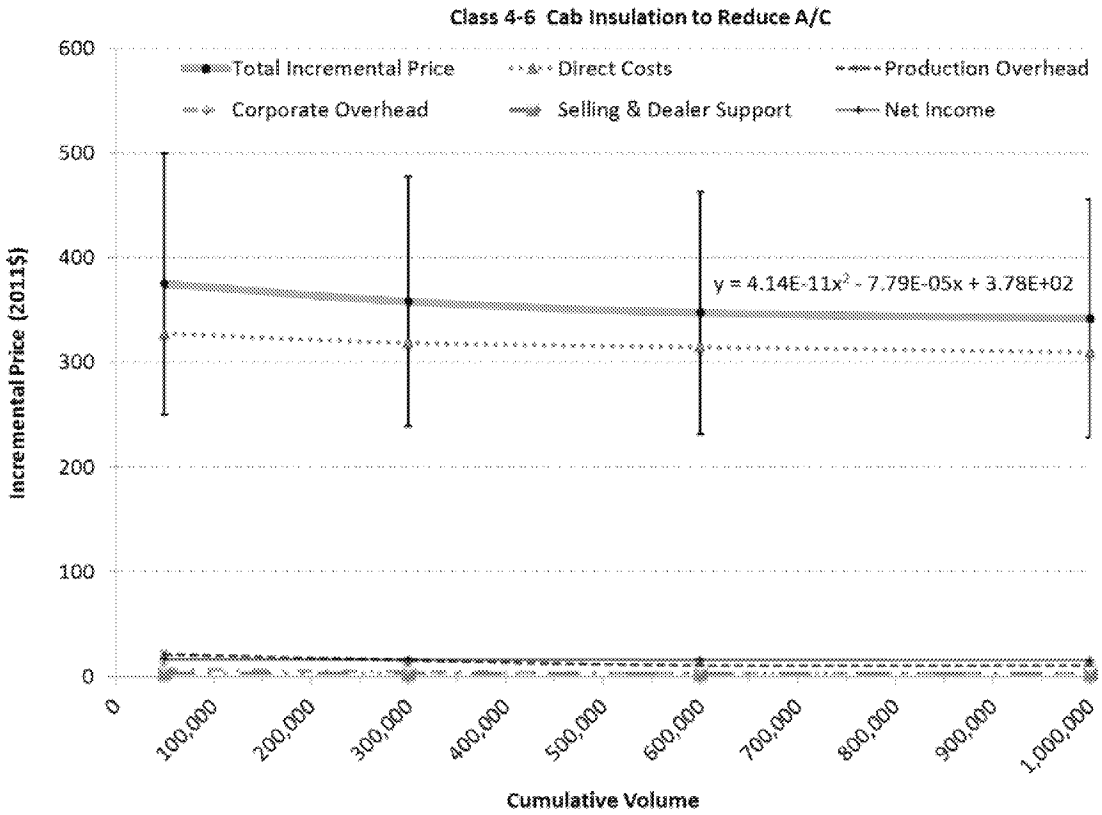
Cab Insulation to Reduce A/C



Class 2b&3 Cab Insulation to Reduce A/C

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$375.00	$358.08	$347.28	$341.89
Direct Costs	$327.57	$318.60	$314.63	$309.73
Production Overhead	$21.23	$15.62	$10.63	$10.47
Corporate Overhead	$6.55	$4.75	$3.15	$3.10
Selling & Dealer Support	$3.28	$3.19	$3.15	$3.10
Net Income	$16.38	$15.93	$15.73	$15.49

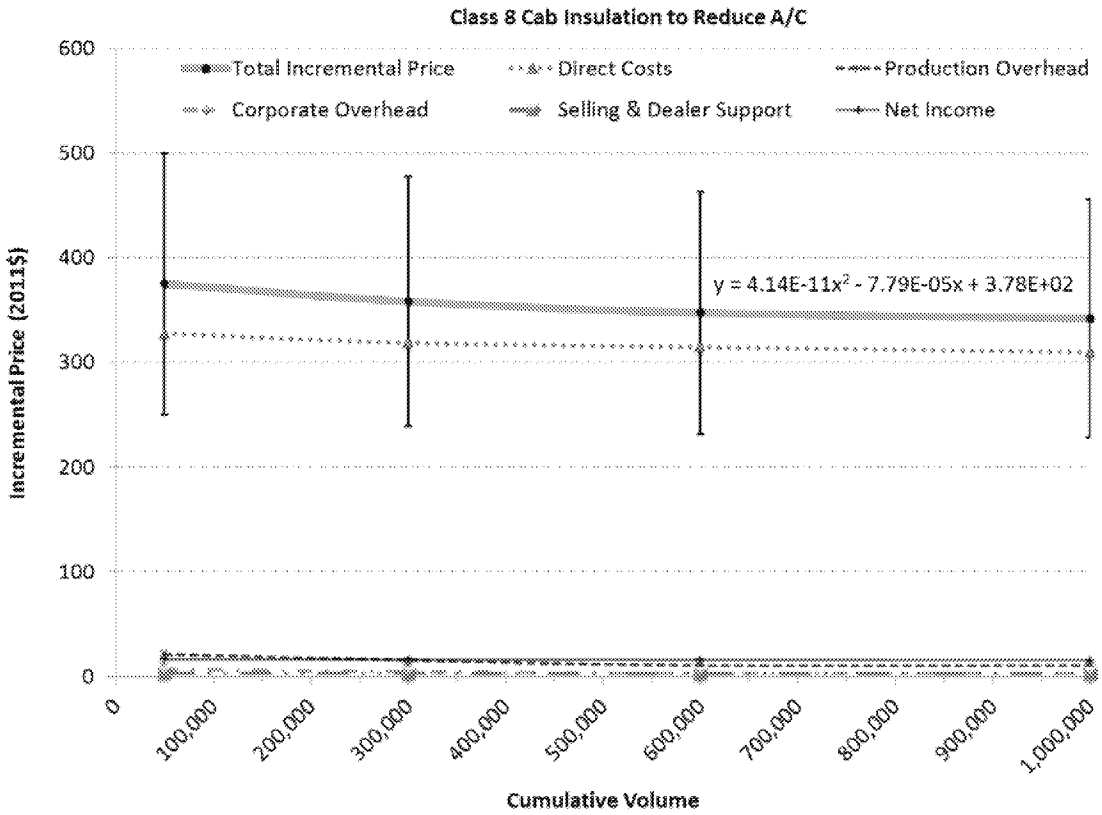
Figure 56. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) Cab Insulation to Reduce A/C



Class 4-6 Cab Insulation to Reduce A/C

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$375.00	$358.08	$347.28	$341.89
Direct Costs	$327.57	$318.60	$314.63	$309.73
Production Overhead	$21.23	$15.62	$10.63	$10.47
Corporate Overhead	$6.55	$4.75	$3.15	$3.10
Selling & Dealer Support	$3.28	$3.19	$3.15	$3.10
Net Income	$16.38	$15.93	$15.73	$15.49

Figure 57. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) Cab Insulation to Reduce A/C

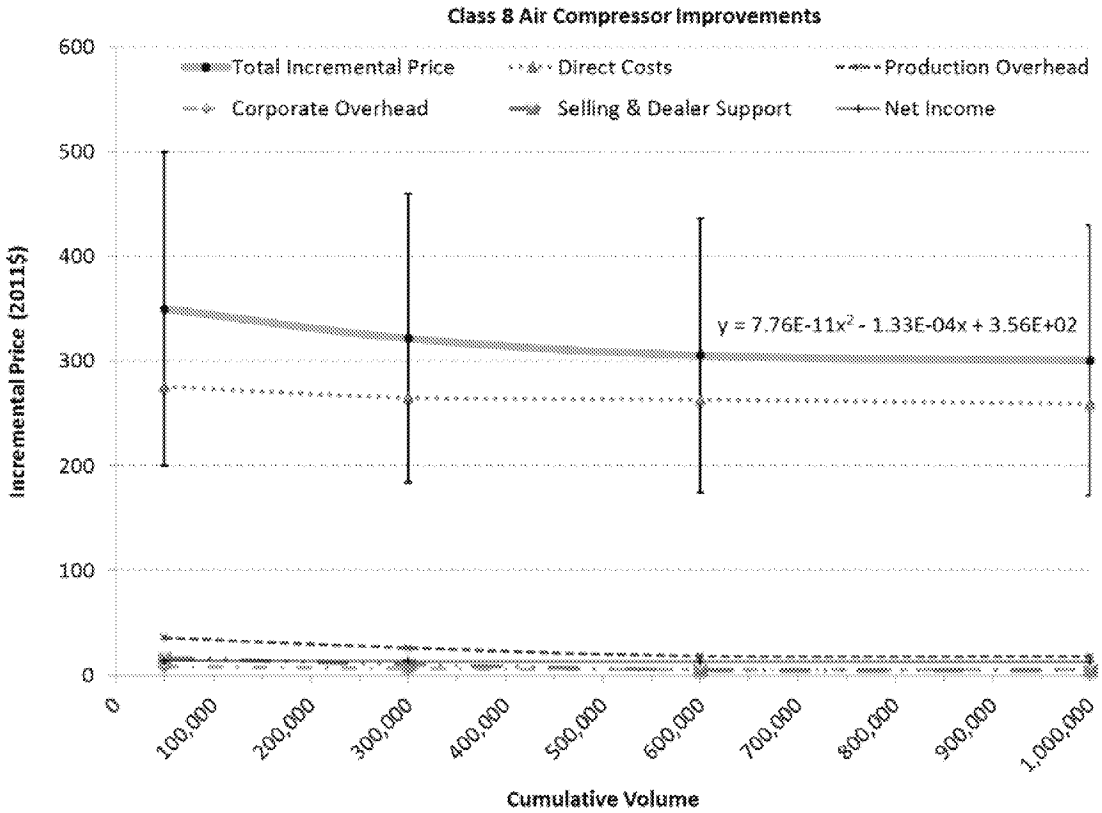


Class 8 Cab Insulation to Reduce A/C

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$375.00	$358.08	$347.28	$341.89
Direct Costs	$327.57	$318.60	$314.63	$309.73
Production Overhead	$21.23	$15.62	$10.63	$10.47
Corporate Overhead	$6.55	$4.75	$3.15	$3.10
Selling & Dealer Support	$3.28	$3.19	$3.15	$3.10
Net Income	$16.38	$15.93	$15.73	$15.49

Figure 58. Incremental Price and Breakouts for Line Haul Cab Insulation to Reduce A/C

Air Compressor Improvements

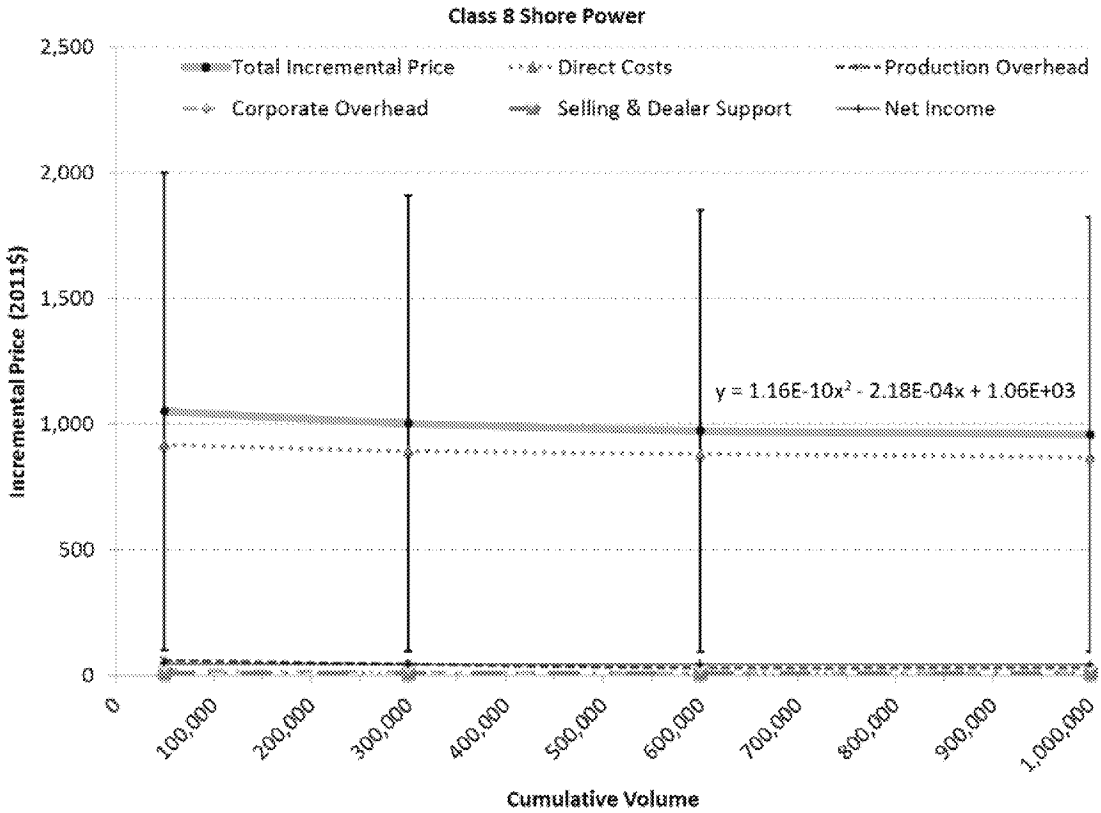


Class 8 Air Compressor Improvements

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$350.00	$321.57	$305.33	$300.46
Direct Costs	$275.59	$265.24	$263.26	$259.06
Production Overhead	$35.83	$26.13	$18.38	$18.08
Corporate Overhead	$8.27	$6.57	$5.27	$5.18
Selling & Dealer Support	$16.54	$10.37	$5.27	$5.18
Net Income	$13.78	$13.26	$13.16	$12.95

Figure 59. Incremental Price and Breakouts for Line Haul Air Compressor Improvements

Shore Power

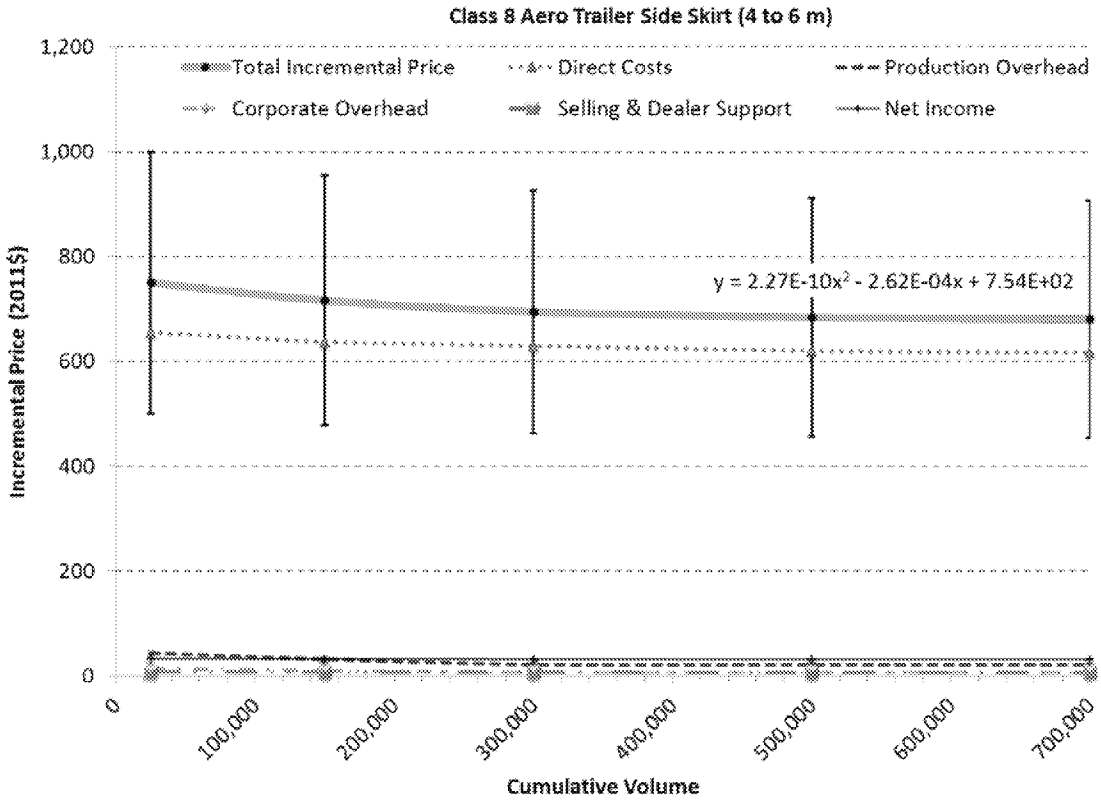


Class 8 Shore Power

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,050.00	$1,002.62	$972.39	$957.28
Direct Costs	$917.19	$892.07	$880.95	$867.26
Production Overhead	$59.43	$43.73	$29.78	$29.31
Corporate Overhead	$18.34	$13.30	$8.81	$8.67
Selling & Dealer Support	$9.17	$8.92	$8.81	$8.67
Net Income	$45.86	$44.60	$44.05	$43.36

Figure 60. Incremental Price and Breakouts for Line Haul Shore Power

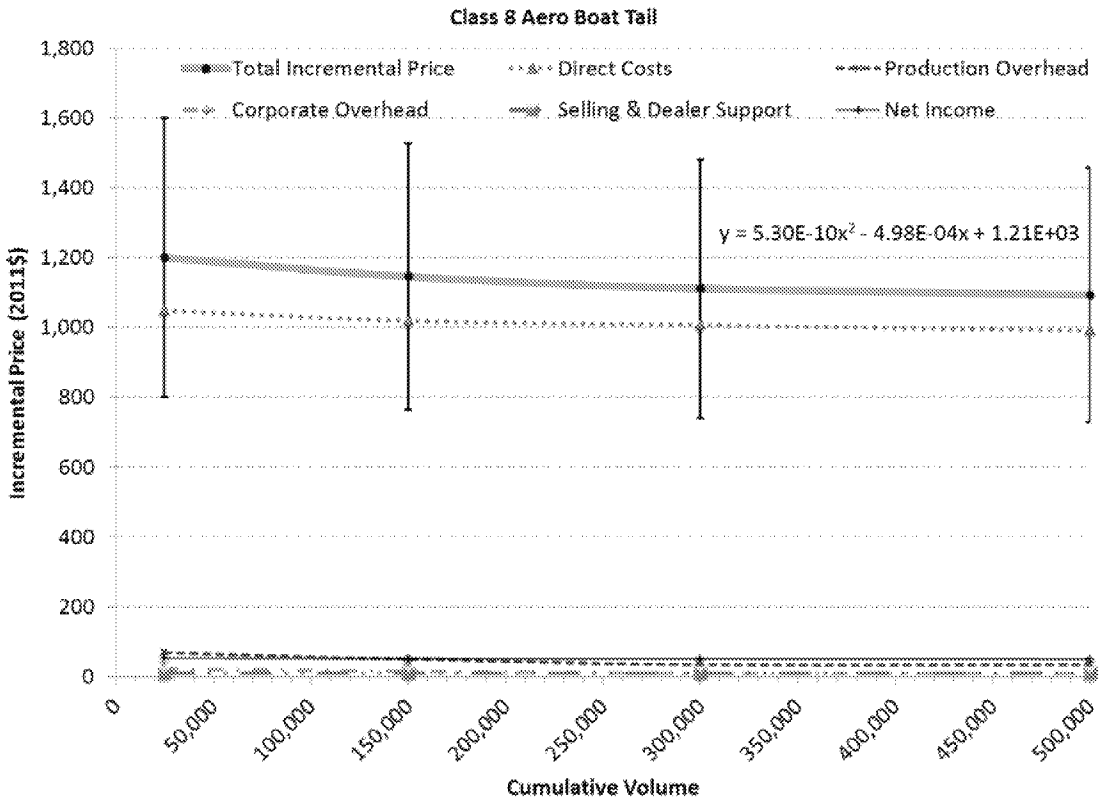
Aero Bin III



Class 8 Aero Trailer Side Skirt (4 to 6 m)

Volume (units):	25,000	150,000	300,000	500,000	700,000
Total Incremental Price	$750.00	$716.16	$694.57	$683.77	$680.17
Direct Costs	$655.14	$637.19	$629.25	$619.47	$616.21
Production Overhead	$42.45	$31.23	$21.27	$20.94	$20.83
Corporate Overhead	$13.10	$9.50	$6.29	$6.19	$6.16
Selling & Dealer Support	$6.55	$6.37	$6.29	$6.19	$6.16
Net Income	$32.76	$31.86	$31.46	$30.97	$30.81

Figure 61. Incremental Price and Breakouts for Line Haul Aero Trailer Side Skirt (4 to 6 m)

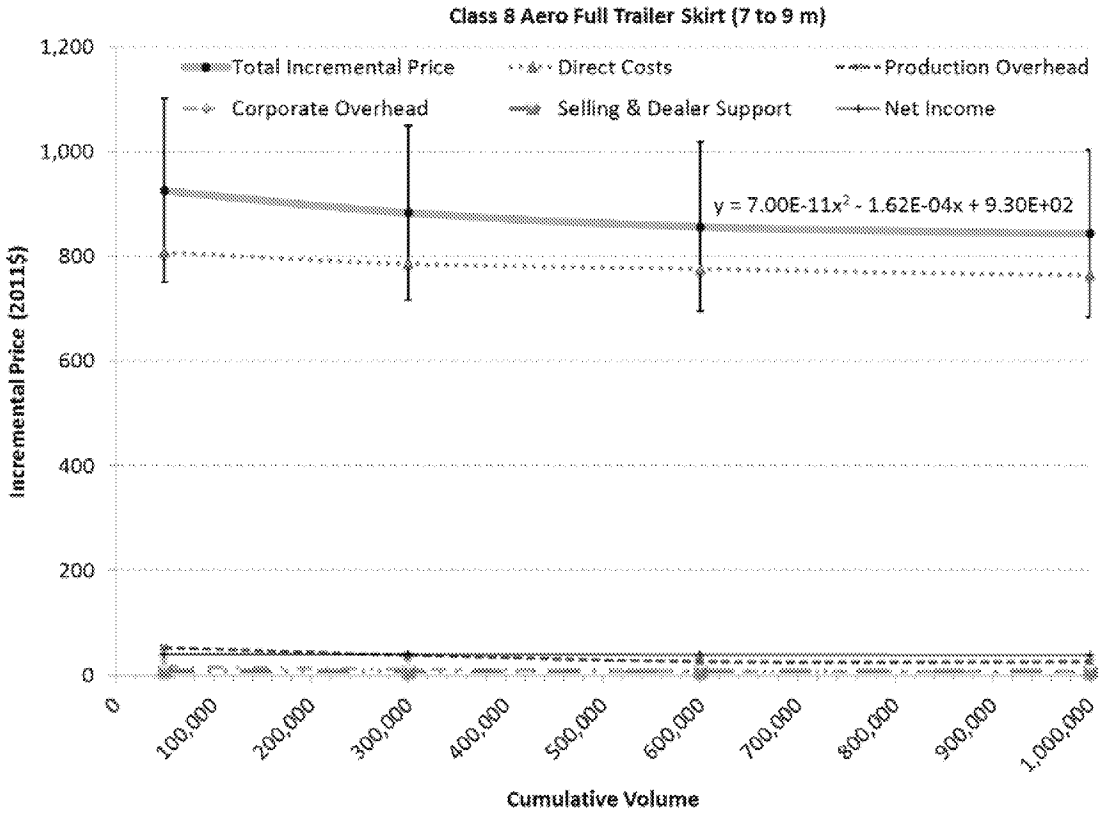


Class 8 Aero Boat Tail

Volume (units):	25,000	150,000	300,000	500,000
Total Incremental Price	$1,200.00	$1,145.85	$1,111.31	$1,094.03
Direct Costs	$1,048.22	$1,019.51	$1,006.80	$991.15
Production Overhead	$67.92	$49.97	$34.03	$33.50
Corporate Overhead	$20.96	$15.20	$10.07	$9.91
Selling & Dealer Support	$10.48	$10.20	$10.07	$9.91
Net Income	$52.41	$50.98	$50.34	$49.56

Figure 62. Incremental Price and Breakouts for Line Haul Aero Boat Tail

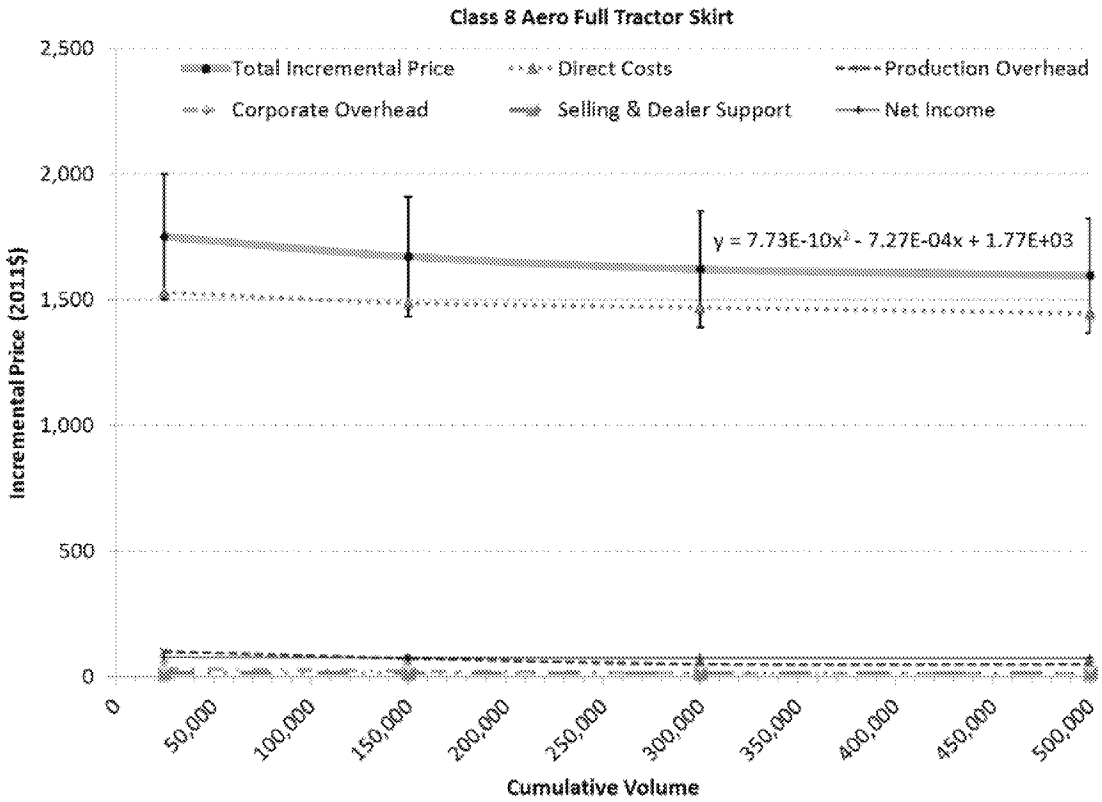
Aero Bin IV and V



Class 8 Aero Full Trailer Skirt (7 to 9 m)

Volume (units):	50,000	300,000	600,000	1,000,000	1,400,000
Total Incremental Price	$925.00	$883.26	$856.63	$843.32	$838.88
Direct Costs	$808.00	$785.87	$776.08	$764.01	$759.99
Production Overhead	$52.36	$38.52	$26.23	$25.82	$25.69
Corporate Overhead	$16.16	$11.72	$7.76	$7.64	$7.60
Selling & Dealer Support	$8.08	$7.86	$7.76	$7.64	$7.60
Net Income	$40.40	$39.29	$38.80	$38.20	$38.00

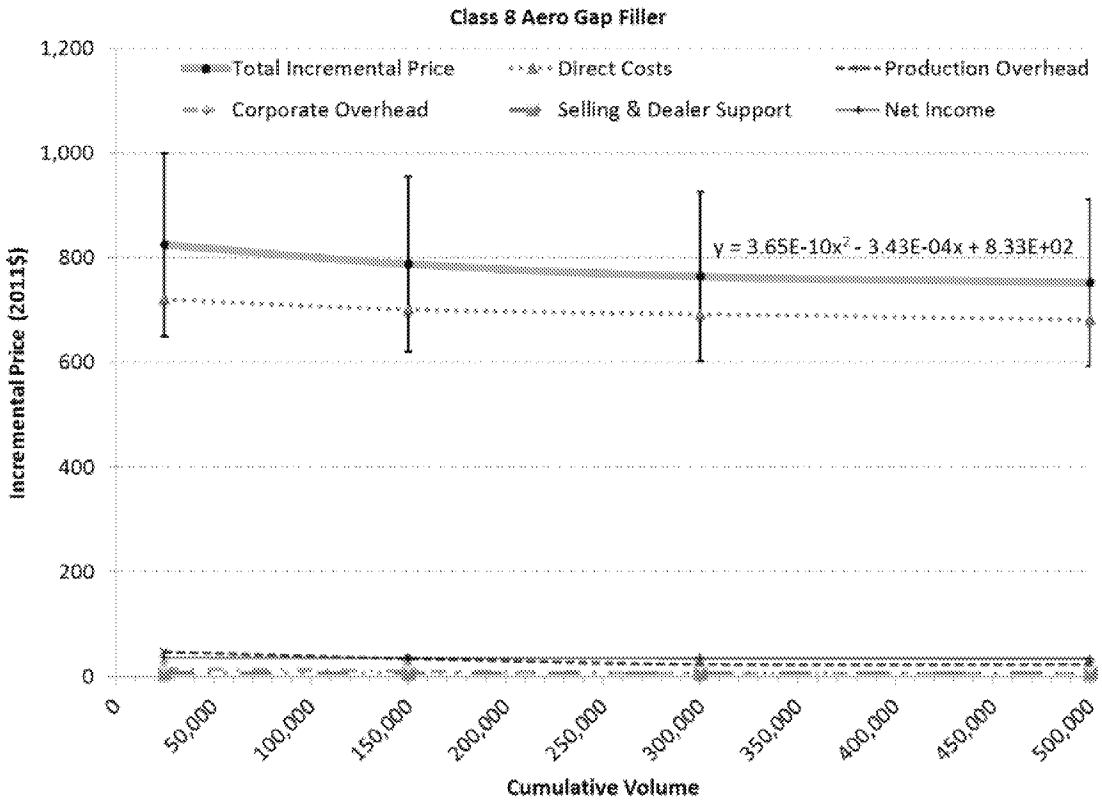
Figure 63. Incremental Price and Breakouts for Line Haul Aero Full Trailer Skirt (7 to 9 m)



Class 8 Aero Full Tractor Skirt

Volume (units):	25,000	150,000	300,000	500,000
Total Incremental Price	$1,750.00	$1,671.04	$1,620.66	$1,595.46
Direct Costs	$1,528.65	$1,486.79	$1,468.25	$1,445.43
Production Overhead	$99.06	$72.88	$49.63	$48.86
Corporate Overhead	$30.57	$22.17	$14.68	$14.45
Selling & Dealer Support	$15.29	$14.87	$14.68	$14.45
Net Income	$76.43	$74.34	$73.41	$72.27

Figure 64. Incremental Price and Breakouts for Line Haul Aero Full Tractor Skirt (over axles)



Class 8 Aero Gap Filler

Volume (units):	25,000	150,000	300,000	500,000
Total Incremental Price	$825.00	$787.78	$764.02	$752.15
Direct Costs	$720.65	$700.91	$692.18	$681.42
Production Overhead	$46.70	$34.36	$23.40	$23.03
Corporate Overhead	$14.41	$10.45	$6.92	$6.81
Selling & Dealer Support	$7.21	$7.01	$6.92	$6.81
Net Income	$36.03	$35.05	$34.61	$34.07

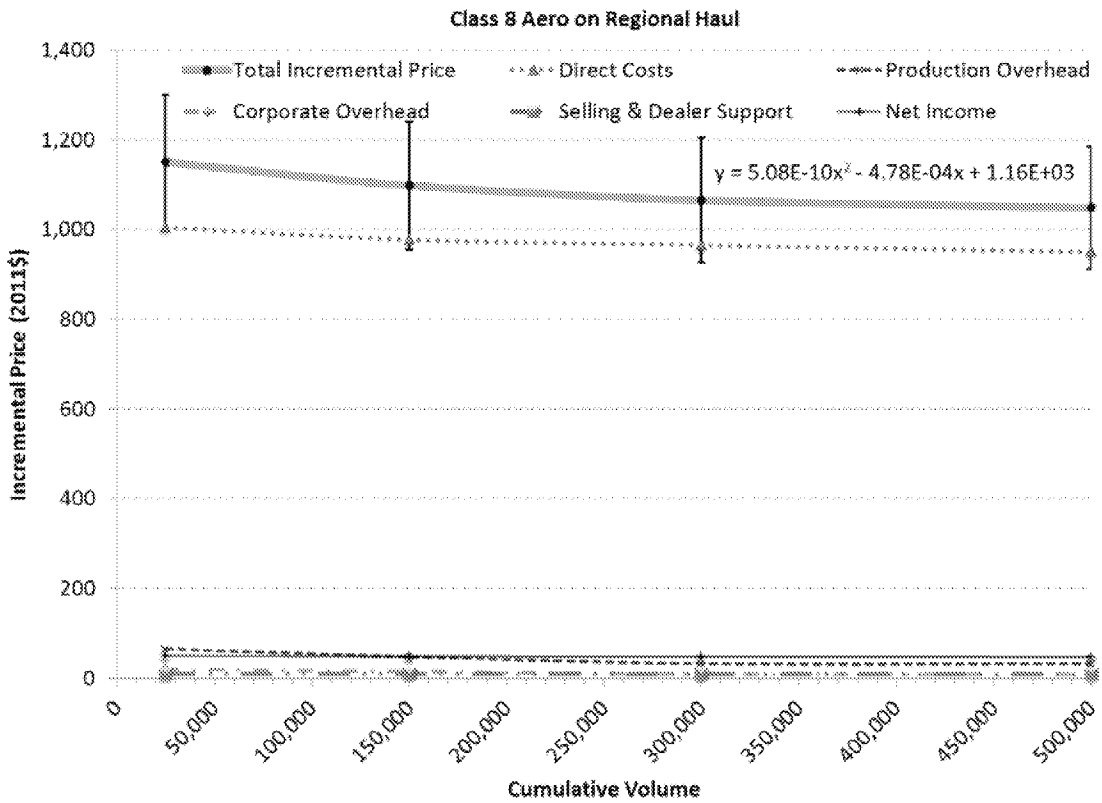
Figure 65. Incremental Price and Breakouts for Line Haul Aero Gap Filler

Include Trailer C_d and C_{rr} in Rule

The SmartWay Designated trailer must meet the requirements for a trailer equipped with SmartWay verified tires and aerodynamics package. The SmartWay trailers may use one of the following configurations for reduced C_d and C_{rr}:[19]

- Trailer Configuration A: Side Skirt; Gap reducer; and Low-rolling resistance tires
- Trailer Configuration B: Side skirt; Boat tail; and Low-rolling resistance tires
- Optional Total Aero Trailer Configuration: Side skirt; Gap reducer; Boat tail; and Low-rolling resistance tires

Aero on Regional Haul



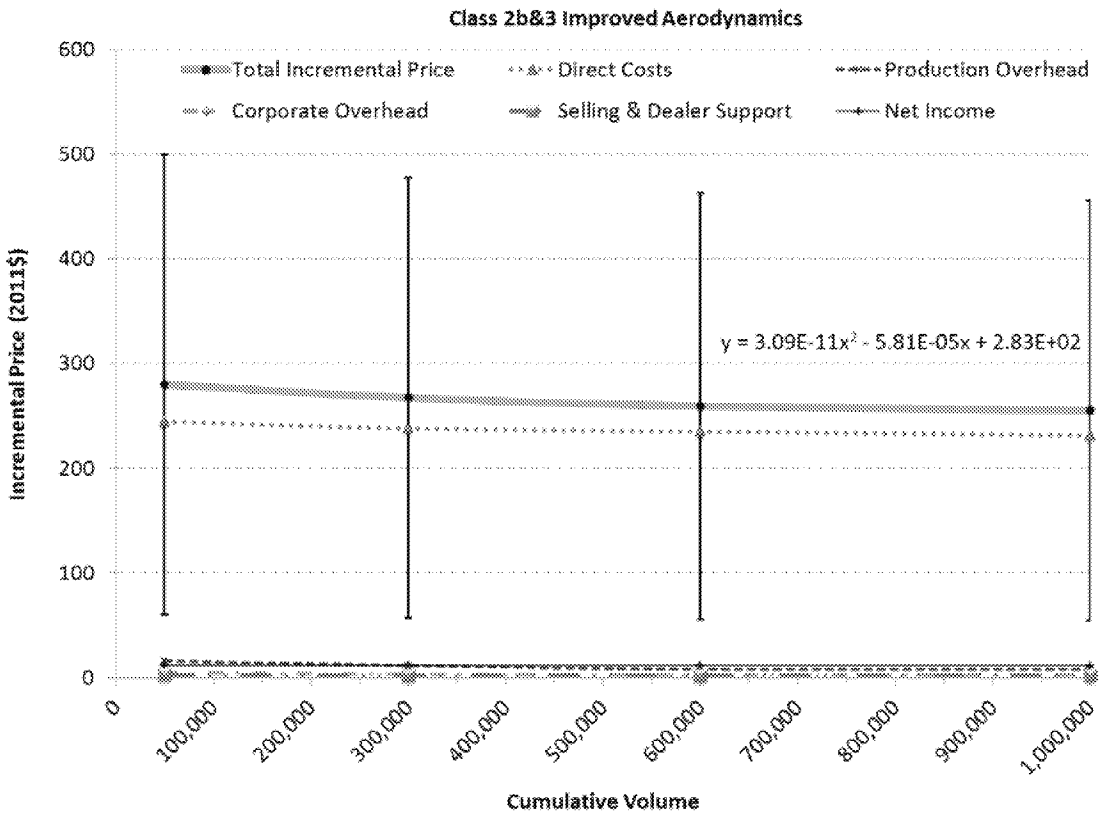
[19] U.S. Environmental Protection Agency, "U.S. EPA Designated SmartWay Mark: License Agreement, Technical Specifications & Requirements, and Graphics Standards & Usage Guide for Tractor & Trailer Manufacturers," Report # EPA420-B11-013, 2011

Class 8 Aero on Regional Haul

Volume (units):	25,000	150,000	300,000	500,000
Total Incremental Price	$1,150.00	$1,098.11	$1,065.00	$1,048.45
Direct Costs	$1,004.54	$977.03	$964.85	$949.85
Production Overhead	$65.09	$47.89	$32.61	$32.11
Corporate Overhead	$20.09	$14.57	$9.65	$9.50
Selling & Dealer Support	$10.05	$9.77	$9.65	$9.50
Net Income	$50.23	$48.85	$48.24	$47.49

Figure 66. Incremental Price and Breakouts for Aero on Regional Haul

Class 2b&3 Improved Aerodynamics

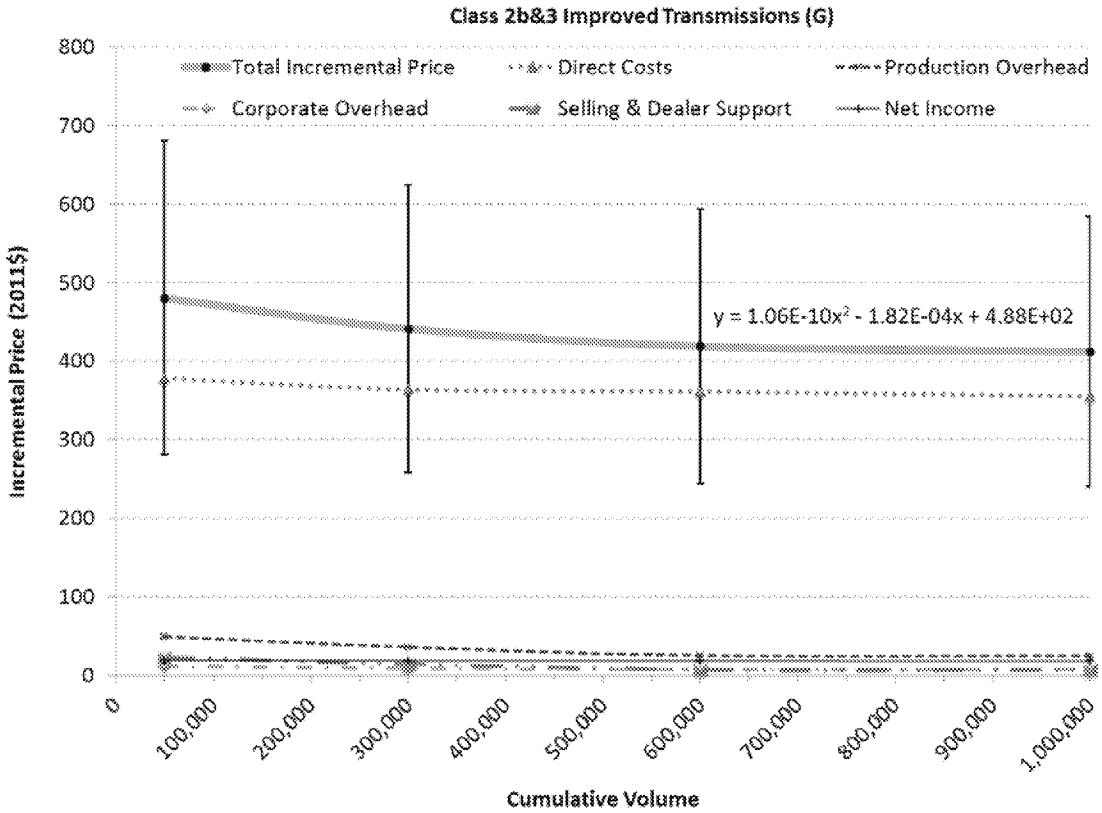


Class 2b&3 Improved Aerodynamics

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$280.00	$267.37	$259.30	$255.27
Direct Costs	$244.58	$237.89	$234.92	$231.27
Production Overhead	$15.85	$11.66	$7.94	$7.82
Corporate Overhead	$4.89	$3.55	$2.35	$2.31
Selling & Dealer Support	$2.45	$2.38	$2.35	$2.31
Net Income	$12.23	$11.89	$11.75	$11.56

Figure 67. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) Improved Aerodynamics

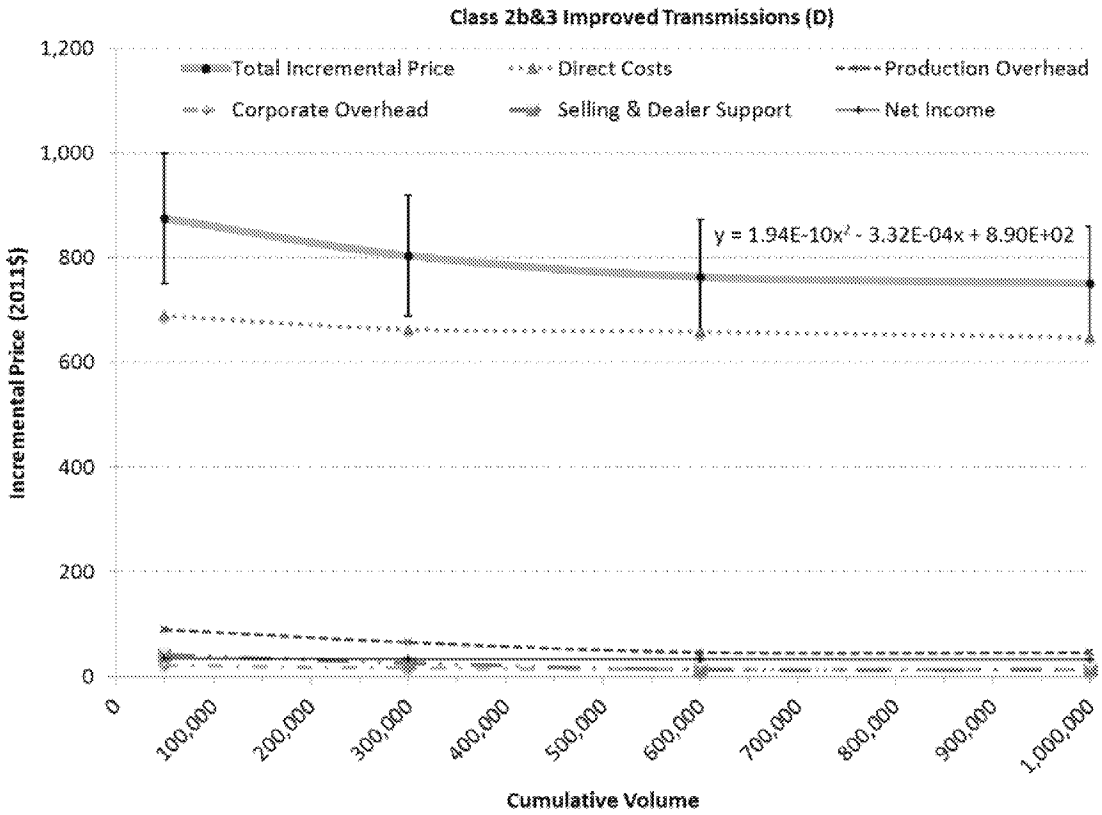
Improved Transmissions



Class 2b&3 Improved Transmissions (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$480.00	$441.01	$418.74	$412.06
Direct Costs	$377.95	$363.75	$361.04	$355.28
Production Overhead	$49.13	$35.84	$25.20	$24.80
Corporate Overhead	$11.34	$9.01	$7.22	$7.11
Selling & Dealer Support	$22.68	$14.22	$7.22	$7.11
Net Income	$18.90	$18.19	$18.05	$17.76

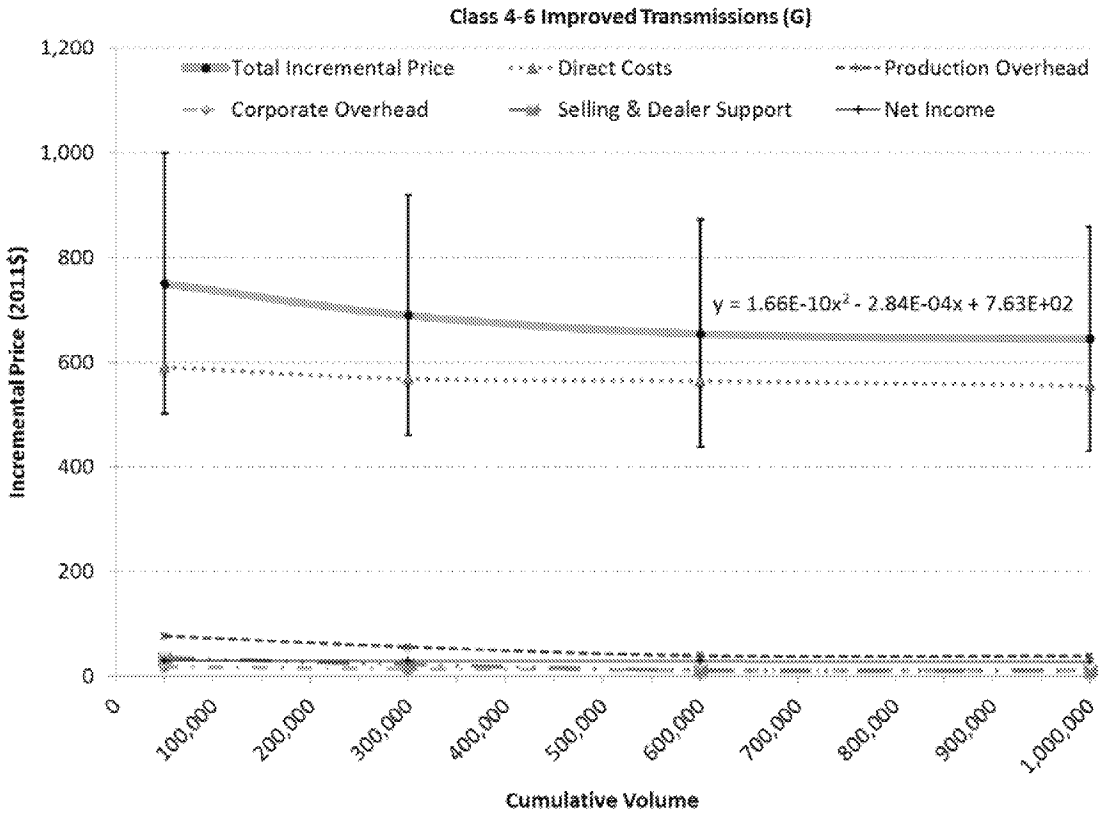
Figure 68. Incremental Price and Breakouts for Class 2b&3 (Gasoline) Improved Transmissions



Class 2b&3 Improved Transmissions (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$875.00	$803.93	$763.33	$751.15
Direct Costs	$688.98	$663.09	$658.15	$647.65
Production Overhead	$89.57	$65.34	$45.94	$45.21
Corporate Overhead	$20.67	$16.43	$13.16	$12.95
Selling & Dealer Support	$41.34	$25.92	$13.16	$12.95
Net Income	$34.45	$33.15	$32.91	$32.38

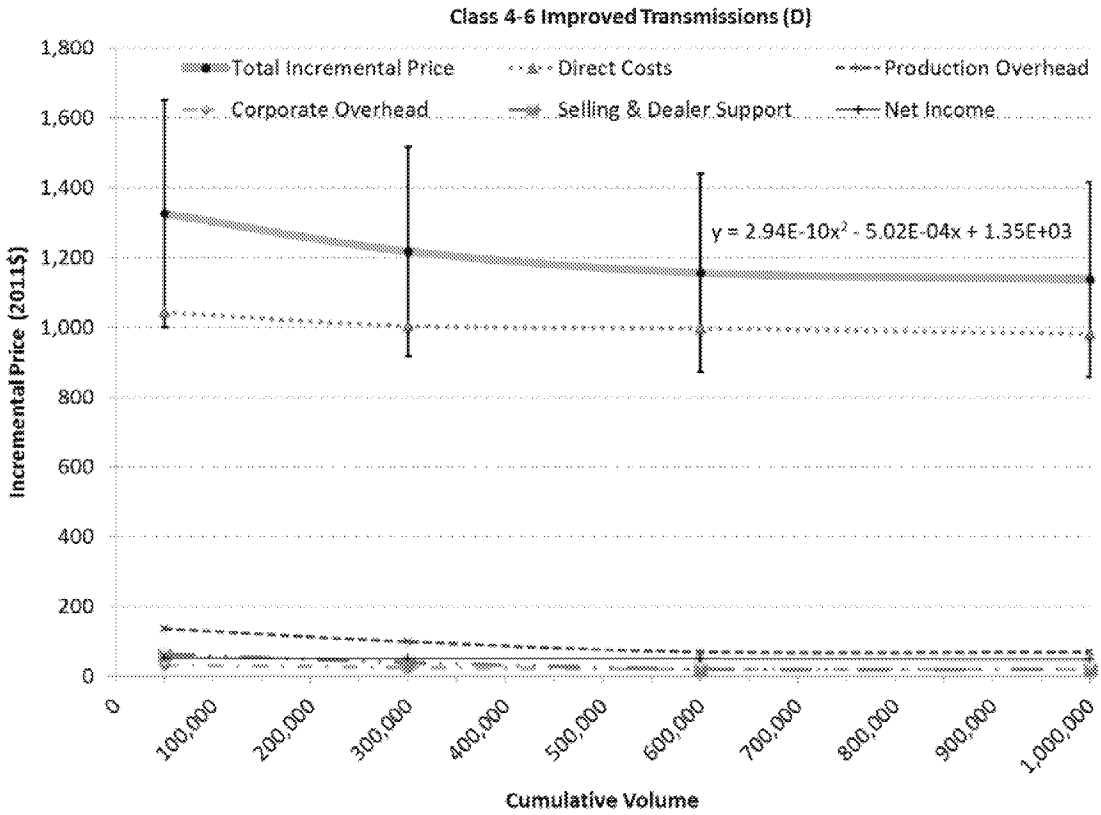
Figure 69. Incremental Price and Breakouts for Class 2b&3 (Diesel) Improved Transmissions



Class 4-6 Improved Transmissions (G)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$750.00	$689.08	$654.28	$643.84
Direct Costs	$590.55	$568.36	$564.13	$555.13
Production Overhead	$76.77	$56.00	$39.38	$38.75
Corporate Overhead	$17.72	$14.08	$11.28	$11.10
Selling & Dealer Support	$35.43	$22.22	$11.28	$11.10
Net Income	$29.53	$28.42	$28.21	$27.76

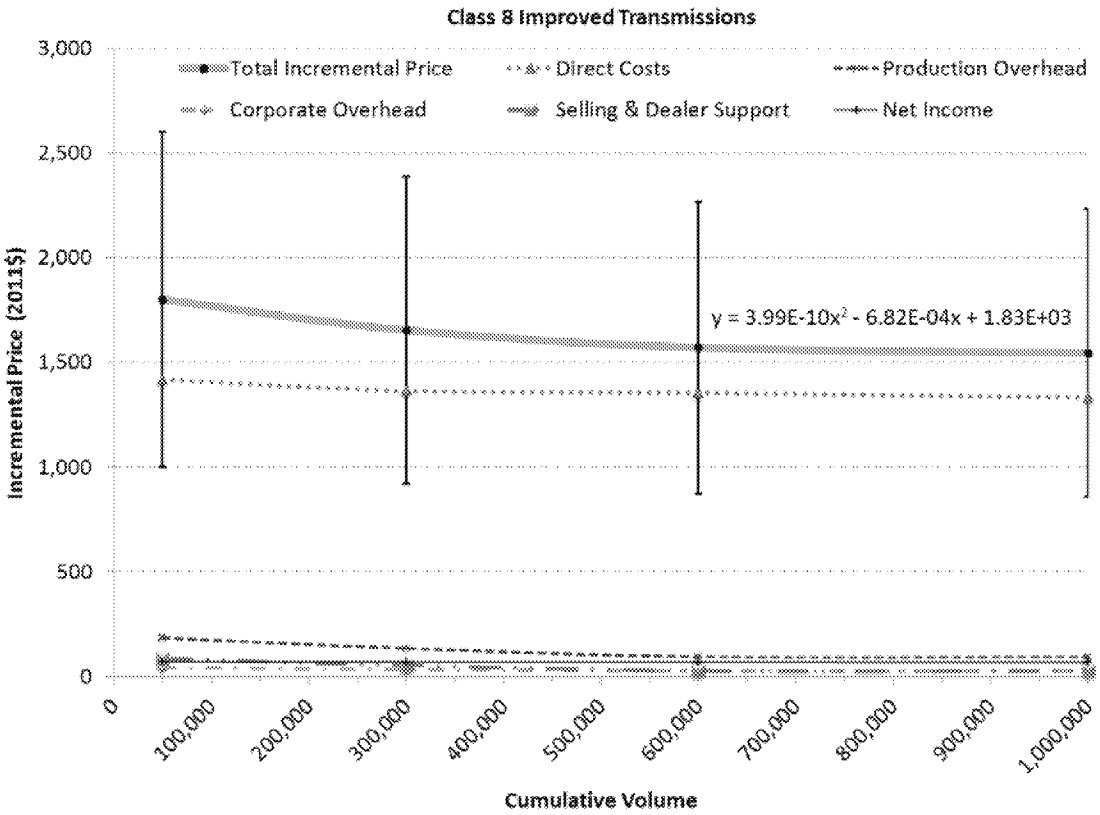
Figure 70. Incremental Price and Breakouts for Vocational (Gasoline) Improved Transmissions



Class 4-6 Improved Transmissions (D)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,325.00	$1,217.38	$1,155.90	$1,137.45
Direct Costs	$1,043.31	$1,004.11	$996.63	$980.73
Production Overhead	$135.63	$98.94	$69.57	$68.45
Corporate Overhead	$31.30	$24.87	$19.93	$19.61
Selling & Dealer Support	$62.60	$39.25	$19.93	$19.61
Net Income	$52.17	$50.21	$49.83	$49.04

Figure 71. Incremental Price and Breakouts for Vocational (Diesel) Improved Transmissions

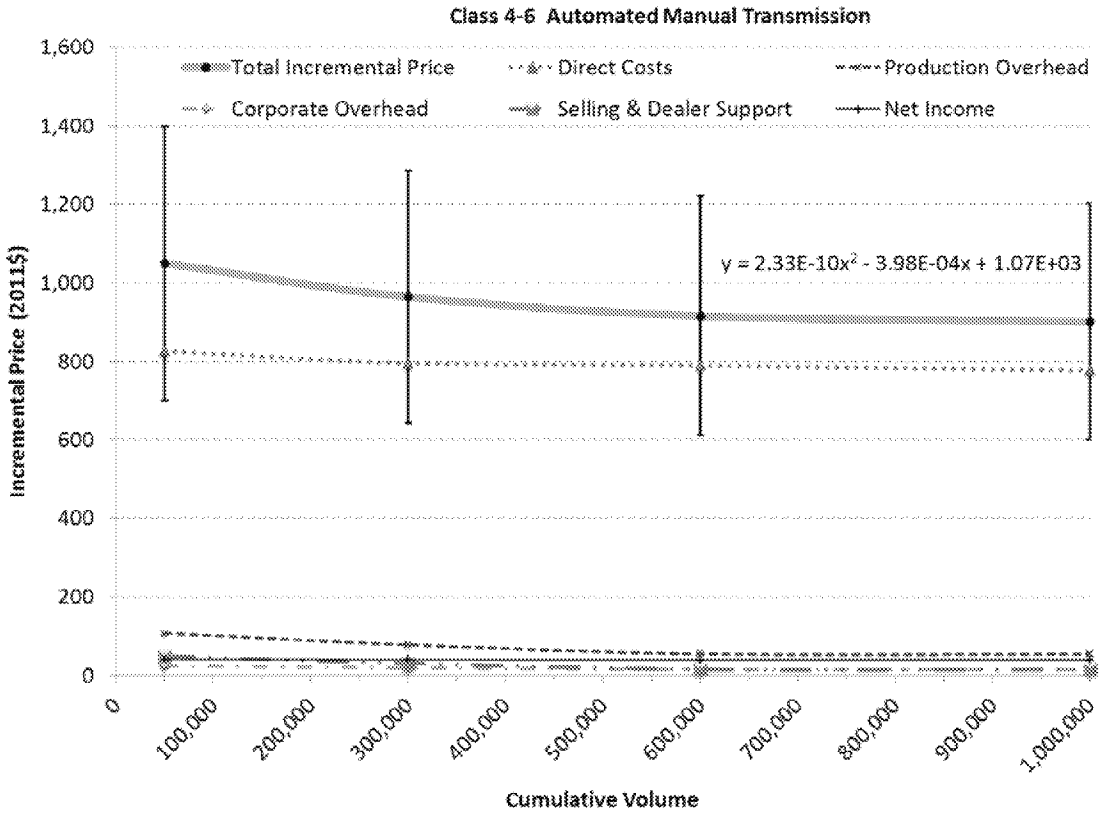


Class 8 Improved Transmissions

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,800.00	$1,653.80	$1,570.27	$1,545.22
Direct Costs	$1,417.32	$1,364.07	$1,353.92	$1,332.31
Production Overhead	$184.25	$134.41	$94.50	$93.00
Corporate Overhead	$42.52	$33.79	$27.08	$26.65
Selling & Dealer Support	$85.04	$53.33	$27.08	$26.65
Net Income	$70.87	$68.20	$67.70	$66.62

Figure 72. Incremental Price and Breakouts for Line Haul Improved Transmissions

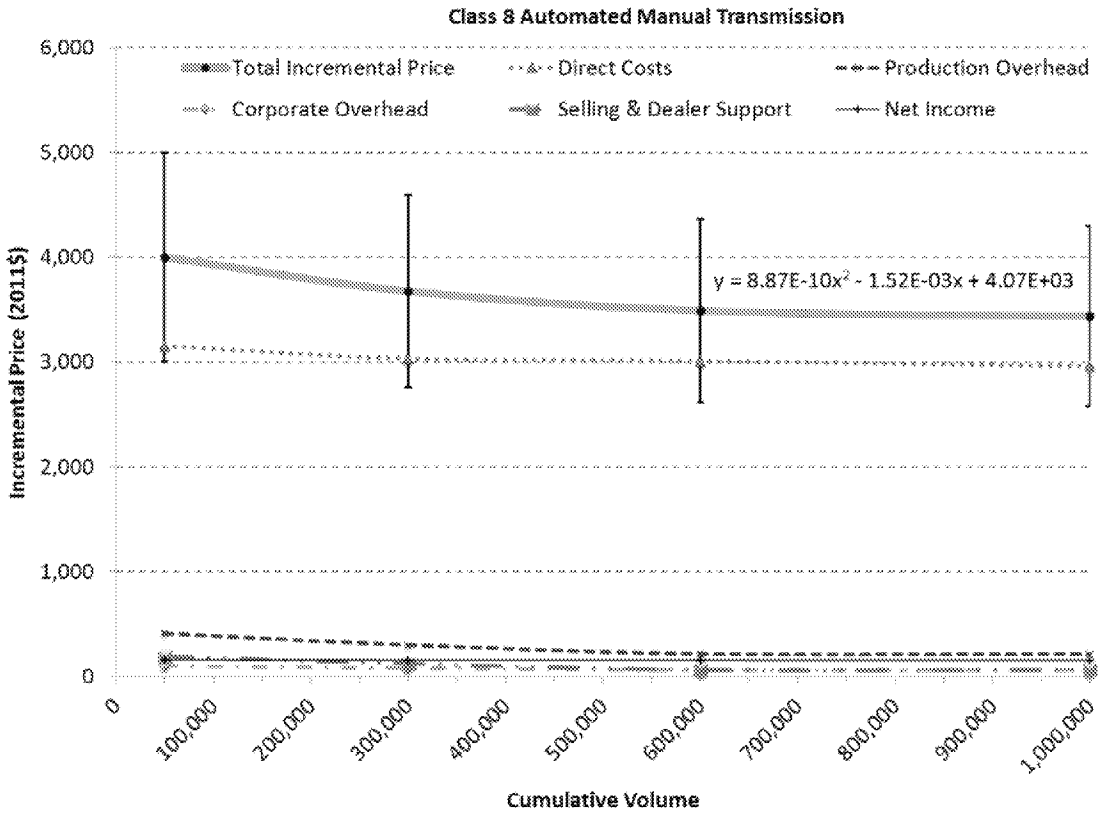
Automated Manual Transmission



Class 4-6 Automated Manual Transmission

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,050.00	$964.72	$915.99	$901.38
Direct Costs	$826.77	$795.71	$789.79	$777.18
Production Overhead	$107.48	$78.40	$55.13	$54.25
Corporate Overhead	$24.80	$19.71	$15.80	$15.54
Selling & Dealer Support	$49.61	$31.11	$15.80	$15.54
Net Income	$41.34	$39.79	$39.49	$38.86

Figure 73. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) AMT

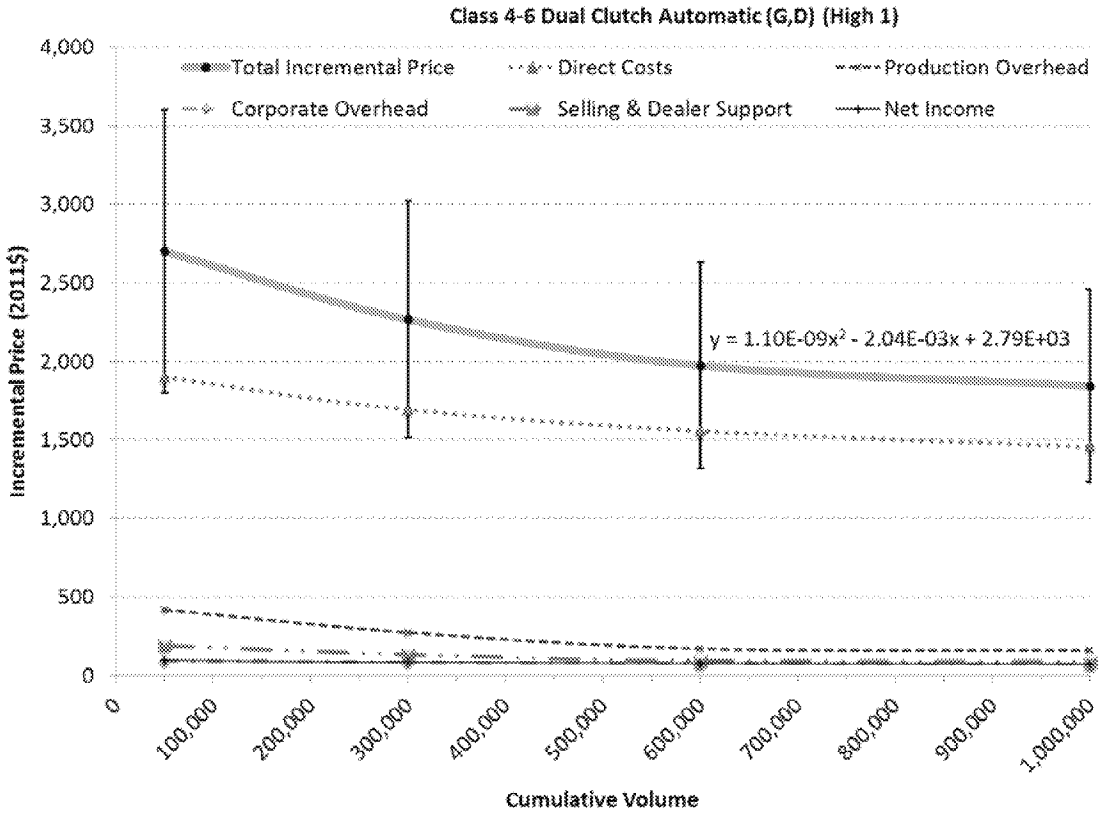


Class 8 Automated Manual Transmission

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$4,000.00	$3,675.11	$3,489.50	$3,433.81
Direct Costs	$3,149.61	$3,031.26	$3,008.71	$2,960.69
Production Overhead	$409.45	$298.69	$210.01	$206.66
Corporate Overhead	$94.49	$75.09	$60.17	$59.21
Selling & Dealer Support	$188.98	$118.50	$60.17	$59.21
Net Income	$157.48	$151.56	$150.44	$148.03

Figure 74. Incremental Price and Breakouts for Line Haul AMT

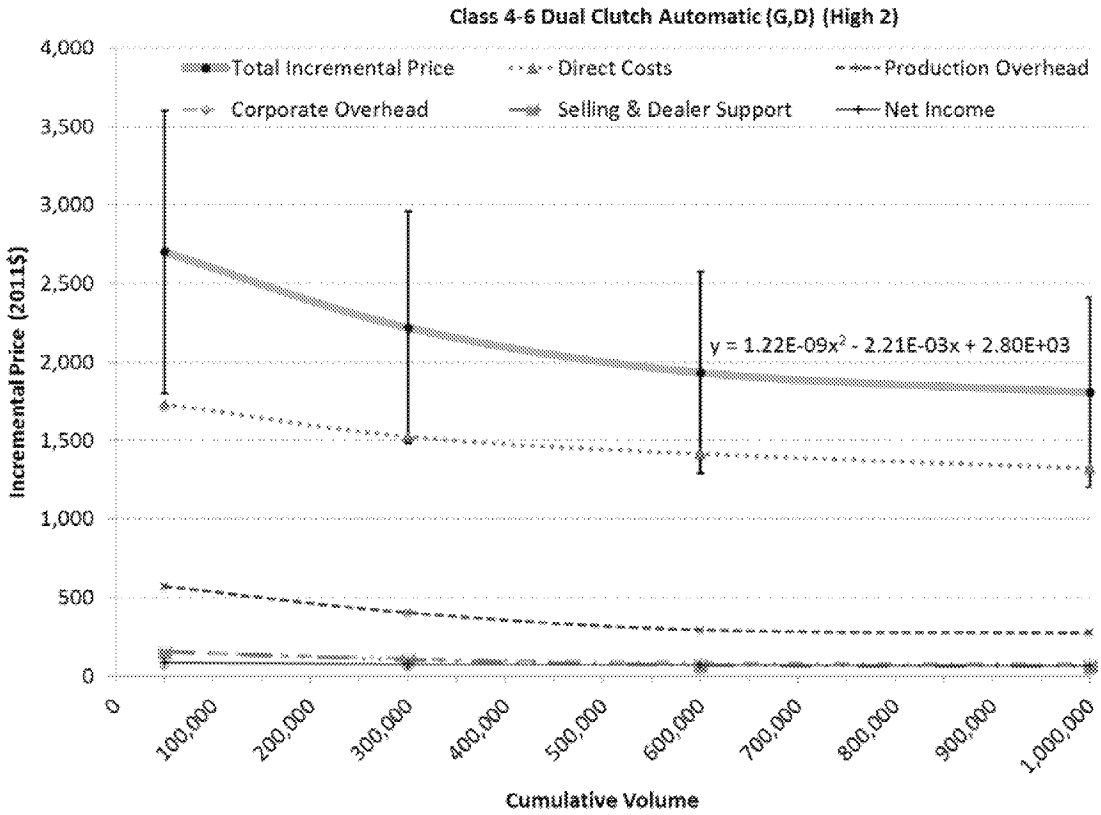
Dual Clutch Automatic



Class 4-6 Dual Clutch Automatic (G,D) (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$2,700.00	$2,266.44	$1,974.38	$1,845.87
Direct Costs	$1,901.41	$1,690.34	$1,554.63	$1,453.44
Production Overhead	$418.31	$273.72	$171.01	$159.88
Corporate Overhead	$95.07	$84.52	$77.73	$72.67
Selling & Dealer Support	$190.14	$133.34	$93.28	$87.21
Net Income	$95.07	$84.52	$77.73	$72.67

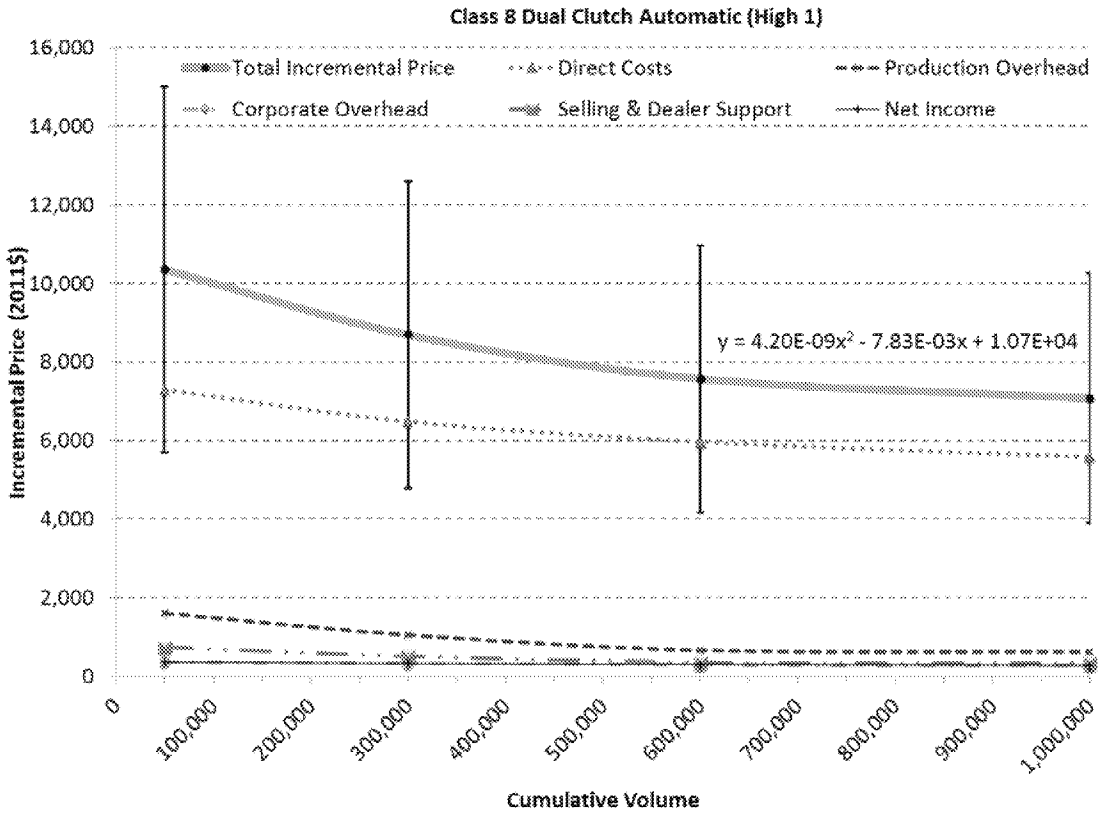
Figure 75. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) Dual Clutch Automatic (High 1)



Class 4-6 Dual Clutch Automatic (G,D) (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$2,700.00	$2,219.49	$1,933.47	$1,807.63
Direct Costs	$1,730.77	$1,522.59	$1,413.36	$1,321.36
Production Overhead	$571.15	$403.49	$293.98	$274.84
Corporate Overhead	$155.77	$112.70	$84.80	$79.28
Selling & Dealer Support	$155.77	$104.58	$70.67	$66.07
Net Income	$86.54	$76.13	$70.67	$66.07

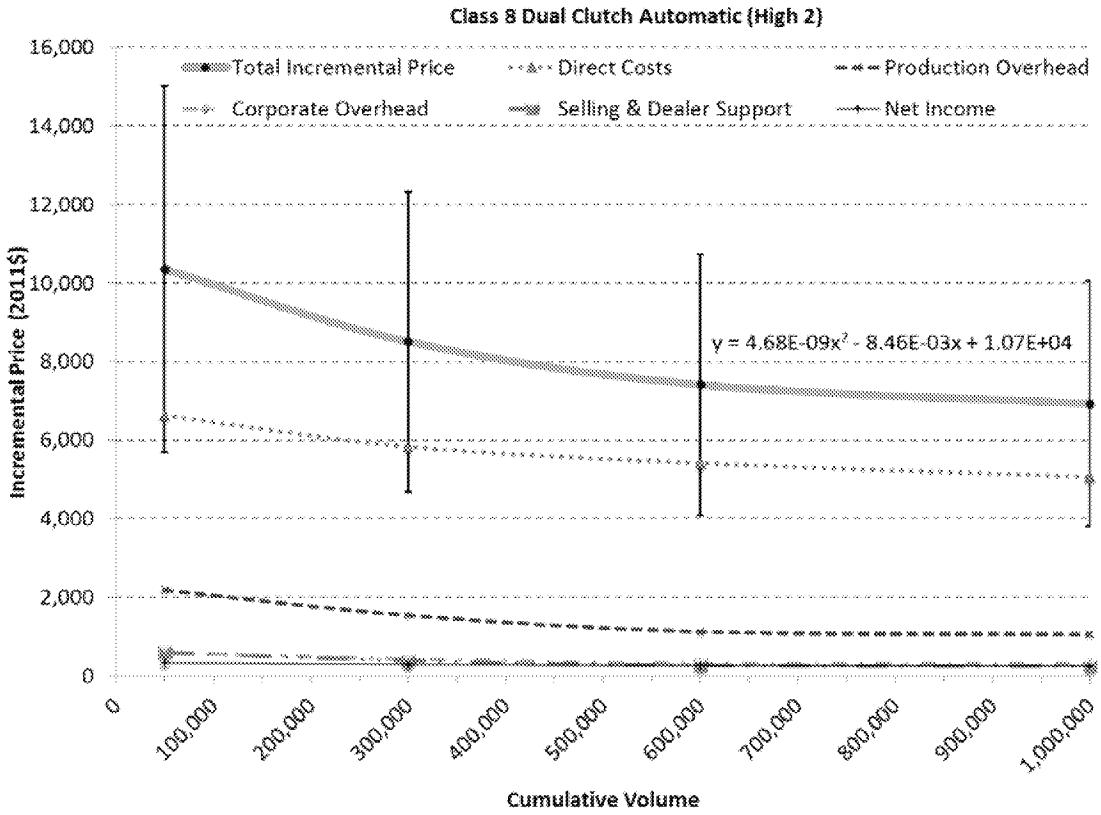
Figure 76. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) Dual Clutch Automatic (High 2)



Class 8 Dual Clutch Automatic (High 1)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$10,350.00	$8,688.03	$7,568.44	$7,075.82
Direct Costs	$7,288.73	$6,479.65	$5,959.40	$5,571.51
Production Overhead	$1,603.52	$1,049.27	$655.53	$612.87
Corporate Overhead	$364.44	$323.98	$297.97	$278.58
Selling & Dealer Support	$728.87	$511.15	$357.56	$334.29
Net Income	$364.44	$323.98	$297.97	$278.58

Figure 77. Incremental Price and Breakouts for Line Haul Dual Clutch Automatic (High 1)

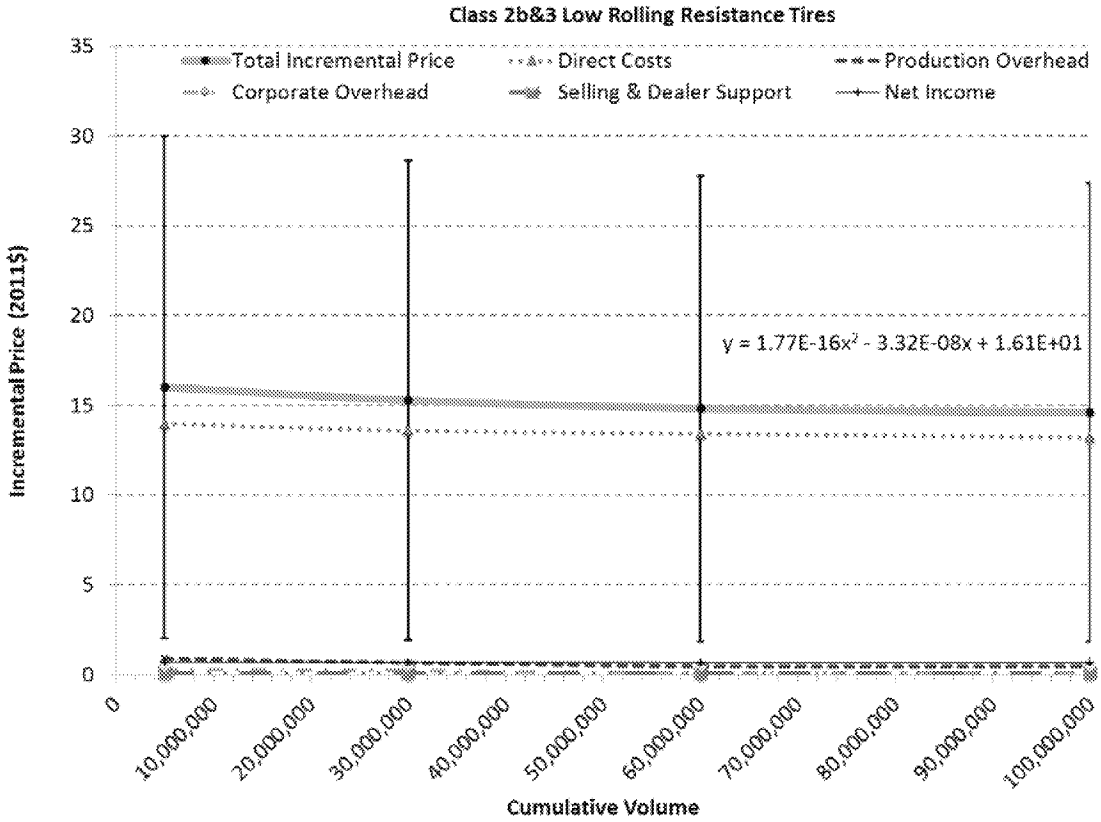


Class 8 Dual Clutch Automatic (High 2)

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$10,350.00	$8,508.05	$7,411.65	$6,929.24
Direct Costs	$6,634.62	$5,836.61	$5,417.87	$5,065.23
Production Overhead	$2,189.42	$1,546.70	$1,126.92	$1,053.57
Corporate Overhead	$597.12	$432.00	$325.07	$303.91
Selling & Dealer Support	$597.12	$400.91	$270.89	$253.26
Net Income	$331.73	$291.83	$270.89	$253.26

Figure 78. Incremental Price and Breakouts for Line Haul Dual Clutch Automatic (High 2)

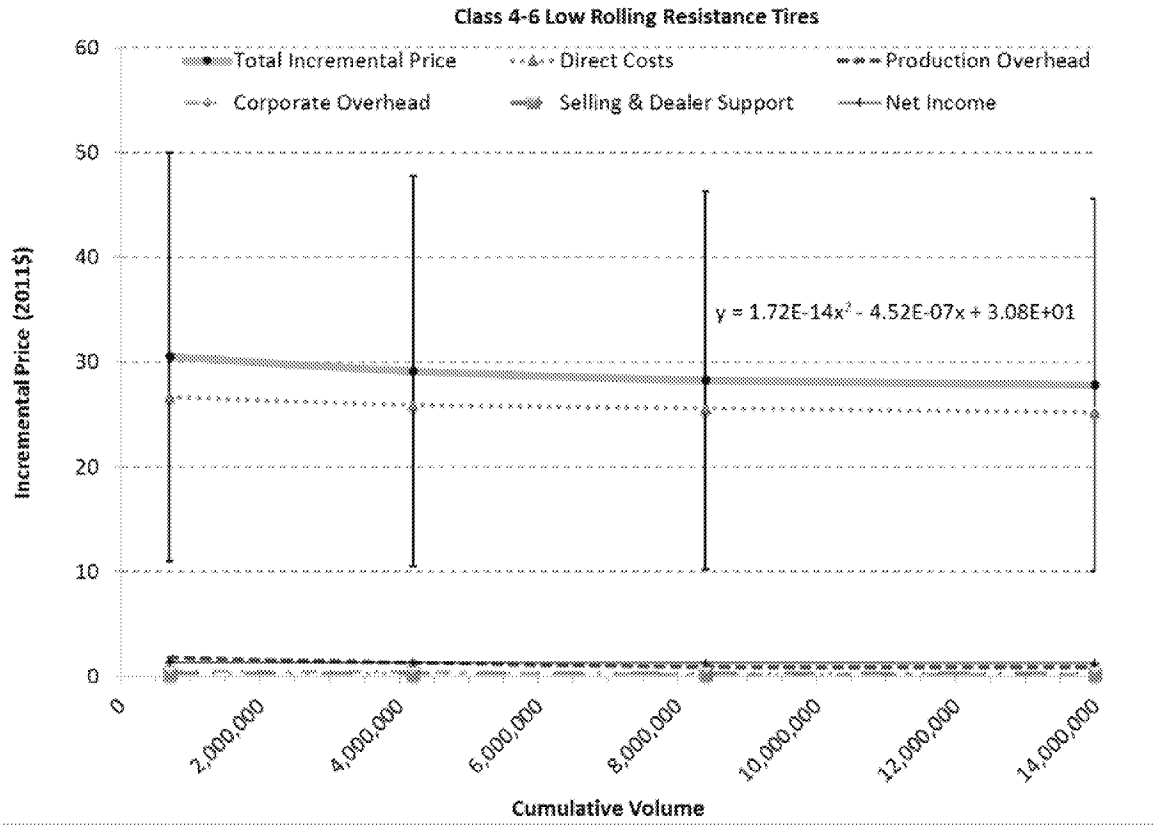
Low Rolling Resistance Tires (priced per tire)



Class 2b&3 Low Rolling Resistance Tires

Volume (units):	5,000,000	30,000,000	60,000,000	100,000,000
Total Incremental Price	$16.00	$15.28	$14.82	$14.59
Direct Costs	$13.98	$13.59	$13.42	$13.22
Production Overhead	$0.91	$0.67	$0.45	$0.45
Corporate Overhead	$0.28	$0.20	$0.13	$0.13
Selling & Dealer Support	$0.14	$0.14	$0.13	$0.13
Net Income	$0.70	$0.68	$0.67	$0.66

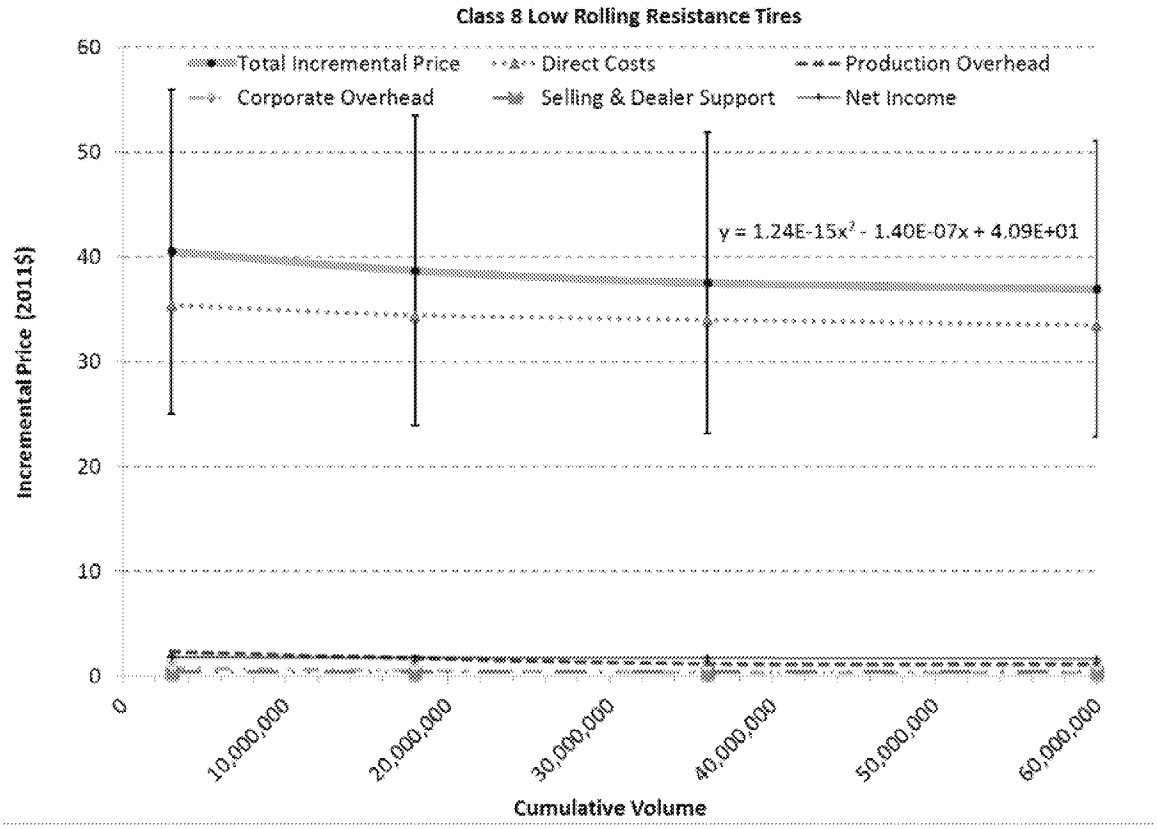
Figure 79. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) LRR Tires



Class 4-6 Low Rolling Resistance Tires

Volume (units):	700,000	4,200,000	8,400,000	14,000,000
Total Incremental Price	$30.50	$29.12	$28.25	$27.81
Direct Costs	$26.64	$25.91	$25.59	$25.19
Production Overhead	$1.73	$1.27	$0.86	$0.85
Corporate Overhead	$0.53	$0.39	$0.26	$0.25
Selling & Dealer Support	$0.27	$0.26	$0.26	$0.25
Net Income	$1.33	$1.30	$1.28	$1.26

Figure 80. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) LRR Tires

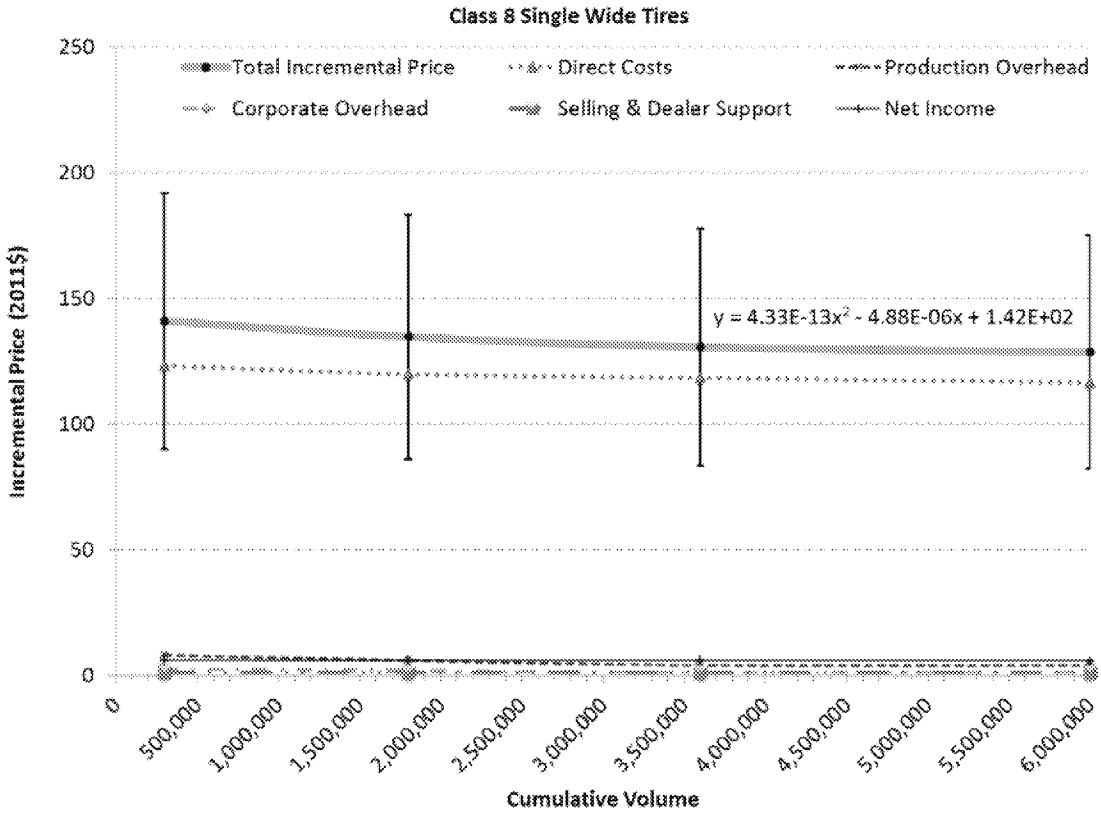


Class 8 Low Rolling Resistance Tires

Volume (units):	3,000,000	18,000,000	36,000,000	60,000,000
Total Incremental Price	$40.50	$38.67	$37.51	$36.92
Direct Costs	$35.38	$34.41	$33.98	$33.45
Production Overhead	$2.29	$1.69	$1.15	$1.13
Corporate Overhead	$0.71	$0.51	$0.34	$0.33
Selling & Dealer Support	$0.35	$0.34	$0.34	$0.33
Net Income	$1.77	$1.72	$1.70	$1.67

Figure 81. Incremental Price and Breakouts for Line Haul Low Rolling Resistance Tires

Single Wide Tires (priced per tire/wheel replacing 2 standard width tires/wheels)

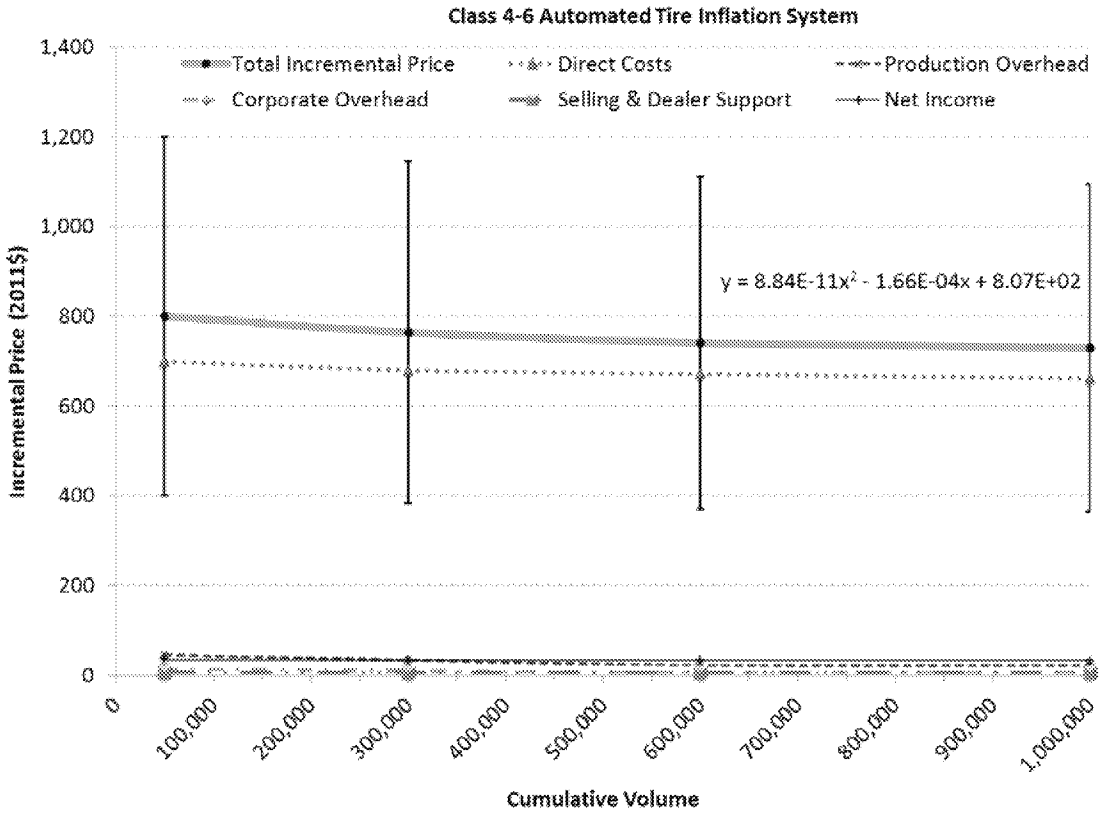


Class 8 Single Wide Tires

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$141.00	$134.64	$130.58	$128.55
Direct Costs	$123.17	$119.79	$118.30	$116.46
Production Overhead	$7.98	$5.87	$4.00	$3.94
Corporate Overhead	$2.46	$1.79	$1.18	$1.16
Selling & Dealer Support	$1.23	$1.20	$1.18	$1.16
Net Income	$6.16	$5.99	$5.91	$5.82

Figure 82. Incremental Price and Breakouts for Line Haul Single Wide Tires

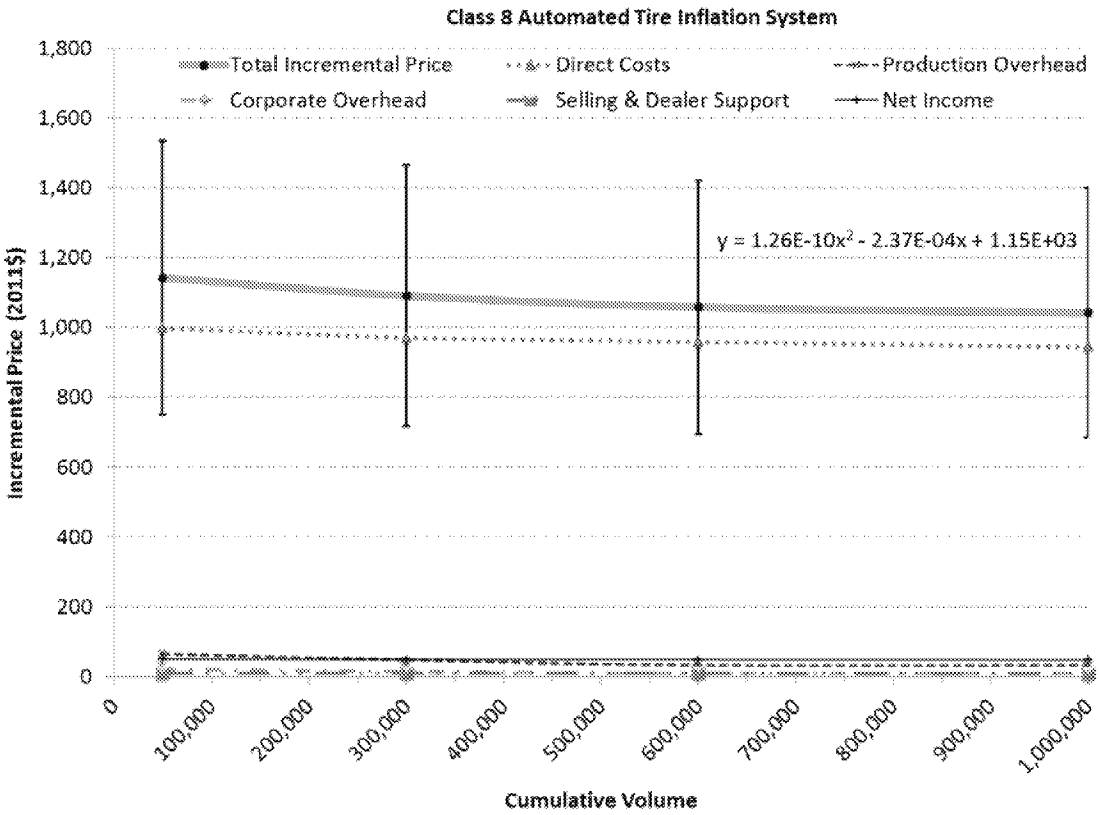
Automatic Tire Inflation System



Class 4-6 Automated Tire Inflation System

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$800.00	$763.90	$740.87	$729.35
Direct Costs	$698.81	$679.67	$671.20	$660.77
Production Overhead	$45.28	$33.32	$22.69	$22.33
Corporate Overhead	$13.98	$10.13	$6.71	$6.61
Selling & Dealer Support	$6.99	$6.80	$6.71	$6.61
Net Income	$34.94	$33.98	$33.56	$33.04

Figure 83. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) ATI

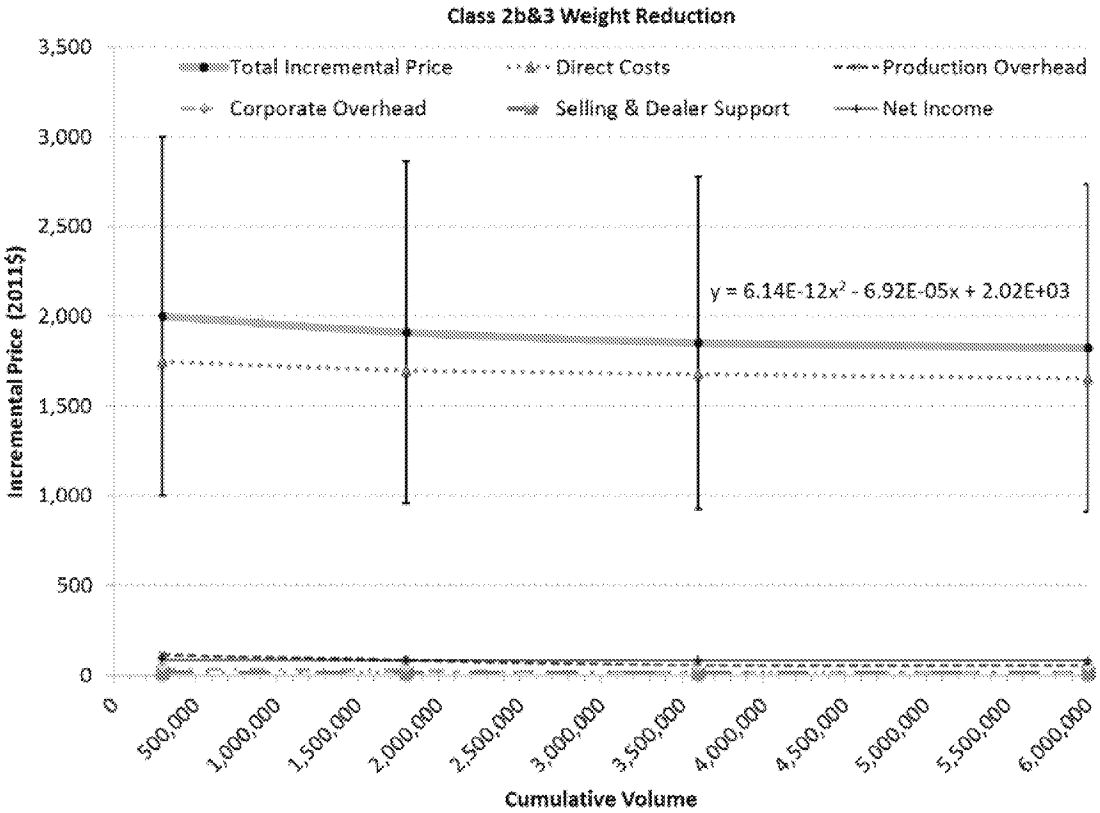


Class 8 Automated Tire Inflation System

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$1,142.50	$1,090.95	$1,058.06	$1,041.61
Direct Costs	$997.99	$970.66	$958.56	$943.66
Production Overhead	$64.67	$47.58	$32.40	$31.90
Corporate Overhead	$19.96	$14.47	$9.59	$9.44
Selling & Dealer Support	$9.98	$9.71	$9.59	$9.44
Net Income	$49.90	$48.53	$47.93	$47.18

Figure 84. Incremental Price and Breakouts for Line Haul ATI

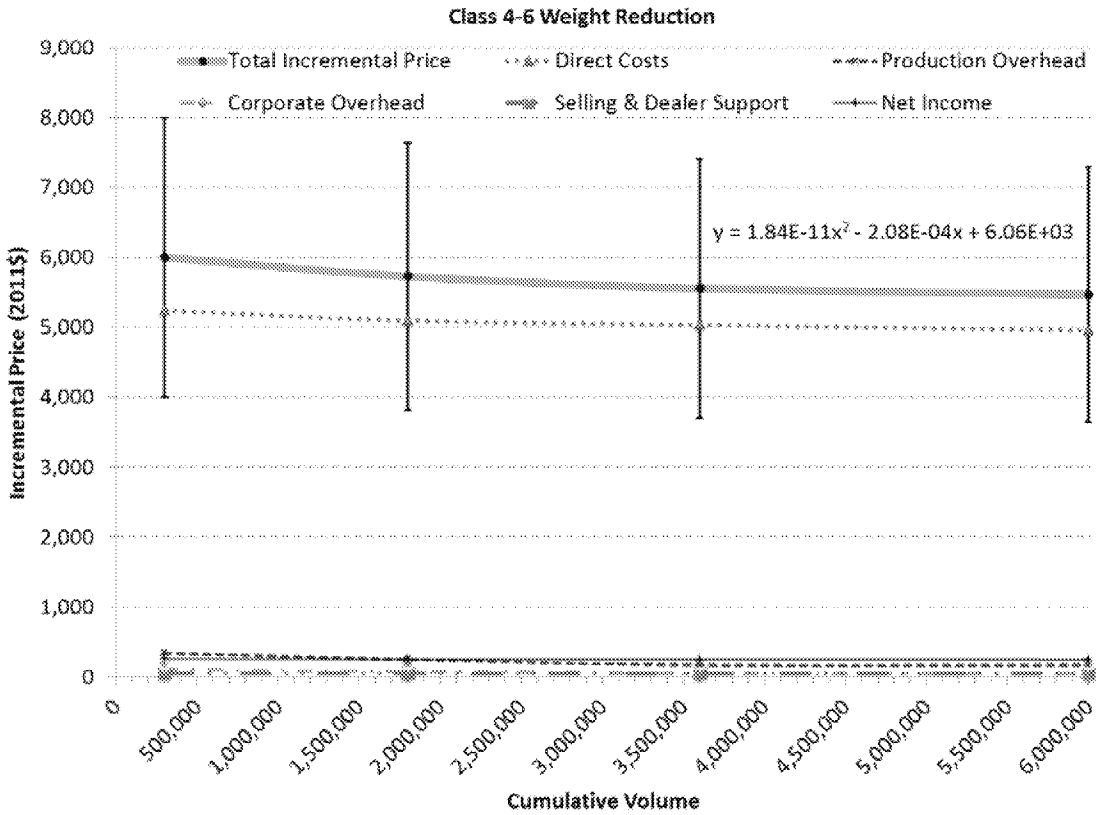
Weight Reduction



Class 2b&3 Weight Reduction

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$2,000.00	$1,909.76	$1,852.18	$1,823.39
Direct Costs	$1,747.03	$1,699.18	$1,678.00	$1,651.92
Production Overhead	$113.21	$83.29	$56.72	$55.83
Corporate Overhead	$34.94	$25.33	$16.78	$16.52
Selling & Dealer Support	$17.47	$16.99	$16.78	$16.52
Net Income	$87.35	$84.96	$83.90	$82.60

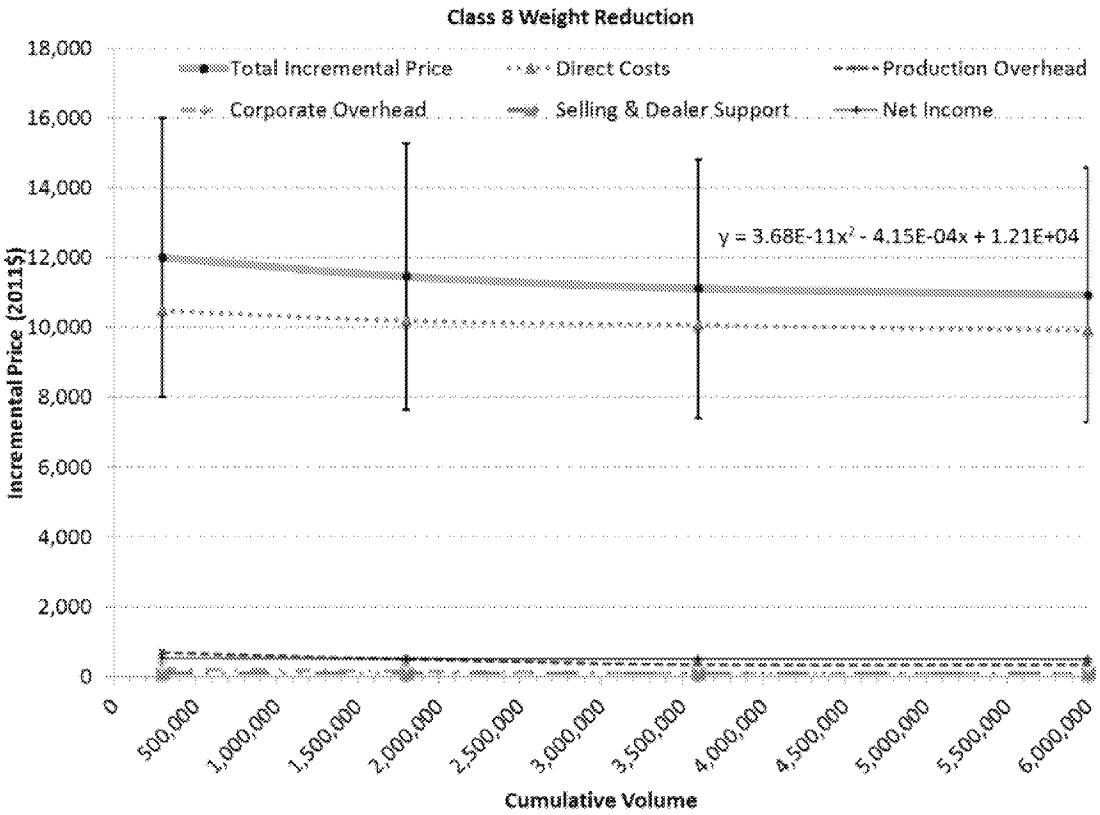
Figure 85. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) Weight Reduction



Class 4-6 Weight Reduction

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$6,000.00	$5,729.27	$5,556.53	$5,470.16
Direct Costs	$5,241.09	$5,097.55	$5,034.00	$4,955.75
Production Overhead	$339.62	$249.87	$170.15	$167.50
Corporate Overhead	$104.82	$76.00	$50.34	$49.56
Selling & Dealer Support	$52.41	$50.98	$50.34	$49.56
Net Income	$262.05	$254.88	$251.70	$247.79

Figure 86. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) Weight Reduction

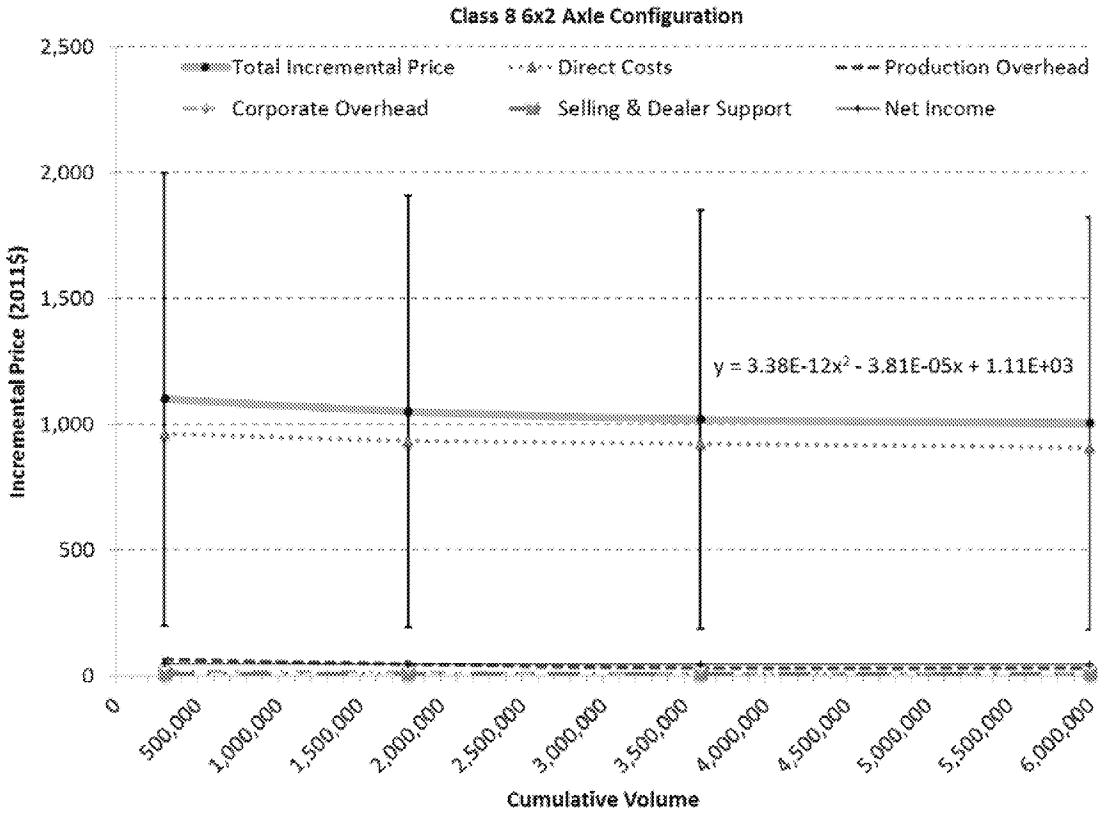


Class 8 Weight Reduction

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$12,000.00	$11,458.55	$11,113.06	$10,940.32
Direct Costs	$10,482.18	$10,195.11	$10,068.01	$9,911.51
Production Overhead	$679.25	$499.74	$340.30	$335.01
Corporate Overhead	$209.64	$152.00	$100.68	$99.12
Selling & Dealer Support	$104.82	$101.95	$100.68	$99.12
Net Income	$524.11	$509.76	$503.40	$495.58

Figure 87. Incremental Price and Breakouts for Line Haul Weight Reduction

6x2 Tractors

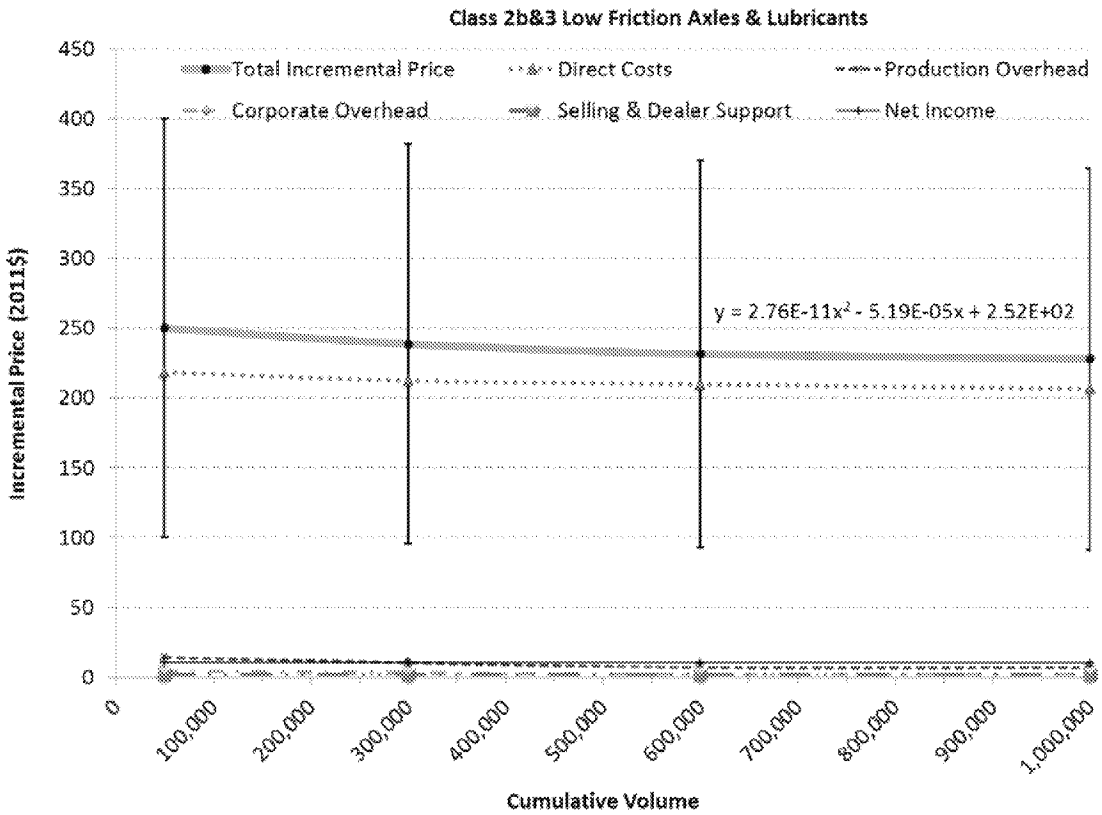


Class 8 6x2 Axle Configuration

Volume (units):	300,000	1,800,000	3,600,000	6,000,000
Total Incremental Price	$1,100.00	$1,050.37	$1,018.70	$1,002.86
Direct Costs	$960.87	$934.55	$922.90	$908.55
Production Overhead	$62.26	$45.81	$31.19	$30.71
Corporate Overhead	$19.22	$13.93	$9.23	$9.09
Selling & Dealer Support	$9.61	$9.35	$9.23	$9.09
Net Income	$48.04	$46.73	$46.15	$45.43

Figure 88. Incremental Price and Breakouts for Line Haul 6x2 Tractors

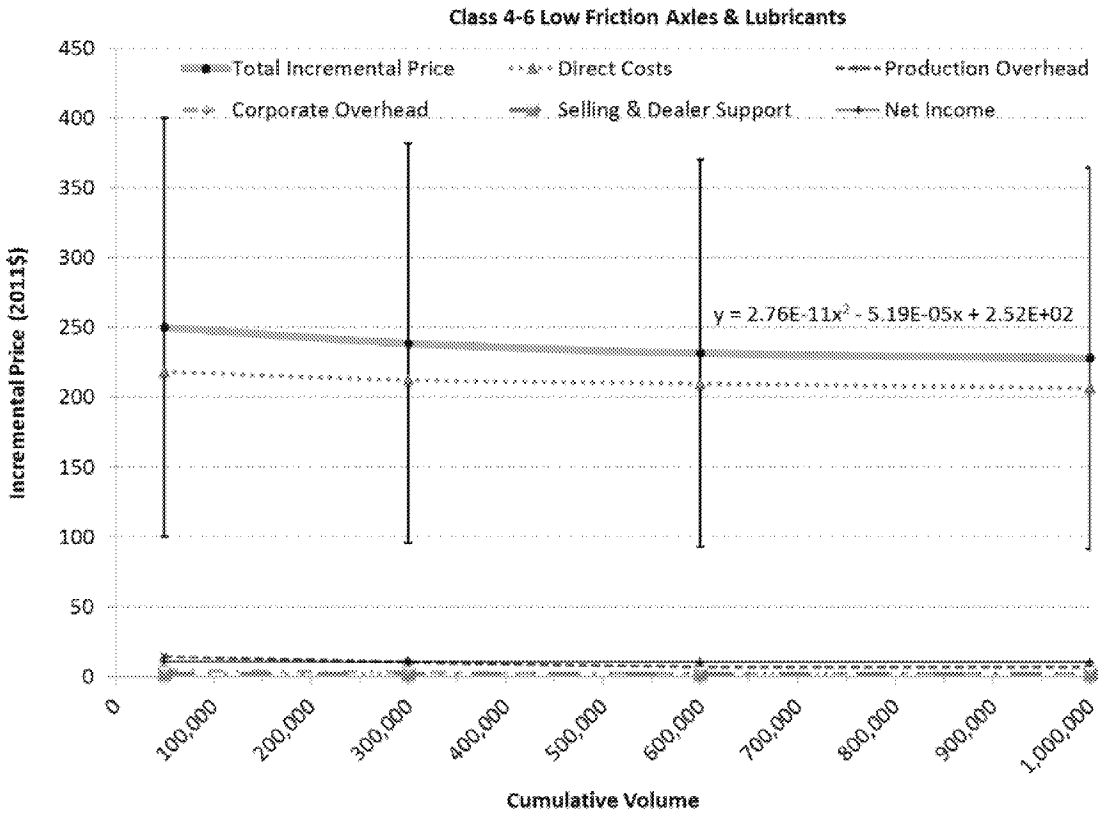
Chassis Friction Reduction & Improved Lube



Class 2b&3 Low Friction Axles & Lubricants

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$250.00	$238.72	$231.52	$227.92
Direct Costs	$218.38	$212.40	$209.75	$206.49
Production Overhead	$14.15	$10.41	$7.09	$6.98
Corporate Overhead	$4.37	$3.17	$2.10	$2.06
Selling & Dealer Support	$2.18	$2.12	$2.10	$2.06
Net Income	$10.92	$10.62	$10.49	$10.32

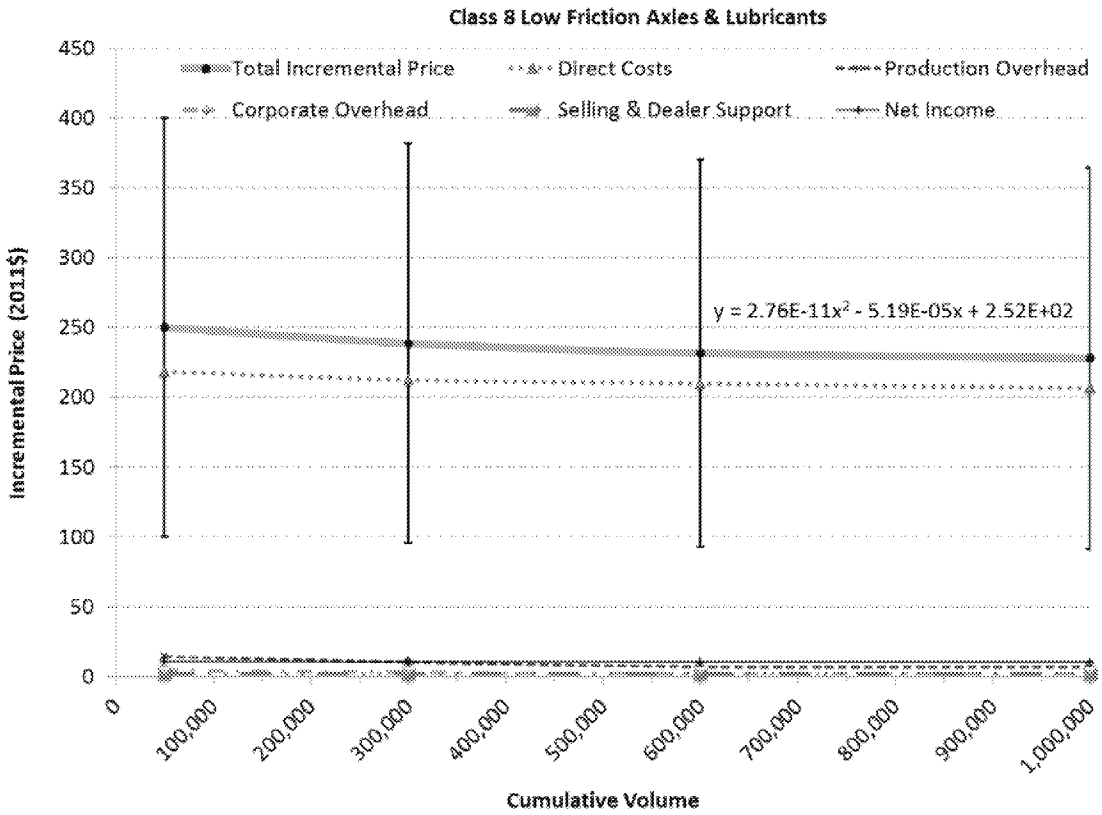
Figure 89. Incremental Price and Breakouts for Class 2b&3 (Gasoline, Diesel) Chassis Friction Reduction & Improved Lube



Class 4-6 Low Friction Axles & Lubricants

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$250.00	$238.72	$231.52	$227.92
Direct Costs	$218.38	$212.40	$209.75	$206.49
Production Overhead	$14.15	$10.41	$7.09	$6.98
Corporate Overhead	$4.37	$3.17	$2.10	$2.06
Selling & Dealer Support	$2.18	$2.12	$2.10	$2.06
Net Income	$10.92	$10.62	$10.49	$10.32

Figure 90. Incremental Price and Breakouts for Vocational (Gasoline, Diesel) Chassis Friction Reduction & Improved Lube



Class 8 Low Friction Axles & Lubricants

Volume (units):	50,000	300,000	600,000	1,000,000
Total Incremental Price	$250.00	$238.72	$231.52	$227.92
Direct Costs	$218.38	$212.40	$209.75	$206.49
Production Overhead	$14.15	$10.41	$7.09	$6.98
Corporate Overhead	$4.37	$3.17	$2.10	$2.06
Selling & Dealer Support	$2.18	$2.12	$2.10	$2.06
Net Income	$10.92	$10.62	$10.49	$10.32

Figure 91. Incremental Price and Breakouts for Line Haul Chassis Friction Reduction & Improved Lube

4 Life Cycle Cost Elements

Incremental retail prices are placed into the vehicle life context by examining life cycle cost elements. This section presents the information currently available on the vehicle life cycle impacts of the identified technologies in the various vehicle categories. Fuel savings are determined from SwRI modeling of technology performance and are not included here. O&M impacts and technology replacement requirements are described in terms of their costs or benefits and corresponding intervals during the vehicle life. Residual value is assessed as the incremental residual value provided by the technology (negative residual value represents having a lower resale value). Phase 2 GHG regulations only apply to new vehicles and would not affect the sales of used vehicles.

In the case of 6x2 Axle technology, the benefit is in fuel savings, and the penalty is primarily in terms of reduced traction under slippery road conditions. Many 6x2 setups have taken steps to mitigate the traction issue, but there isn't a lot of field experience with them yet. Today, the used truck market is wary of the traction issue due to the newness of the technology. They may become more or less comfortable with this issue over time as experience is gained. This could then affect the resale value of 6x2 trucks up or down.

As noted earlier, life cycle cost elements reported here are intended to inform separate full life cycle analysis, which will also make use of inputs outside the scope of this report. TBD and NNI were entered into the following tables when data was not available (if data was available, it was entered in the units that were reported by the sources). There is limited maintenance, replacement, and residual value data due to the technologies being new and not being widely deployed for long periods of time.

Advanced Bottoming Cycle

Table 12. Life Cycle Cost Elements of Line Haul Advanced Bottoming Cycle

Class 8 Advanced Bottoming Cycle

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2015	0	$0.003/mi	TBD	TBD
Interval			n/a	n/a	End of first owner life

Coolant/Oil Pump

Table 13. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Coolant/Oil Pump

Class 2b&3 2-Stage Pump (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	TBD	TBD
Interval			n/a	100,000 miles	End of first owner life

Class 2b&3 Variable Displ Pump (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	TBD	TBD
Interval			n/a	100,000 miles	End of first owner life

Class 4-6 2-Stage Pump (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	TBD	TBD
Interval			n/a	100,000 miles	End of first owner life

Class 4-6 Variable Displ Pump (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	TBD	TBD
Interval			n/a	100,000 miles	End of first owner life

Class 8 Variable Displ Pump

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	2012	20,000	TBD	TBD	TBD
Interval			n/a	n/a	End of first owner life

Variable Valve Actuation

Table 14. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul VVA

Class 2b&3 VVA (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	2008MY	TBD	10% increase	NNI	NNI
Interval			100,000 mile valve job	n/a	End of first owner life

Class 4-6 VVA (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	2008MY	TBD	10% increase	NNI	NNI
Interval			100,000 mile valve job	n/a	End of first owner life

Class 8 VVA

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	20014MY	0	10% increase	NNI	NNI
Interval			100,000 mile valve job	n/a	End of first owner life

Cylinder Deactivation

Table 15. Life Cycle Cost Elements of Class 2b&3 and Vocational Cylinder Deactivation

Class 2b&3 Cylinder Deactivation (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Cylinder Deactivation (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Stoichiometric GDI

Table 16. Life Cycle Cost Elements of Class 2b&3 and Vocational Stoichiometric GDI

Class 2b&3 Stoichiometric GDI (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Stoichiometric GDI (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Lean Burn GDI with SCR

Table 17. Life Cycle Cost Elements of Class 2b&3 and Vocational Lean Burn GDI with SCR

Class 2b&3 Lean Burn GDI with SCR (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2016	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Lean Burn GDI with SCR (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2016	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Stoichiometric GDI+EGR

Table 18. Life Cycle Cost Elements of Vocational Stoichiometric GDI+EGR

Class 4-6 Stoichiometric GDI + EGR (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Turbocharging & Downsizing

Table 19. Life Cycle Cost Elements of Class 2b&3 and Vocational Turbocharging & Downsizing

Class 2b&3 Turbocharging & Downsizing (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Turbocharging & Downsizing (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Engine Downspeeding

Table 20. Life Cycle Cost Elements of Class 2b&3 and Vocational Engine Downspeeding

Class 2b&3 Engine Downspeeding (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Engine Downspeeding (G)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Low Friction Engine Oil

Table 21. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Low Friction Engine Oil

Class 2b&3 Low Friction Engine Oil (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			5,000 mile	n/a	End of first owner life

Class 2b&3 Low Friction Engine Oil (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			15,000 mile	n/a	End of first owner life

Class 4-6 Low Friction Engine Oil (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			5,000 mile	n/a	End of first owner life

Class 4-6 Low Friction Engine Oil (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			15,000 mile	n/a	End of first owner life

Class 8 Low Friction Engine Oil

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			25,000 mile	n/a	End of first owner life

Engine Friction Reduction

Table 22. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Engine Friction Reduction

Class 2b&3 Engine Friction Reduction (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	TBD	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 4-6 Engine Friction Reduction (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	TBD	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 8 Engine Friction Reduction

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	TBD	NNI	NNI
Interval			n/a	n/a	End of first owner life

Stop/Start

Table 23. Life Cycle Cost Elements of Class 2b&3 and Vocational Stop/Start

Class 2b&3 Stop/Start (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	$455 for battery	Portion of remaining battery life
Interval			45,000 miles	100,000 miles	End of first owner life

Class 2b&3 Stop/Start (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	$455 for battery	Portion of remaining battery life
Interval			45,000 miles	100,000 miles	End of first owner life

Class 4-6 Stop/Start (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	$455 for battery	Portion of remaining battery life
Interval			45,000 miles	100,000 miles	End of first owner life

Class 4-6 Diesel Stop/Start (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	$455 for battery	Portion of remaining battery life
Interval			45,000 miles	100,000 miles	End of first owner life

Reduce Aftertreatment Backpressure

Table 24. Life Cycle Cost Elements of Line Haul Reduced Aftertreatment Backpressure

Class 8 Reduced Aftertreatment Backpressure

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	TBD	NNI	NNI
Interval			TBD	n/a	End of first owner life

Air Handling Improvements

Table 25. Life Cycle Cost Elements of Line Haul Air Handling Improvements

Class 8 Air Handling Improvements

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Mechanical Turbocompound

Table 26. Life Cycle Cost Elements of Line Haul Mechanical Turbocompound

Class 8 Mechanical Turbocompound

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	2010	TBD	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Electric Turbocompound

Table 27. Life Cycle Cost Elements of Line Haul Electric Turbocompound

Class 8 Electrical Turbocompound

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	2014?	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Hybrid Electric Vehicle

Table 28. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Hybrid Electric Vehicle

Class 2b&3 Hybrid Electric Vehicles

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing		NNI	$0.006/mi	NNI
Interval			n/a	6 year battery life	End of first owner life

Class 4-6 Hybrid Electric Vehicles

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing		NNI	$0.006/mi	NNI
Interval			n/a	6 year battery life	End of first owner life

Class 8 Hybrid Electric Vehicles

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing		NNI	$0.006/mi	NNI
Interval			n/a	6 year battery life	End of first owner life

Diesel APU

Table 29. Life Cycle Cost Elements of Line Haul Diesel APU

Class 8 Diesel APU

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	2012	20,000	$400/yr	NNI	1,000
Interval			500-2,000 hrs	n/a	End of first owner life

Battery APU

Table 30. Life Cycle Cost Elements of Line Haul Battery APU

Class 8 Battery APU

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	10,000	$200/yr	$220	NNI
Interval			annual	Batteries every 2 yrs	End of first owner life

Fuel Fired Heater

Table 31. Life Cycle Cost Elements of Line Haul Fuel Fired Heater

Class 8 Fuel Fired Heater

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	50,000	$110/yr	TBD	NNI
Interval			annual	n/a	End of first owner life

Air Conditioning System Improvements

Table 32. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul A/C System Improvements

Class 2b&3 Air Conditioning Improvements

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 4-6 Air Conditioning Improvements

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 8 Air Conditioning Improvements

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Cab Insulation to Reduce A/C

Table 33. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Cab Insulation to Reduce A/C

Class 2b&3 Cab Insulation to Reduce A/C

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	TBD	$1,000 - $1,700	NNI
Interval			TBD	replace when damaged	End of first owner life

Class 4-6 Cab Insulation to Reduce A/C

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	TBD	$1,000 - $1,700	NNI
Interval			TBD	replace when damaged	End of first owner life

Class 8 Cab Insulation to Reduce A/C

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	TBD	$1,000 - $1,700	NNI
Interval			TBD	replace when damaged	End of first owner life

Air Compressor Improvements

Table 34. Life Cycle Cost Elements of Line Haul Air Compressor Improvements

Class 8 Air Compressor Improvements

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	2012	20,000	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Shore Power

Table 35. Life Cycle Cost Elements of Line Haul Shore Power

Class 8 Shore Power

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	40,000	NNI	TBD	NNI
Interval			n/a	n/a	End of first owner life

Aero Bin III

Table 36. Life Cycle Cost Elements of Line Haul Aero Bin III

Class 8 Aero Trailer Side Skirt (4 to 6 m)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Class 8 Aero Boat Tail

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Aero Bin IV and V

Table 37. Life Cycle Cost Elements of Line Haul Aero Bin IV and V

Class 8 Aero Full Trailer Skirt (7 to 9 m)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	50,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Class 8 Aero Full Tractor Skirt

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Class 8 Aero Gap Filler

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Aero on Regional Haul

Table 38. Life Cycle Cost Elements of Aero on Regional Haul

Class 8 Aero on Regional Haul

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Class 2b&3 Improved Aerodynamics

Table 39. Life Cycle Cost Elements of Class 2b&3 Improved Aerodynamics

Class 2b&3 Improved Aerodynamics

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	25,000	10% of incremental	Full Incremental	NNI
Interval			annual	10 year life	End of first owner life

Improved Transmissions

Table 40. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Improved Transmissions

Class 2b&3 Improved Transmissions (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 2b&3 Improved Transmissions (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 4-6 Improved Transmissions (G)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 4-6 Improved Transmissions (D)

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Class 8 Improved Transmissions

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	NNI	NNI	NNI
Interval			n/a	n/a	End of first owner life

Automated Manual Transmission

Table 41. Life Cycle Cost Elements of Vocational and Line Haul AMT

Class 4-6 Automated Manual Transmission

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 8 Automated Manual Transmission

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			300,000 mile	n/a	End of first owner life

Dual Clutch Automatic

Table 42. Life Cycle Cost Elements of Vocational and Line Haul Dual Clutch Automatic

Class 4-6 Dual Clutch Automatic (G,D)

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Class 8 Dual Clutch Automatic

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production	Maintenance	Replacement	Residual Value
Value	~2014	0	TBD	NNI	NNI
Interval			100,000 mile	n/a	End of first owner life

Low Rolling Resistance Tires

Table 43. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul LRR Tires

Class 2b&3 Low Rolling Resistance Tires

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	5,400,000	Full Incremental	NNI	NNI
Interval			40,000 mile	n/a	End of first owner life

Class 4-6 Low Rolling Resistance Tires

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	700,000	Full Incremental	NNI	NNI
Interval			40,000 mile	n/a	End of first owner life

Class 8 Low Rolling Resistance Tires

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	3,000,000	NNI	$40/tire	NNI
Interval			40,000 mile	125,000 mile	End of first owner life

Single Wide Tires

Table 44. Life Cycle Cost Elements of Line Haul Single Wide Tires

Class 8 Single Wide Tires

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	300,000	NNI	$30/tire	NNI
Interval			40,000 mile (tire)	125,000 mile (tire)	End of first owner life
			450,000 mile (wheel)	450,000 mile (wheel)	

Automated Tire Inflation System

Table 45. Life Cycle Cost Elements of Vocational and Line Haul ATI

Class 4-6 Automated Tire Inflation System

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	20014MY	0	TBD	NNI	NNI
Interval			TBD	n/a	End of first owner life

Class 8 Automated Tire Inflation System

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	20014MY	0	TBD	NNI	NNI
Interval			TBD	n/a	End of first owner life

Weight Reduction

Table 46. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Weight Reduction

Class 2b&3 Weight Reduction

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	NNI	NNI	NNI
Interval			450,000 mile	450,000 mile	End of first owner life

Class 4-6 Weight Reduction

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	NNI	NNI	NNI
Interval			450,000 mile	450,000 mile	End of first owner life

Class 8 Weight Reduction

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	NNI	NNI	NNI
Interval			450,000 mile	450,000 mile	End of first owner life

6x2 Tractors

Table 47. Life Cycle Cost Elements of Line Haul 6x2 Tractors

Class 8 6x2 Axle Configuration

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	NNI	NNI	($4,000)
Interval			450,000 mile	450,000 mile	End of first owner life

Negative residual value represents the lower resale value of a 6x2 tractor when compared to 6x4 tractors.

Chassis Friction Reduction & Improved Lube

Table 48. Life Cycle Cost Elements of Class 2b&3, Vocational, and Line Haul Chassis Friction Reduction & Improved Lube

Class 2b&3 Low Friction Axles & Lubricants

Life Cycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			10,000 mile	n/a	End of first owner life

Class 4-6 Low Friction Axles & Lubricants

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			180,000 mile	n/a	End of first owner life

Class 8 Low Friction Axles & Lubricants

Lifecycle Cost Element:	Start of Production	Estimated 2012 Production Volume	Maintenance	Replacement	Residual Value
Value	Ongoing	TBD	Full Incremental	NNI	NNI
Interval			500,000 mile	n/a	End of first owner life

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6 Appendix A: Reference Data

The following tables provide detailed information for the specific data gathered from the listed references. The incremental prices and life cycle costs are in this report are derived from these data, which are presented by vehicle category and technology and include assumptions regarding baselines and prior technologies.

Advanced Bottoming Cycle

Table 49. Reference Data for Line Haul Advanced Bottoming Cycle

Class 8 Advanced Bottoming Cycle

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$7,200 to $30,200	7, 54, 58, 69	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2015 Introduction	11-15L diesel with bottoming cycle. Steam cycle. 30 kW.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Advanced Bottoming Cycle

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$15,100 to $30,200	Bottoming cycle includes electric bottoming cycle expander connected to a generator.	Steam cycle. 30 kW. Accessory power demand on the engine is reduced from an average of 5 kW to 3 kW.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$23,000	Advanced 11-15L diesel with bottoming cycle	
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$7,200 to $15,100	Advanced 11-15L diesel with bottoming cycle.	Steam Cycle 15 to 60 kW
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$7,200 to $15,100	Advanced 11-15L diesel with bottoming cycle.	Steam Cycle 32 kW

Coolant/Oil Pump

Table 50. Reference Data for Class 2b&3 (Gasoline) 2-Stage Pump

Class 2b&3 2-Stage Pump (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$120 to $240	54, 55, 57	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring (see 2013 DD15 and DD13): combined coolant/oil pump tech to 2-stage oil pump for gasoline engines, variable displacement for diesels.

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 2-Stage Pump (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories—Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.

Table 51. Reference Data for Class 2b&3 (Diesel) Variable Displacement Pump

Class 2b&3 Variable Displ Pump (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$200 to $500	54, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	2014 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring (see 2013 DD15 and DD13): combined coolant/oil pump tech to 2-stage oil pump for gasoline engines, variable displacement for diesels.

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Variable Displ Pump (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories—Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.

Table 52. Reference Data for Vocational (Gasoline) 2-Stage Pump

Class 4-6 2-Stage Pump (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$120 to $240	54, 55, 57	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring (see 2013 DD15 and DD13): combined coolant/oil pump tech to 2-stage oil pump for gasoline engines, variable displacement for diesels.

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 2-Stage Pump (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories—Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.

Table 53. Reference Data for Vocational (Diesel) Variable Displacement Pump

Class 4-6 Variable Displ Pump (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$200 to $500	54, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	2014 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring (see 2013 DD15 and DD13): combined coolant/oil pump tech to 2-stage oil pump for gasoline engines, variable displacement for diesels.

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Variable Displ Pump (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories—Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.

Table 54. Reference Data for Line Haul Variable Displacement Pump

Class 8 Variable Displ Pump

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$200 to $500	54, 55, 57, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2012 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring, variable displacement pump

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Variable Displ Pump

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories—Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Belt-driven mechanical accessories

Variable Valve Actuation

Table 55. Reference Data for Class 2b&3 (Gasoline) VVA

Class 2b&3 VVA (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$520 to $720	11, 54, 55, 57	6.2 V-8: gasoline PFI, fixed valve	2011$	2008 introduction	Variable valve lift and timing mechanism similar to BMW Valvetronic, Sturman is an option for diesel

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission
Prior Technology: None additional required (VVT and VVL packaged together)

Class 2b&3 VVA (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54, 11	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$122	Gasoline, PFI, fixed valve VVT	Cost of VVT only
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$520-$720	Gasoline, PFI	including $120 for VVT
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$105	Gasoline, PFI, fixed valve	VVT - Dual Cam Phasing (DCP)
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$555	Gasoline, PFI, VVT	Continuously Variable Valve Lift (CVVL)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$326	LT V8 Gasoline Engine	Discrete variable valve lift (DVVL) on DOHC
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	?	LT V8 Gasoline Engine	Continuously Variable Valve Lift (CVVL)

Table 56. Reference Data for Vocational (Gasoline) VVA

Class 4-6 VVA (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$520 to $750	11, 54, 55, 57	6.2 V-8: gasoline PFI, fixed valve	2011$	2008 introduction	Variable valve lift and timing mechanism similar to BMW Valvetronic, Sturman is an option for diesel

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 VVA (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54, 11	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$122	Gasoline, PFI, fixed valve VVT	Cost of VVT only
3, 4, 5, 7	TIAX site visits during research for Source 54	$500 to $750	6-9L Diesel Engines	VVA
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$326	LT V8 Gasoline Engine	Discrete variable valve lift (DVVL) on DOHC
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.:	$300	11 to 15L Engines	We think that VVA would work best when combined with turbocompound. (50$/cyl)
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,500	Class 7 and Class 8 Truck Technologies	Improved injectors and more efficient combustion
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$300	11 to 15L Engines	Costs & benefits from SwRI/TIAX; reasonable to reviewers
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$555	V8	Continuously Variable Valve Lift (CVVL)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$326	LT V8 Gasoline Engine	Discrete variable valve lift (DVVL) on DOHC
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$300	11 to 15L Engines	11-15 Liter Engine Diesel Technology Matrix

Table 57. Reference Data for Line Haul VVA

Class 8 VVA

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$300 to $750	7, 28, 54, 55, 57, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2014 introduction	Variable valve lift and timing mechanism similar to BMW Valvetronic, Sturman is an option for diesel

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required (VVT and VVL packaged together)

Class 8 VVA

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$300	11 to 15L Engines	We think that VVA would work best when combined with turbocompound. (50$/cyl)
3, 4, 5, 7	TIAX site visits during research for Source 54	$500 to $750	6-9L Diesel Engines	VVA
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,500	Class 7 and Class 8 Truck Technologies	Improved injectors and more efficient combustion
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$300	11 to 15L Engines	Costs & benefits from SwRI/TIAX; reasonable to reviewers
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$555	V8	Continuously Variable Valve Lift (CVVL)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$326	LT V8 Gasoline Engine	Discrete variable valve lift (DVVL) on DOHC
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$300	11 to 15L Engines	11-15 Liter Engine Diesel Technology Matrix

Cylinder Deactivation

Table 58. Reference Data for Class 2b&3 (Gasoline) Cylinder Deactivation

Class 2b&3 Cylinder Deactivation (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$75 to $500	54, 55, 57	6.2 V-8: gasoline PFI, VVA, friction reductionI, OHV to DOHC	2011$	2014 introduction	Cost range to cover OHV to DOHC configurations

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: VVA (VVT + VVL); engine friction reduction

Class 2b&3 Cylinder Deactivation (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$75	6.2 V-8 (OHC)	Baseline + VVL and VVT + reduced friction ($110-$500)
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$400	6.2 V-8 (OHV)	Baseline + VVL and VVT
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$383	V8	Cylinder Deactivation, OHV
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$583	V8	Cylinder Deactivation, SOHC
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$208	LT V8 Gasoline Engine	Baseline + VVL and VVT + reduced friction

Table 59. Reference Data for Vocational (Gasoline) Cylinder Deactivation

Class 4-6 Cylinder Deactivation (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$75 to $500	54, 55, 57	6.2 V-8: gasoline PFI, VVA, friction reductionI, OHV to DOHC	2011$	2014 introduction	Cost range to cover OHV to DOHC configurations

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: VVA (VVT + VVL); engine friction reduction

Class 4-6 Cylinder Deactivation (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$75	6.2 V-8 (OHC)	Baseline + VVL and VVT + reduced friction ($110-$500)
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$400	6.2 V-8 (OHV)	Baseline + VVL and VVT
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$383	V8	Cylinder Deactivation, OHV
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$583	V8	Cylinder Deactivation, SOHC
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$208	LT V8 Gasoline Engine	Baseline + VVL and VVT + reduced friction

Stoichiometric GDI

Table 60. Reference Data for Class 2b&3 (Gasoline) Stoichiometric GDI

Class 2b&3 Stoichiometric GDI (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$500 to $750	28, 47, 54, 55, 57	6.2 V-8: gasoline PFI, VVA, friction reduction	2011$	2014 introduction	GDI without Nox aftertreatment

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: VVA (VVT + VVL); engine friction reduction

Class 2b&3 Stoichiometric GDI (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$700	V8 Gasoline	unknown baseline
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. Environmental Protection Agency. December 21, 2007.	?	5.4L V8 gasoline	Applied to engines with and without VVL + VVT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$512 to $930	5-8L Gasoline Engine	VVT + VVL + Cylinder deactivation
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$485	V8	Does not include VVL + VVT
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$537	LT V8 OHV Gasoline Engine	Baseline + VVL and VVT + reduced friction

Table 61. Reference Data for Vocational (Gasoline) Stoichiometric GDI

Class 4-6 Stoichiometric GDI (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$500 to $750	28, 47, 54, 55, 57	6.2 V-8: gasoline PFI, VVA, friction reduction	2011$	2014 introduction	GDI without NOx aftertreatment

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: VVA (VVT + VVL); engine friction reduction

Class 4-6 Stoichiometric GDI (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$700	V8 Gasoline	unknown baseline
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. Environmental Protection Agency. December 21, 2007.	?	5.4L V8 gasoline	Applied to engines with and without VVL + VVT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$512 to $930	5-8L Gasoline Engine	VVT + VVL + Cylinder deactivation
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$485	V8	Does not include VVL + VVT
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$537	LT V8 OHV Gasoline Engine	Baseline + VVL and VVT + reduced friction

Lean Burn GDI with SCR

Table 62. Reference Data for Class 2b&3 (Gasoline) Lean Burn GDI with SCR

Class 2b&3 Lean Burn GDI with SCR (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,380 to $2,480	11, 28, 47, 54, 55, 57, 58	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2016 introduction	GDI with SCR NOx aftertreatment

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission
Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 2b&3 Lean Burn GDI with SCR (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$480	LT V8 Gasoline Engine	Stoich GDI w/ DPF
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$250	V8 Gasoline	Improved DOC
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$75	V8 Gasoline	O2 Sensor
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000	V8 Gasoline	Nox Adsorber; NOx adsorber (integrated) system
54, 47	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	?	6.2 V-8 (OHC)	Lean Burn GDI w/ SCR; add SCR system similar to that used on diesel pickup trucks
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$750	5-8L Gasoline Engine	Lean Burn GDI; aove + VVL + Cylinder deactivation + Stoich GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$6,000 to $8,000	6-9L diesel	Add SCR system - Diesel Engine; only SCR priced near class recently
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$270	3.5L gasoline	Stoich GDI w/ DPF; adv. cordierite brick & can; coated DPF
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$274	3.5L gasoline	SCR brick and Can
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$363	3.5L gasoline	SCR dosing system
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$3,250 to $4,350	5-8L Gasoline Engine	Lean burn GDI; requires low sulfur gasoline

Table 63. Reference Data for Vocational (Gasoline) Lean Burn GDI with SCR

Class 4-6 Lean Burn GDI with SCR (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,380 to $2,480	11, 28, 47, 54, 55, 57, 58	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2016 introduction	GDI with SCR NOx aftertreatment

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 4-6 Lean Burn GDI with SCR (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$480	LT V8 Gasoline Engine	Stoich GDI w/ DPF
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$250	V8 Gasoline	Improved DOC
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$75	V8 Gasoline	O2 Sensor
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000	V8 Gasoline	Nox Adsorber; NOx adsorber (integrated) system
54, 47	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	?	6.2 V-8 (OHC)	Lean Burn GDI w/ SCR; add SCR system similar to that used on diesel pickup trucks
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$750	5-8L Gasoline Engine	Lean Burn GDI; aove + VVL + Cylinder deactivation + Stoich GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$6,000 to $8,000	6-9L diesel	Add SCR system - Diesel Engine; only SCR priced near class recently
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$270	3.5L gasoline	Stoich GDI w/ DPF; adv. cordierite brick & can; coated DPF
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$274	3.5L gasoline	SCR brick and Can
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$363	3.5L gasoline	SCR dosing system
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$3,250 to $4,350	5-8L Gasoline Engine	Lean burn GDI; requires low sulfur gasoline

Stoichiometric GDI+EGR

Table 64. Reference Data for Vocational (Gasoline) Stoichiometric GDI+EGR

Class 4-6 Stoichiometric GDI + EGR (G)						
Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1060 to $1800	28, 47, 54, 55, 57	6.2 V-8: gasoline PFI, VVA, friction reduction	2011$	2014 introduction	GDI without NOx aftertreatment

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission
Prior Technology: Variable Valve Actuation (VVT + VVL), Engine Friction Reduction

Class 4-6 Stoichiometric GDI + EGR (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$700	V8 Gasoline	unknown baseline
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. EPA. Report #EPA420-R-08-004a. June 2008.	?	5.4L V8 gasoline	Applied to engines with and without VVL + VVT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$512 to $930	5-8L Gasoline Engine	VVT + VVL + Cylinder deactivation
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$485	V8	Does not include VVL + VVT
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$537	LT V8 OHV Gasoline Engine	Baseline + VVL and VVT + reduced friction
70	"European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles", TIAX report to The International Council on Clean Transportation, Dec, 2011	$3,728	2020 Engine Class 3	Advanced 6-9L 2020 engine (220 to 230 bar cylinder pressure, 3,000 bar fuel injection, electrically boosted dual-stage variable geometry turbocharger, improved closed-loop engine controls, electric accessories, peak thermal efficiency 46 to 49%)*
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$336	Cooled Exhaust Gas Recirculation (EGR)—Level 1 (24 bar BMEP).	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$3,250 to $4,350	Lean burn GDI	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$750	Advanced EGR	High-rate EGR
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$500 - $750	High-rate EGR	
	internet searches, no realiable source found yet	$10-$50/plg	Advanced Corona Ignition System (ACIS)	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$537	LT V8 OHV Gasoline Engine	Baseline + VVL and VVT + reduced friction

Turbocharging & Downsizing

Table 65. Reference Data for Class 2b&3 (Gasoline) Turbocharging & Downsizing

Class 2b&3 Turbocharging & Downsizing (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $1,780	54, 55, 57, 58	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2014 introduction	System cost includes turbocharging engine, higher BMEP capability

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 2b&3 Turbocharging & Downsizing (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$3,000 to $4,200 Package cost	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $2,000	5-8L Gasoline Engine	added to the cost of VVT, VVL, and GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,229	5-8L Gasoline Engine	Above + VVL + Cylinder deactivation + Stoich GDI
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$986	V8	Gasoline, PFI, VVT, VVL, GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,339	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 1 18-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,781	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 2 24-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2500 to $3600	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT

Table 66. Reference Data for Vocational (Gasoline) Turbocharging & Downsizing

Class 4-6 Turbocharging & Downsizing (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $1,780	54, 55, 57, 58	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2014 introduction	System cost includes turbocharging engine, higher BMEP capability

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 4-6 Turbocharging & Downsizing (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$3,000 to $4,200 Package cost	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $2,000	5-8L Gasoline Engine	added to the cost of VVT, VVL, and GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,229	5-8L Gasoline Engine	Above + VVL + Cylinder deactivation + Stoich GDI
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$986	V8	Gasoline, PFI, VVT, VVL, GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,339	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 1 18-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,781	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 2 24-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2500 to $3600	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT

Engine Downspeeding

Table 67. Reference Data for Class 2b&3 (Gasoline) Engine Down Speeding

Class 2b&3 Engine Downspeeding (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1,600 to $3,600	11, 28, 54, 55, 57, 58, 69	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2015 introduction	High BMEP V-6 with EGR plus Higher Speed Transmission

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 2b&3 Engine Downspeeding (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$3,000 to $4,200 Package cost	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $2,000	5-8L Gasoline Engine	added to the cost of VVT, VVL, and GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,229	5-8L Gasoline Engine	Above + VVL + Cylinder deactivation + Stoich GDI
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$986	V8	Gasoline, PFI, VVT, VVL, GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,339	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 1 18-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,781	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 2 24-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2500 to $3600	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix

54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA LDV Rulemaking -- primarily tables on Pp 334-341, plus supporting text	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$638	8-spd AT	V8
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$500-$1500	6-9L Diesel engine Increase cyliner pressure	20 to 23 Bar
	Research Notes	$500-$2000	6-9L Diesel engine Increase cyliner pressure	Eckerle (Cummins) identified this as a higher cost process; requires new materials, higher maching costs; Frey has this at $1,000; TIAX/Global insights has this + FI at $2,200
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$638	8-spd AT	V8

Table 68. Reference Data for Vocational (Gasoline) Engine Down Speeding

Class 4-6 Engine Downspeeding (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1,600 to $3,600	11, 28, 54, 55, 57, 58, 69	6.2 V-8: gasoline PFI, GDI, VVA, friction reduction	2011$	2015 introduction	High BMEP V-6 with EGR plus Higher Speed Transmission

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: Stoichiometric GDI; VVA (VVT + VVL); engine friction reduction

Class 4-6 Engine Downspeeding (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$3,000 to $4,200 Package cost	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $2,000	5-8L Gasoline Engine	added to the cost of VVT, VVL, and GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,229	5-8L Gasoline Engine	Above + VVL + Cylinder deactivation + Stoich GDI
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$986	V8	Gasoline, PFI, VVT, VVL, GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,339	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 1 18-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$1,781	LT V8 OHV Gasoline Engine	Turbocharging and Downsizing—Level 2 24-bar BMEP with downsize from V8 OHV to V6 DOHC - Total package cost including VVT, VVL, and GDI
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2500 to $3600	5-8L Gasoline Engine	Package 3: Turbo-charged gasoline, down-sized engine; Includes SGDI, VVLT
28	Vyas, A., C. Saricks, F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix

54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA LDV Rulemaking -- primarily tables on Pp 334-341, plus supporting text	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$638	8-spd AT	V8
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$500-$1500	6-9L Diesel engine Increase cyliner pressure	20 to 23 Bar
	Research Notes	$500-$2000	6-9L Diesel engine Increase cyliner pressure	Eckerle (Cummins) identified this as a higher cost process; requires new materials, higher maching costs; Frey has this at $1,000; TIAX/Global insights has this + FI at $2,200
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$638	8-spd AT	V8

Low Friction Engine Oil

Table 69. Reference Data for Class 2b&3 (Gasoline) Low Friction Engine Oil

Class 2b&3 Low Friction Engine Oil (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$5 to $10	11, 42, 54, 55, 57	6.2 V-8: gasoline PFI	2011$	continuous improvement	Low Friction Engine Oil only

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission
Prior Technology: None additional required

Class 2b&3 Low Friction Engine Oil (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$8-$11	3.5L gasoline	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	11 to 15L Engines estimate	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$6	3.5L gasoline	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$5	LT V8 Gasoline Engine	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$35 to $55		synthetic lube in tandem-drive axles
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$4	LT V8 Gasoline Engine	Low Friction Lubricants—Level 1

Table 70. Reference Data for Class 2b&3 (Diesel) Low Friction Engine Oil

Class 2b&3 Low Friction Engine Oil (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$9 to $19	11, 42, 54, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	continuous improvement	Low Friction Engine Oil only

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Low Friction Engine Oil (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$8-$11	3.5L gasoline	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	11 to 15L Engines estimate	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$0 to $500	6-9L Diesel Engines	Packaged with all Engine Friction Reduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$6	3.5L gasoline	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$5	LT V8 Gasoline Engine	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$35 to $55		synthetic lube in tandem-drive axles
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$4	LT V8 Gasoline Engine	Low Friction Lubricants—Level 1

Table 71. Reference Data for Vocational (Gasoline) Low Friction Engine Oil

Class 4-6 Low Friction Engine Oil (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$5 to $10	11, 42, 54, 55, 57	6.2 V-8: gasoline PFI	2011$	continuous improvement	Low Friction Engine Oil only

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Low Friction Engine Oil (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$8-$11	3.5L gasoline	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	11 to 15L Engines estimate	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$6	3.5L gasoline	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$5	LT V8 Gasoline Engine	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$35 to $55		synthetic lube in tandem-drive axles
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$4	LT V8 Gasoline Engine	Low Friction Lubricants—Level 1

Table 72. Reference Data for Vocational (Diesel) Low Friction Engine Oil

Class 4-6 Low Friction Engine Oil (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$9 to $19	11, 42, 54, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	continuous improvement	Low Friction Engine Oil only

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Low Friction Engine Oil (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$8-$11	3.5L gasoline	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	11 to 15L Engines estimate	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$0 to $500	6-9L Diesel Engines	Packaged with all Engine Friction Reduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$6	3.5L gasoline	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$5	LT V8 Gasoline Engine	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$35 to $55		synthetic lube in tandem-drive axles
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$4	LT V8 Gasoline Engine	Low Friction Lubricants—Level 1

Table 73. Reference Data for Line Haul Low Friction Engine Oil

Class 8 Low Friction Engine Oil

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$55 to $150	11, 28, 42, 54, 57	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Low Friction Engine Oil only

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Low Friction Engine Oil

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$8-$11	3.5L gasoline	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	11 to 15L Engines estimate	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class7 & 8	Internal friction reduction through better lubricants and improved bearings.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$35 to $55		synthetic lube in tandem-drive axles
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$54-$75	Scaled from 11	3.5L: 6.2 Quarts or 5.9 Litres is the oil capacity (including filter); MaxxForce 11L and 13L: Lub Capacity 40L (42 quarts)

Engine Friction Reduction

Table 74. Reference Data for Class 2b&3 (Gasoline) Engine Friction Reduction

Class 2b&3 Engine Friction Reduction (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$64 to $392	11, 55, 69	6.2 V-8: gasoline PFI	2011$	continuous improvement	Improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology:

Class 2b&3 Engine Friction Reduction (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$52 to $196	4 cylinder gasoline or diesel engine	improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.
		$78 to $294	6 cylinder gasoline or diesel engine	
		$104 to $392	8 cylinder gasoline or diesel engine	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$32 to $52	4 cylinder gasoline or diesel engine	Improvements of surface engineering (surface coatings, material substitutions, selective surface hardening and surface topography control).
		$48 to $78	6 cylinder gasoline or diesel engine	
		$64 to $104	8 cylinder gasoline or diesel engine	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$0 to $500	Up to 8 cylinders	Friction Reduction (lubricants, bearings, materials, coatings, etc)

Table 75. Reference Data for Class 2b&3 (Diesel) Engine Friction Reduction

Class 2b&3 Engine Friction Reduction (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$48 to $294	11, 55, 69	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	continuous improvement	Improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology:

Class 2b&3 Engine Friction Reduction (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$52 to $196	4 cylinder gasoline or diesel engine	improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.
		$78 to $294	6 cylinder gasoline or diesel engine	
		$104 to $392	8 cylinder gasoline or diesel engine	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$32 to $52	4 cylinder gasoline or diesel engine	Improvements of surface engineering (surface coatings, material substitutions, selective surface hardening and surface topography control).
		$48 to $78	6 cylinder gasoline or diesel engine	
		$64 to $104	8 cylinder gasoline or diesel engine	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$0 to $500	Up to 8 cylinders	Friction Reduction (lubricants, bearings, materials, coatings, etc)

Table 76. Reference Data for Vocational (Gasoline) Engine Friction Reduction

Class 4-6 Engine Friction Reduction (G)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$64 to $392	11, 55, 69	6.2 V-8: gasoline PFI	2011$	continuous improvement	Improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology:

Class 4-6 Engine Friction Reduction (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$52 to $196	4 cylinder gasoline or diesel engine	improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.
		$78 to $294	6 cylinder gasoline or diesel engine	
		$104 to $392	8 cylinder gasoline or diesel engine	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$32 to $52	4 cylinder gasoline or diesel engine	Improvements of surface engineering (surface coatings, material substitutions, selective surface hardening and surface topography control).
		$48 to $78	6 cylinder gasoline or diesel engine	
		$64 to $104	8 cylinder gasoline or diesel engine	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$0 to $500	Up to 8 cylinders	Friction Reduction (lubricants, bearings, materials, coatings, etc)

Table 77. Reference Data for Vocational (Diesel) Engine Friction Reduction

Class 4-6 Engine Friction Reduction (D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$48 to $294	11, 55, 69	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	continuous improvement	Improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology:

Class 4-6 Engine Friction Reduction (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$52 to $196	4 cylinder gasoline or diesel engine	improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.
		$78 to $294	6 cylinder gasoline or diesel engine	
		$104 to $392	8 cylinder gasoline or diesel engine	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$32 to $52	4 cylinder gasoline or diesel engine	Improvements of surface engineering (surface coatings, material substitutions, selective surface hardening and surface topography control).
		$48 to $78	6 cylinder gasoline or diesel engine	
		$64 to $104	8 cylinder gasoline or diesel engine	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$0 to $500	Up to 8 cylinders	Friction Reduction (lubricants, bearings, materials, coatings, etc)

Table 78. Reference Data for Line Haul Engine Friction Reduction

Class 8 Engine Friction Reduction

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$48 to $294	11, 55, 69	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Engine Friction Reduction

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$52 to $196	4 cylinder gasoline or diesel engine	improve low-tension piston rings, roller cam followers, crankshaft design/bearings, material substitution, and piston/cylinder surface treatments.
		$78 to $294	6 cylinder gasoline or diesel engine	
		$104 to $392	8 cylinder gasoline or diesel engine	
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$32 to $52	4 cylinder gasoline or diesel engine	Improvements of surface engineering (surface coatings, material substitutions, selective surface hardening and surface topography control).
		$48 to $78	6 cylinder gasoline or diesel engine	
		$64 to $104	8 cylinder gasoline or diesel engine	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$0 to $500	Up to 8 cylinders	Friction Reduction (lubricants, bearings, materials, coatings, etc)

Stop/Start

Table 79. Reference Data for Class 2b&3 (Gasoline) Stop/Start

Class 2b&3 Stop/Start (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$500 to $900	54, 55, 28, 47	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	More capable vehicle battery and starter, control system development, Belt driven generator only
Battery replacement	$455	56	Varta stop/start battery	2013$		Stop/start capable battery

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Stop/Start (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,200	Focus on Diesel engines	Belt driven 42V system
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. Environmental Protection Agency. December 21, 2007.	No cost analysis in study	belt driven or ISG 42V	Only discussion of system characteristics
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2,000	belt driven or ISG 42V	Need volume to get costs down; probably requires 42V alternator
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$720 to $880	Belt driven Alterntor	12V BAS Micro-Hybrid
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/5809	455	Stop/Start capable battery	used as replacement cost (full cost)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	480	12V Micro Hybrid	12V BAS Micro-Hybrid

Table 80. Reference Data for Class 2b&3 (Diesel) Stop/Start

Class 2b&3 Stop/Start (D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $2,000	54, 55, 28, 47	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	2014 introduction	More capable vehicle battery and starter, control system development, ISG only
Battery replacement	$455	56	Varta stop/start battery	2013$		Stop/start capable battery

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Stop/Start (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,200	Focus on Diesel engines	Belt driven 42V system
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. EPA. Report #EPA420-R-08-004a. June 2008.	No cost analysis in study	belt driven or ISG 42V	Only discussion of system characteristics
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2,000	belt driven or ISG 42V	Need volume to get costs down; probably requires 42V alternator
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$720 to $880	Belt driven Alterntor	12V BAS Micro-Hybrid
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/580901-(f21).html. Accessed July 2013.	455	Stop/Start capable battery	used as replacement cost (full cost)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	976	Mild Hybrid	ISG
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$3,111	Strong Hybrid (Level 2)	Strong Hybrid

Table 81. Reference Data for Vocational (Gasoline) Stop/Start

Class 4-6 Stop/Start (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$500 to $900	54, 55, 28, 47	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	More capable vehicle battery and starter, control system development, Belt driven generator only
Battery replacement	$455	56	Varta stop/start battery	2013$		Stop/start capable battery

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Stop/Start (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,200	Focus on Diesel engines	Belt driven 42V system
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. Environmental Protection Agency. December 21, 2007.	No cost analysis in study	belt driven or ISG 42V	Only discussion of system characteristics
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2,000	belt driven or ISG 42V	Need volume to get costs down; probably requires 42V alternator
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2010.	$720 to $880	Belt driven Alterntor	12V BAS Micro-Hybrid
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/5809	455	Stop/Start capable battery	used as replacement cost (full cost)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	480	12V Micro Hybrid	12V BAS Micro-Hybrid

Table 82. Reference Data for Vocational (Diesel) Stop/Start

Class 4-6 Stop/Start (D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $2,000	54, 55, 28, 47	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$	2014 introduction	More capable vehicle battery and starter, control system development, ISG only
Battery replacement	$455	56	Varta stop/start battery	2013$		Stop/start capable battery

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Diesel Stop/Start (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,200	Focus on Diesel engines	Belt driven 42V system
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. EPA. Report #EPA420-R-08-004a. June 2008.	No cost analysis in study	belt driven or ISG 42V	Only discussion of system characteristics
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2,000	belt driven or ISG 42V	Need volume to get costs down; probably requires 42V alternator
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$720 to $880	Belt driven Alterntor	12V BAS Micro-Hybrid
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/580901-(f21).html. Accessed July 2013.	455	Stop/Start capable battery	used as replacement cost (full cost)
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	976	Mild Hybrid	ISG
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$3,111	Strong Hybrid (Level 2)	Strong Hybrid

Reduced Aftertreatment Backpressure

Table 83. Reference Data for Line Haul Reduced Aftertreatment Backpressure

Class 8 Reduced Aftertreatment Backpressure

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$440 to $1015	11, 28, 54, 55, 74	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Increase catalyst volume by 50% to reduce backpressure

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Reduced Aftertreatment Backpressure

Reference Number	Reference	Value from Reference	Description	Additional Notes
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$480	LT V8 Gasoline Engine	Stoich GDI w/ DPF
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$250	V8 Gasoline	Improved DOC
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$75	V8 Gasoline	O2 Sensor
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000	V8 Gasoline	Nox Adsorber; NOx adsorber (integrated) system
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$750	5-8L Gasoline Engine	Lean Burn GDI; aove + VVL + Cylinder deactivation + Stoich GDI
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$6,000 to $8,000	6-9L diesel	Add SCR system - Diesel Engine; only SCR priced near class recently
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$270	3.5L gasoline	Stoich GDI w/ DPF; adv. cordierite brick & can; coated DPF
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$274	3.5L gasoline	SCR brick and Can
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$363	3.5L gasoline	SCR dosing system
74	TIAX Offroad Engine Manufacturers Association Study, not published	$440 - $1015	DPF and DOC volume increase by 50%	Catalyst substrates for diesel truck applications are usually about 180-250 mm (7-10") in diameter and 150-180 mm (6-7") in length. Smaller substrates are used for passenger car applications.

Air Handling Improvements

Table 84. Reference Data for Line Haul Air Handling Improvements

Class 8 Air Handling Improvements

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$750 to $1,500	28, 47, 54, 55, 7	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2014 introduction	Air Handling Improvements through medium rate cooled EGR

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: VVA (VVT + VVL); engine friction reduction

Class 8 Air Handling Improvements

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000	Pre-2004 base engine technology	Reduced waste heat and improved thermal management
47	Ricardo. "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies." Prepared for U.S. EPA. Report #EPA420-R-08-004a. June 2008.	?	Gas Handling System	Advanced EGR cooling will likely include increased cooling capacity, EGR DOC for fouling mitigation, and EGR bypass
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1000 to $2000	11-15 Liter Engine Diesel	Accessory Electrification — Electric Auxiliaries (alternator, air compressor, power steering pump, air cond, fan, fuel pump, water pump); in combination with hybrid or other vehicle electrification.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $750	11-15 Liter Engine Diesel	Advanced low-temperature EGR, lower pressure drop
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$1,500	11-15 Liter Engine Diesel	1400 RPM and 60 percent load, the EGR temperature coming out of the EGR cooler was reduced from 167° C down to 104° C.

Mechanical Turbocompound

Table 85. Reference Data for Line Haul Mechanical Turbocompound

Class 8 Mechanical Turbocompound

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$2,000 to $3,000	7, 54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2010 Introduction	Mechanical Turbocompund

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Mechanical Turbocompound

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$2650 to $5300	Turbocompound – Mechanical	Includes VVA
7 research notes	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$2,200	Mechanical turno-compound	with port liners
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$2,000 to $3,000	Turbocompound – Mechanical	No WHR
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2,000 to $3,000	Turbocompound – Mechanical	No WHR

Electric Turbocompound

Table 86. Reference Data for Line Haul Electric Turbocompound

Class 8 Electrical Turbocompound

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$3,400 to $5,000	7, 54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2010 Introduction	Electrical Turbocompund

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Electrical Turbocompound

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$2650 to $5300	Turbocompound – Mechanical	Includes VVA
7 research notes	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$5,000 - $7,000	Electrical turbocompound	including site visit to DD
52	Kruiswyk, R. "Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology." Caterpillar, Inc., 2005 Annual Progress Report for Advanced Combustion Engine Technologies, US Department of Energy. Pp 276-281. January 2006.	$2,000 to $3,400	Electrical turbocompound	Power electronics account for 50% of the cost
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$6,000 to $7,000	Electric Turbocompound, including accessory electricification	No WHR ($3,000 to $4,000 inc.to Hybrid)

Hybrid Electric Vehicle

Table 87. Reference Data for Class 2b&3 Hybrid Electric Vehicle

Class 2b&3 Hybrid Electric Vehicles

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$9,000 to $30,000	7, 28, 45, 54, 55, 58, 59, 79	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$		Parallel hybrid-electric powertrain, integrated starter-alternator technology with idle off, and regenerative braking capability

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Hybrid Electric Vehicles

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$30,000 to $40,000	Class 8 Line Haul	Parallel hybrid-electric powertrain. 50kW motor/generator. 4 kW-hr battery pack.
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$6,000 to $8,000	Class 2b to 6 Truck Technologies	Hybrid electric powertrain
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000 (diesel) $1,000-1,200 (gasoline)	Class 2b to 6 Truck Technologies	Integrated starter-alternator technology with idle off and regenerative braking capability
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$7,100	medium-duty package and beverage delivery trucks	Idle off and regenerative braking capability
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$38,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$50,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$8,700	Light Duty Vehicles	Large SUV/pickup (V8)
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/580901-(f21).html. Accessed July 2013.	455	Stop/Start capable battery	used as replacement cost (full cost)
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$35,000 to $40,000 (w PTO $49k to $52k)	Class 3 to 6 box and bucket trucks	Parallel Hybrid Electric Vehicle
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$20,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$30,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$9,000	Class 2b pickup and van	Parallel hybrid. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$25,000	Class 8 Line Haul	Parallel electric hybrid with idle reduction (2015-2020)
79	California Air Resources Board, "Implementation Manual for the FY 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, November 1, 2012	$25,000 to $30,000	Class 2b to Class 3	Alternate incremental costs for specific vehicles can be used on a case-by-case basis

Table 88. Reference Data for Vocational Hybrid Electric Vehicle

Class 4-6 Hybrid Electric Vehicles

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$24,000 to $40,000	7, 28, 45, 54, 55, 58, 59, 79, 81	6.7L V8 Turbo Diesel, High Pressure direct inject	2011$		Parallel hybrid-electric powertrain, integrated starter-alternator technology with idle off, and regenerative braking capability with power takeoff.

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Hybrid Electric Vehicles

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$30,000 to $40,000	Class 8 Line Haul	Parallel hybrid-electric powertrain. 50kW motor/generator. 4 kW-hr battery pack.
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$6,000 to $8,000	Class 2b to 6 Truck Technologies	Hybrid electric powertrain
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000 (diesel) $1,000-1,200 (gasoline)	Class 2b to 6 Truck Technologies	Integrated starter-alternator technology with idle off and regenerative braking capability
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$7,100	medium-duty package and beverage delivery trucks	Idle off and regenerative braking capability
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$38,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$50,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$8,700	Light Duty Vehicles	Large SUV/pickup (V8)
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/580901-(f21).html. Accessed July 2013.	455	Stop/Start capable battery	used as replacement cost (full cost)
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$35,000 to $40,000 (w PTO $49k to $52k)	Class 3 to 6 box and bucket trucks	Parallel Hybrid Electric Vehicle
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$20,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$30,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$9,000	Class 2b pickup and van	Parallel hybrid. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$25,000	Class 8 Line Haul	Parallel electric hybrid with idle reduction (2015-2020)
79	California Air Resources Board, "Implementation Manual for the FY 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, November 1, 2012	$40,000 to $50,000	Class 4 to Class 6	Alternate incremental costs for specific vehicles can be used on a case-by-case basis
81	California Air Resources Board, "HVIP Eligible Vehicles – Hybrid," Updated February 21, 2014	$24,000 to $40,000	Class 4 to Class 7	Hino, Kenworth, Peterbilt, Navistar, & Freightliner Package Delivery Trucks

Table 89. Reference Data for Line Haul Hybrid Electric Vehicle

Class 8 Hybrid Electric Vehicles

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$30,000 to $50,000	7, 28, 45, 54, 55, 58, 59, 79, 81	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$		Parallel hybrid-electric powertrain, integrated starter-alternator technology with idle off, and regenerative braking capability.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Hybrid Electric Vehicles

Reference Number	Reference	Value from Reference	Description	Additional Notes
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$30,000 to $40,000	Class 8 Line Haul	Parallel hybrid-electric powertrain. 50kW motor/generator. 4 kW-hr battery pack.
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$6,000 to $8,000	Class 2b to 6 Truck Technologies	Hybrid electric powertrain
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$2,000 (diesel) $1,000-1,200 (gasoline)	Class 2b to 6 Truck Technologies	Integrated starter-alternator technology with idle off and regenerative braking capability
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$7,100	medium-duty package and beverage delivery trucks	Idle off and regenerative braking capability
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$38,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$50,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$8,700	Light Duty Vehicles	Large SUV/pickup (V8)
56	Batteries Direct. "Varta 580901 (F21)." http://www.batteriesdirect.com.au/shop/product/22640/580901-(f21).html. Accessed July 2013.	455	Stop/Start capable battery	used as replacement cost (full cost)
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$35,000 to $40,000 (w PTO $49k to $52k)	Class 3 to 6 box and bucket trucks	Parallel Hybrid Electric Vehicle
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$20,000	Class 3 to Class 6 Straight Box Truck	Parallel hybrid-electric powertrain. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$30,000	Class 3 to 6 Bucket Truck	Parallel hybrid with electric power takeoff. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$9,000	Class 2b pickup and van	Parallel hybrid. (2015-2020)
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$25,000	Class 8 Line Haul	Parallel electric hybrid with idle reduction (2015-2020)
79	California Air Resources Board, "Implementation Manual for the FY 2011-12 California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project, November 1, 2012	$70,000	Class 8 (not only line haul)	Alternate incremental costs for specific vehicles can be used on a case-by-case basis
81	California Air Resources Board, "HVIP Eligible Vehicles – Hybrid," Updated February 21, 2014	$40,000 to $50,000	Class 8: Eligible Hybrid Tractors	Kenworth, Freightliner, Navistar, & Peterbilt Tractors w/Eaton Hybrid System (voucher amounts half of incremental costs)

Diesel APU

Table 90. Reference Data for Line Haul Diesel APU

Class 8 Diesel APU

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$6,000 to $12,000	54, 59, 60	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Diesel engine, generator, particulate filter, and NOx trap. Diesel fuel consumption of 0.20 to 0.33 gal/hr.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Diesel APU

Reference Number	Reference	Value from Reference	Description	Additional Notes
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$8,000	Diesel APU: Diesel engine, generator, particulate filter, NOx trap	add $1,000 for DPF. Fuel Consumption of 0.20 to 0.33 gal/hr. Maintenance Cost of $400/yr
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$6,000 to $8,000	Auxiliary Power Unit	Emissions control needed in California. 0.2 to 0.3 gal/hr fuel use.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$7,499 to $8,100	Black Rock Systems	Heat/Cools Cab, 0.2 or 0.3 gal/hr
		$7,200 to $8,100	Comfort Master	Heat/Cools Cab, 0.25 gal/hr, 110V AC, Auto-on, Shorepower
		$6,500	Diamond Power Systems	Heat/Cools Cab, 0.26 gal/hr, 110V AC, Auto-on, Shorepower
		$7,000 to $9,000	Double Eagle Industries	Heat/Cools Cab, Heat Engine, 0.3 gal/hr, DC
		$6,999	Flying J	Heat/Cools Cab, Heat Engine, 110V AC, Auto-on, Shorepower
		$6,000 to $7,500	Frigette Truck Climate System	Heat/Cools Cab, 110V AC
		$6,900 to $7,750	Idlebuster	Heat/Cools Cab, Heat Engine, 110V AC, Auto-on, Shorepower
		$6,925	Kool-Gen	Heat(optional)/Cools Cab, 110V AC
		$7,500	Pony Pack	Heat/Cools Cab, Heat Engine, 0.2 gal/hr, DC
		$6,300	Rig Master Power	Heat/Cools Cab, Heat Engine, 0.2 gal/hr, 110V AC
		$5,995 to $6,500	Star Class	
		$8000 to $10000 (+$3000 DPF for CA)	Thermo King	Heat/Cools Cab, Heat Engine, 0.04 to 0.14 gal/hr, 110V AC, Auto-on
		$8,499	TRIDAKO Energy Systems	Heat/Cools Cab, Heat Engine, 0.4 gal/hr
		$6,000 to $7,000	Truck Gen	Heat/Cools Cab, 0.2 gal/hr, 110V AC, Shorepower
60	North American Council for Freight Efficiency, "Trucking Efficiency Summit." October 7, 2013 http://nacfe.org/wp-content/uploads/2013/10/Master-TE-Summit-Oct7-100313.pdf	$6,900 to $10,000	Preliminary Anti-Idling Estimate: Diesel APU	Heat/Cools Cab, Heat Engine
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	$8,000 to $12,000	Preliminary Anti-Idling Estimate: Diesel APU	Heat/Cools Cab, Heat Engine, 0.1 to 0.5 gal/hr. 7 to 18 HP engine. 110V AC to cab
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	$1,000	Residual value in 4 year old (MY2009)	

Battery APU

Table 91. Reference Data for Line Haul Battery APU

Class 8 Battery APU

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$4,000 to $8,800	59, 60, 61	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Cools with some electricity availability. Heating system not included.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Battery APU

Reference Number	Reference	Value from Reference	Description	Additional Notes
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$4,000	Battery-powered air-conditioning system	Battery, motor, vapor compression air conditioning components. 0.15 gal/hr, Maintenance Cost of $200/yr
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$3,000 to $8,000	Battery that requires recharge infrastructure	Heats and cools with some electricity availability (no diesel fuel consumption) Need recharge infrastructure
60	North American Council for Freight Efficiency, "Trucking Efficiency Summit." October 7, 2013 http://nacfe.org/wp-content/uploads/2013/10/Master-TE-Summit-Oct7-100313.pdf	$5,200 to $6,700	Preliminary Anti-Idling Estimate: Battery APU	Heat/Cools Cab, Heat Engine
61	Shorepower Technologies (formerly Shurepower) website accessed November 2013 http://www.shorepower.com/docs/Shorepower-capable-APUs.pdf	$3,495	Bergstrom Inc. www.nitesystem.com	10 hours of full operational use. It takes 4-6 hours to recharge.
61	Shorepower Technologies (formerly Shurepower) website accessed November 2013 http://www.shorepower.com/docs/Shorepower-capable-APUs.pdf	$6,895	Driver Comfort System www.drivercomfort.com	AC and Heat. 3000 watt inverter/charger, 270 amp alternator.
61	Shorepower Technologies (formerly Shurepower) website accessed November 2013 http://www.shorepower.com/docs/Shorepower-capable-APUs.pdf	$7,995	Idle Free Systems, LLC www.idlefree.net	10,000 BTU Dometic Air conditioner; Espar D-5 Hydronic Heater; Xantrex Prosine 2.0 Inverter/Charger; cab power/shore power kit Reefer Link System w/reefer alternator upgrade
61	Shorepower Technologies (formerly Shurepower) website accessed November 2013 http://www.shorepower.com/docs/Shorepower-capable-APUs.pdf		Kenworth Truck Company www.kenworth.com	Thermal capacity of 21,000 BTUs and requires 4-6 hours of charging to provide up to 10 hours of cooling in 95°, low-solar load environment.
61	Shorepower Technologies (formerly Shurepower) website accessed November 2013 http://www.shorepower.com/docs/Shorepower-capable-APUs.pdf	$1,600	Safer Corporation www.saferco.com	"Viesa," Evaporative Cooling System. does not provide heat or electrical power. Best in hot, dry climates, <60% humidity.
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	$8,500 to $8,800	Battery APU not including optional diesel fuel heater for heating	Used to power air conditioning and hotel loads. Heating system optional.

Fuel Fired Heater

Table 92. Reference Data for Line Haul Fuel Fired Heater

Class 8 Fuel Fired Heater

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$900 to $1,500	54, 59, 60	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Diesel fuel heater. Heats Cab, 0.04 to 0.06 gal/hr diesel fuel use. Maintenance cost: $110/yr

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Fuel Fired Heater

Reference Number	Reference	Value from Reference	Description	Additional Notes
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012.	$1,000 to $3,000	Idle Reduction Technology: Heater	Heats Cab, 0.2 to 0.3 gal/hr diesel fuel use
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$1,300	Cab Confort Technology Summary: Cab bunk heater	Heats Cab, 0.04 to 0.06 gal/hr diesel fuel use. Maintenance cost: $110/yr
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$900 to $1,200	Automotive Climate Control	Heats Cab, battery-powered fuel-fired heater, 1 gal/24 hr
		$1,000 to $3,000	Espar Heater System: Cab	Heats Cab, battery-powered fuel-fired heater, 1 gal/20 hr
		$1,000 to $3,000	Espar Heater System: Engine	Heats Engine, battery-powered fuel-fired heater, 1 gal/(4 to 6 hrs)
		$1,000 to $3,000	Webasto Product North America: Cab	Heats Cab, battery-powered fuel-fired heater, 1 gal/20 hr
		$1,000 to $3,000	Webasto Product North America: Engine	Heats Engine, battery-powered fuel-fired heater, (0.03 to 0.24 gal)/hr
60	North American Council for Freight Efficiency, "Trucking Efficiency Summit." October 7, 2013 http://nacfe.org/wp-content/uploads/2013/10/Master-TE-Summit-Oct7-100313.pdf	$500 to $1,600	Preliminary Anti-Idling Estimate: Diesel Fired Heater	Heats Cab, diesel fuel use.
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	$900 to $1,500	Diesel fuel-operated air heater	Heats Cab, diesel fuel use.

A/C System Improvements

Table 93. Reference Data for Class 2b&3 (Gasoline, Diesel) A/C System Improvements

Class 2b&3 Air Conditioning Improvements

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$135 to $500	28, 45, 54, 55, 75	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	Air Conditioning Improvements - Higher efficiency compressor, separate electric condensor fan to avoid use of engine-driven fan.

Baseline Engine:

Prior Technology:

Class 2b&3 Air Conditioning Improvements

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class 7 & 8 Truck Technologies	Electrical auxiliaries (air compressor, hydraulic pump, radiator fan). Stage 1
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,500	Class 7 & 8 Truck Technologies	Fuel-cell (with reformer) - operated auxiliaries (HVAC included). Stage 2
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Diesel Engine	Electricfy auxiliaries, such as air-conditioning compressor, air compressor, fans, hydraulic pump, and coolant pump, are gear- or belt-driven by truck base engine.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2000	5-8 L Gasoline Engine	Accessory Electrification — Electric Auxiliaries (alternator, air compressor, power steering pump, air cond, fan, fuel pump, water pump); in combination with hybrid or other vehicle electrification.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$70 to $90	Light Duty Vehicles	HVAC—variable stroke, increased efficiency (A/C system and reducing refrigerant leakage from the system at less than $110 to the consumer)
75	Vyas, A., L. Gaines, and R. Cuenca, "Evaluation of Electric Vehicle Production and Operating Costs", ANL/ESD-41, Nov. 1999	$135	Air-conditioning drive	Subcompact EV Powertrain Characteristics and Purchase Price

Table 94. Reference Data for Vocational (Gasoline, Diesel) A/C System Improvements

Class 4-6 Air Conditioning Improvements

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$135 to $500	28, 45, 54, 55, 75	6.2 V-8: gasoline PFI, fixed valve	2011$	2014 introduction	Air Conditioning Improvements - Higher efficiency compressor, separate electric condensor fan to avoid use of engine-driven fan.

Baseline Engine:
Prior Technology:

Class 4-6 Air Conditioning Improvements

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class 7 & 8 Truck Technologies	Electrical auxiliaries (air compressor, hydraulic pump, radiator fan). Stage 1
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,500	Class 7 & 8 Truck Technologies	Fuel-cell (with reformer) - operated auxiliaries (HVAC included). Stage 2
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Diesel Engine	Electricfy auxiliaries, such as air-conditioning compressor, air compressor, fans, hydraulic pump, and coolant pump, are gear- or belt-driven by truck base engine.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $2000	6-9L Diesel Engines	Accessory Electrification — Electric Auxiliaries (alternator, air compressor, power steering pump, air cond, fan, fuel pump, water pump); in combination with hybrid or other vehicle electrification.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$70 to $90	Light Duty Vehicles	HVAC—variable stroke, increased efficiency (A/C system and reducing refrigerant leakage from the system at less than $110 to the consumer)
75	Vyas, A., L. Gaines, and R. Cuenca, "Evaluation of Electric Vehicle Production and Operating Costs", ANL/ESD-41, Nov. 1999	$135	Air-conditioning drive	Subcompact EV Powertrain Characteristics and Purchase Price

Table 95. Reference Data for Line Haul A/C System Improvements

Class 8 Air Conditioning Improvements

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$135 to $500	28, 45, 54, 55, 75	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2014 introduction	Air Conditioning Improvements - Higher efficiency compressor, separate electric condensor fan to avoid use of engine-driven fan.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: Variable Valve Actuation (VVT + VVL), Engine Friction Reduction

Class 8 Air Conditioning Improvements

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class 7 & 8 Truck Technologies	Electrical auxiliaries (air compressor, hydraulic pump, radiator fan). Stage 1
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,500	Class 7 & 8 Truck Technologies	Fuel-cell (with reformer) - operated auxiliaries (HVAC included). Stage 2
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Diesel Engine	Electricfy auxiliaries, such as air-conditioning compressor, air compressor, fans, hydraulic pump, and coolant pump, are gear- or belt-driven by truck base engine.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1000 to $2000	11-15 Liter Engine Diesel	Accessory Electrification — Electric Auxiliaries (alternator, air compressor, power steering pump, air cond, fan, fuel pump, water pump); in combination with hybrid or other vehicle electrification.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$70 to $90	Light Duty Vehicles	HVAC—variable stroke, increased efficiency (A/C system and reducing refrigerant leakage from the system at less than $110 to the consumer)
75	Vyas, A., L. Gaines, and R. Cuenca, "Evaluation of Electric Vehicle Production and Operating Costs", ANL/ESD-41, Nov. 1999	$135	Air-conditioning drive	Subcompact EV Powertrain Characteristics and Purchase Price

Cab Insulation to Reduce A/C

Table 96. Reference Data for Class 2b&3 (Gasoline, Diesel) Cab Insulation to Reduce A/C

Class 2b&3 Cab Insulation to Reduce A/C

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$250 - $500	64,65,66	6.2 V-8: gasoline PFI, fixed valve	2011$	2015 Intro	Cab thermal insulation and improved glass glazing to reject sunload

Baseline Engine:

Prior Technology: None additional required

Class 2b&3 Cab Insulation to Reduce A/C

Reference Number	Reference	Value from Reference	Description	Additional Notes
64	http://shop.hushmat.com/k/search?q=peterbilt, accessed 12/4/2013	$200-$400	HushMat Ultra Sound Deadening and Thermal Insulation material	aftermarket price for truck cab insulation material (no install)
65	"An Evaluation of the Effects of Glass-Plastic Windshield Glazing in Passenger Cars", NHTSA Report Number DOT HS 808 062 November, 1993	$65 - $100	glass-plastic windshield glazing, auto application	initial cost expected to be manageable, but replacement cost significantly higher than convenitional auto glass
66	http://www.greencarcongress.com/2012/12/sabic-20121219.html, accessed 12/2013	n/a	glass-plastic windshield glazing, auto application	The Fiat 500L has already launched in Europe and is set to roll out in the United States in early 2013. The rear fixed side windows of the vehicle will be the first in the United States to use two-shot injection compression molding

Table 97. Reference Data for Vocational (Gasoline, Diesel) Cab Insulation to Reduce A/C

Class 4-6 Cab Insulation to Reduce A/C

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$250 - $500	64,65,66	6.2 V-8: gasoline PFI, fixed valve	2011$	2015 Intro	Cab thermal insulation and improved glass glazing to reject sunload

Baseline Engine:

Prior Technology: None additional required

Class 4-6 Cab Insulation to Reduce A/C

Reference Number	Reference	Value from Reference	Description	Additional Notes
64	http://shop.hushmat.com/k/search?q=peterbilt, accessed 12/4/2013	$200-$400	HushMat Ultra Sound Deadening and Thermal Insulation material	aftermarket price for truck cab insulation material (no install)
65	"An Evaluation of the Effects of Glass-Plastic Windshield Glazing in Passenger Cars", NHTSA Report Number DOT HS 808 062 November, 1993	$65 - $100	glass-plastic windshield glazing, auto application	initial cost expected to be manageable, but replacement cost significantly higher than convenitional auto glass
66	http://www.greencarcongress.com/2012/12/sabic-20121219.html, accessed 12/2013	n/a	glass-plastic windshield glazing, auto application	The Fiat 500L has already launched in Europe and is set to roll out in the United States in early 2013. The rear fixed side windows of the vehicle will be the first in the United States to use two-shot injection compression molding

Table 98. Reference Data for Line Haul Cab Insulation to Reduce A/C

Class 8 Cab Insulation to Reduce A/C

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$250 - $500	64, 65, 66, 78	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2015 Intro	Cab thermal insulation and improved glass glazing to reject sunload

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Cab Insulation to Reduce A/C

Reference Number	Reference	Value from Reference	Description	Additional Notes
64	http://shop.hushmat.com/k/search?q=peterbilt, accessed 12/4/2013	$200-$400	HushMat Ultra Sound Deadening and Thermal Insulation material	aftermarket price for truck cab insulation material (no install)
65	"An Evaluation of the Effects of Glass-Plastic Windshield Glazing in Passenger Cars", NHTSA Report Number DOT HS 808 062 November, 1993	$65 - $100	glass-plastic windshield glazing, auto application	initial cost expected to be manageable, but replacement cost significantly higher than convenitional auto glass
66	http://www.greencarcongress.com/2012/12/sabic-20121219.html, accessed 12/2013	n/a	glass-plastic windshield glazing, auto application	The Fiat 500L has already launched in Europe and is set to roll out in the United States in early 2013. The rear fixed side windows of the vehicle will be the first in the United States to use two-shot injection compression molding
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	no price provided		wall/window insulation can reduce heat/cool loads 34-36%

Air Compressor Improvements

Table 99. Reference Data for Line Haul Air Compressor Improvements

Class 8 Air Compressor Improvements

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$200 to $500	54, 55, 57, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2012 introduction	Viscous drive clutch, actuator pin-out on ECM, wiring

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Air Compressor Improvements

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Accessory Electrification -- Electric Auxiliaries (air comp, ps pump, air cond, fan, alt, water pump); in combination with upgrade to 42V electrical system or hybrid.
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$120	Improved Accessories	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$822	Improved Accessories — Level 1 (IACC1) (shown in package cost)	Included in pacakge with Auto 4VDV6 +EFR2 +ASL2 +LDB +IACC1 +EPS +Aero1 +LRRT1 +HEG +DCP +WR5% +6sp.
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$200 to $500	Variable displacement pumps, incremental improvements	Belt-driven mechanical accessories

Shore Power

Table 100. Reference Data for Line Haul Shore Power

Class 8 Shore Power

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$100 to $2,000	59, 60	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Heats and cools with electricity availability. No diesel fuel consumption. Requires recharge infrastructure.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF

Prior Technology:

Class 8 Shore Power

Reference Number	Reference	Value from Reference	Description	Additional Notes
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	$10 ($9,000 to $16,700 infrastructure cost)	Electrified parking space (single system)	Heating, cooling module on pedestal connected to window-mounted module (includes communications entertainment). Usage cost of $1.00/hr to $2.45/hr
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	($2,500 to $6,000 infrastructure cost)	Electrified parking space (dual system)	Onboard equipment (e.g., inverter/charger, electric heating/cooling device) powered by extension cord. Usage cost of $1/hr
59	National Research Council. "Review of the 21st Century Truck Partnership, Second Report." 2012. http://www.nap.edu/catalog.php?record_id=13288	~$100	Shore power	Heats and cools with electricity availability. No diesel fuel consumption. Requires recharge infrastructure
60	North American Council for Freight Efficiency, "Trucking Efficiency Summit." October 7, 2013 http://nacfe.org/wp-content/uploads/2013/10/Master-TE-Summit-Oct7-100313.pdf	$250 to $2,000	Preliminary Anti-Idling Estimate: Shorepower	Heat/Cools Cab, Heat Engine
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$125	Dual System: Philips and Temro	
		$200 to $2,000	Dual System: Shurepower	Service Fee: $0.50/hr
		$2,500	Dual System: Teleflex (Proheat)	
		$1,500 inverter/charger : $1,500 electric HVAC	Dual System: Xantrex	Service Fee: $2,500/space
			Single System: Craufurd Manufacturing	Service Fee: $8,550/space
		$10 adapter	Single System: IdleAire Technologies	Service Fee: $2.18/hr retail Service Fee: $1.85/hr fleet
78	North American Council for Freight Efficiency, "Confidence Report on Idle-Reduction Solutions," June 25, 2014	no price provided		AC power port (off-board AC power). Many variations in AC wiring systems. Difficult to show a range of prices.

Aero Bin III

Table 101. Reference Data for Line Haul Aero Bin III

Class 8 Aero Trailer Side Skirt (4 to 6 m)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$450 to $650	42, 45, 54, 58, 76, 80	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, partial Side Skirts trailer will be added cost

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Aero Trailer Side Skirt (4 to 6 m)

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,500	Trailer aero	Vehicle Profile Improvement II - Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$1,500	Trailer aero	front fairing/nose, side skirt, rear flaps
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $4000	Side skirts or belly box- va	Price range varies with length, flexibility, retractability, underside coverings, etc
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,500 to $2,000	Aerodynamic Technology Matrix	partial Skirts (4 to 6 m)
		$3,000 per trailer	Aerodynamic Technology Matrix	Smartway trailer – partial skirts + partial gap fairing or boat tail
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$700 to $1,100	High volume price ($700) including installation to low volume price ($1100)	Full skirts (7-9 m) at low volume price.
80	National Research Council. "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report." The National Academies Press Pre-Publication copy, 2014.	$750 and up	Skirt data for A,B,C,D combined.	Full Skirts on 53+ ft trailers. Installed price for trailer side skirts has decreased from $2,800 to less than $1,000

Class 8 Aero Boat Tail

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$800 to $1600	42, 45, 54, 58, 76, 80	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, boat tail trailer will be added cost

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Aero Boat Tail

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,500	Trailer aero	Vehicle Profile Improvement II - Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$1,500	Trailer aero	front fairing/nose, side skirt, rear flaps
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	300 to 500	cab Extender	
		$1,500 to $2,000	Boat tail -- structural or inflatable	17, 23 (structural), 26 (inflatable)
		$2,800 (inflatable)	Boat tail -- inflatable	17, 23 (structural), 26 (inflatable)
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,500 to $2,000	Aerodynamic Technology Matrix	Boat tail — structural or inflatable
		$3,000 per trailer	Aerodynamic Technology Matrix	Smartway trailer – partial skirts + partial gap fairing or boat tail
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$1,600	Low volume price including installation (high volume $1,000)	Boat tail — structural or inflatable
80	National Research Council. "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report." The National Academies Press Pre-Publication copy, 2014.	$800 and up	Trailer Tail	Smartway categories "trailer boat tails" and "advanced trailer end fairing."

Aero Bin IV and V

Table 102. Reference Data for Line Haul Aero Bin IV and V

Class 8 Aero Full Trailer Skirt (7 to 9 m)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$750 to $1100	42, 45, 54, 58, 76, 80	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, trailer will be added cost

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Aero Full Trailer Skirt (7 to 9 m)

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,500	Trailer aero	Vehicle Profile Improvement II - Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$1,500	Trailer aero	front fairing/nose, side skirt, rear flaps
		$2,250	Trailer aero	undercarriage flow treatment device (UFD)
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,600 to $2400	Side skirts or belly box-varying length	Price range varies with length, flexibility, retractability, underside coverings, etc
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$2,000 to $4,000	Aerodynamic Technology Matrix	Full Skirts (7 to 9 m)
		$800 to $1,000	Aerodynamic Technology Matrix	Partial Gap Fairing
		$3,000 per trailer	Aerodynamic Technology Matrix	Smartway trailer – partial skirts + partial gap fairing or boat tail
		$4,000 per trailer	Aerodynamic Technology Matrix	Full next-generation trailer aero – full skirts, boat tail, and full gap fairing
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$700 to $1,100	High volume price ($700) including installation to low volume price ($1100)	Full skirts (7-9 m) at low volume price.
80	National Research Council. "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report." The National Academies Press Pre-Publication copy, 2014.	$750 and up	Skirt data for A,B,C,D combined.	Full Skirts on 53+ ft trailers. Installed price for trailer side skirts has decreased from $2,800 to less than $1,000

Class 8 Aero Full Tractor Skirt

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1500 to $2000	42, 54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, Full tractor skirts including wheel covering

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Aero Full Tractor Skirt

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,500	Trailer aero	Vehicle Profile Improvement II - Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$2,750	Tractor Aero	radical cab streamlining
54	National Research Council. “Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles.” 2010.	$1,500 to $2,000	Chassis Skirts (aka, "chassis fairing", "fuel tank fairing") -- full length	Long Haul, sleeper cabs
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,500 to $2,000	Chassis Skirts (aka, "chassis fairing", "fuel tank fairing") -- full length	Long Haul, sleeper cabs

Class 8 Aero Gap Filler

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$650 to $1,000	42, 45, 54, 58, 76, 80	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, add full gap filler device

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Aero Gap Filler

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,500	Trailer aero	Vehicle Profile Improvement II - Closing and Covering of Gap Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$1,500	Trailer aero	front fairing/nose, side skirt, rear flaps
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$300 to $500	Cab Extender	Class 8 in 2012 time frame. 80-90% adoption rate
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$800 to $1,000	Aerodynamic Technology Matrix	Partial Gap Fairing
		$1,000 to $1,500	Aerodynamic Technology Matrix	Full Gap fairing
		$3,000 per trailer	Aerodynamic Technology Matrix	Smartway trailer – partial skirts + partial gap fairing or boat tail
		$4,000 per trailer	Aerodynamic Technology Matrix	Full next-generation trailer aero – full skirts, boat tail, and full gap fairing
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$700 to $1000	High volume price ($700) including installation to low volume price ($1000)	Gap reducers
80	National Research Council. "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report." The National Academies Press Pre-Publication copy, 2014.	$650 and up	Tractor-trailer gap reducer	

Aero on Regional Haul

Table 103. Reference Data for Aero on Regional Haul

Class 8 Aero on Regional Haul

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $1,300	42, 45, 54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Aero Bin III Tractor features will be baseline 2019, trailer will be added cost

Baseline Engine:

Prior Technology:

Class 8 Aero on Regional Haul

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$750	Trailer aero	Vehicle Profile Improvement I - Cab Top Deflector, Sloping Hood and Cab Side Flares Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$1,000	Front Fairing for Tractor Trailer	tractor trailer
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,300	Roof top deflector, day cab	day cabs only
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,000 to $1,300	Roof top deflector, day cab	day cabs only

Class 2b&3 Improved Aerodynamics

Table 104. Reference Data for Class 2b&3 (Gasoline, Diesel) Improved Aerodynamics

Class 2b&3 Improved Aerodynamics

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$60 to $500	54, 55, 28, 47	6.2 V-8: gasoline PFI, fixed valve, 6-speed AT	2011$	2014 introduction	Improved 2b & 3 Aerodynamics- Active grill shutters, belly pan under engine, belly pan under complete chassis, wheel well skirts

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Improved Aerodynamics

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$750	Trailer aero	Vehicle Profile Improvement I - Cab Top Deflector, Sloping Hood and Cab Side Flares Between Tractor and Trailer, Aerodynamic Bumper, Underside Air Baffles, and Wheel Well Covers
42	TIAX/UCS	$650-$1,000	Front Fairing/Nosecone	Straight Truck
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$400 to $500	Fuel Tank fairings	Class 3 -6
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,000	Box Skirts - (Laydon composites makes a modular design)	Class 3 -6
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $650	Cab side extension or Cab/Box Gap fairing	Class 3 -6
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$750	2010 Aero cab: aero mirrors, aero bumper, fuel tank fairings, streamlined shape	Class 3 -6
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$2,900	2012 Aero: roof deflector, rear-mounted frame extension in addition to 2010 aero cab	Class 3 -6
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$68	Aero Improvements - 10%	LD Truck V8
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$60 - $116	Vehicle Streamlining	Class 2b Van and Pickup—
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,300	Roof top deflector, day cab	day cabs only
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,000 to $1,300	Roof top deflector, day cab	day cabs only

Improved Transmissions

Table 105. Reference Data for Class 2b&3 (Gasoline) Improved Transmissions

Class 2b&3 Improved Transmissions (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$280 to $680	11, 28, 54, 55	6.2 V-8: gasoline PFI, fixed valve, 6-speed AT	2011$	2013 introduction	6-spd AT to 8-speed AT

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Improved Transmissions (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$638	8-spd AT	V8

Table 106. Reference Data for Class 2b&3 (Diesel) Improved Transmissions

Class 2b&3 Improved Transmissions (D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$750 to $1,000	11, 28, 54, 55	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	2013 introduction	6-spd AT to 8-speed AT

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Improved Transmissions (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$638	8-spd AT	V8

Table 107. Reference Data for Vocational (Gasoline) Improved Transmissions

Class 4-6 Improved Transmissions (G)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$500 to $1,000	11, 28, 54, 55	6.2 V-8: gasoline PFI, fixed valve, 6-speed AT	2011$	2013 introduction	6-spd AT to 8-speed AT

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Improved Transmissions (G)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$638	8-spd AT	V8

Table 108. Reference Data for Vocational (Diesel) Improved Transmissions

Class 4-6 Improved Transmissions (D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1,000 to $1,650	11, 28, 54, 55	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	2013 introduction	6-spd AT to 8-speed AT

Baseline Engine: 6.7L V-8 turbo diesel, high pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 4-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Improved Transmissions (D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$251	High Efficiency Gearbox	combined w. 6-speed auto with inmproved internals
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$638	8-spd AT	V8

Table 109. Reference Data for Line Haul Improved Transmissions

Class 8 Improved Transmissions

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1000 to $2600	11, 28, 54, 55	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF, 10-spd MT	2011$	2014 introduction	10-spd manual to 16-spd manual or automatic

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Improved Transmissions

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$750		Advanced transmission with lock-up, electronic controls, and reduced friction.
		$1,000	Advanced transmission	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$500 to $1,650	6-speed to 8-speed AT	Class 2b pickup and van technology matrix
		$1,000 to $1,650	6-speed to 8-speed AT	Class 3-6 box and bucket truck technology matrix
11	NHTSA: 49 CFR Parts 523, 531, 533, 534, 536 and 537: Average Fuel Economy Standards: Passanger Cars and Light Trucks MY2011: Final Rule	$140 to $280	4-speed to 6-speed	TABLE 3-3 Fuel Consumption Technology Matrix—Pickup Trucks
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$1,000	Advanced transmission	
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	2,100 to $2,600	Incresed 2 gears (6 to 8 on Refuse)	Increase in 2 gears, Line haul not ideintfied in this category
		$5,800	Tractor trailer	NAS Summary of Technologies for 2015-2020

Automated Manual Transmission

Table 110. Reference Data for Vocational (Gasoline, Diesel) AMT

Class 4-6 Automated Manual Transmission

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$700 to $1,400	54, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	2014 introduction	Eaton Ultrashift AMT or similar

Baseline Powertrain: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 6-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Automated Manual Transmission

Reference Number	Reference	Value from Reference	Description	Additional Notes
54 research notes	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$4,000 (Freightliner) to $9,500 (Volvo)	AMT/Optimized Shift Strategy	found large variation in price estimates amoung manufacturers
54 research notes	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$600	AMT/Optimized Shift Strategy Class 2b	found large variation in price estimates amoung manufacturers
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	4,500 to $5,700	AMT/Optimized Shift Strategy	+70 lbs
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	4,500 to $5,700	AMT/Optimized Shift Strategy	Tractor Trailer Application+70 lbs
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$700 to $1400	AMT/Optimized Shift Strategy	Class 2b&3 application

Table 111. Reference Data for Line Haul AMT

Class 8 Automated Manual Transmission

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$4,500 to $5,700	54, 55, 57	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF, 10-spd MT	2011$	2014 introduction	Eaton Ultrashift AMT or similar

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Automated Manual Transmission

Reference Number	Reference	Value from Reference	Description	Additional Notes
54 research notes	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$4,000 (Freightliner) to $9,500 (Volvo)	AMT/Optimized Shift Strategy	found large variation in price estimates amoung manufacturers
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	4,500 to $5,700	AMT/Optimized Shift Strategy	+70 lbs
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	4,500 to $5,700	AMT/Optimized Shift Strategy	+70 lbs

Dual Clutch Automatic

Table 112. Reference Data for Vocational (Gasoline, Diesel) Dual Clutch Automatic

Class 4-6 Dual Clutch Automatic (G,D)

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$1,800 to $3,600	54, 55, 58	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	2014 introduction	Dual Clutch automatic tranmission with 10 gears

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 6-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Dual Clutch Automatic (G,D)

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$15,000	10-spd Automatic	Tractor Trailer Application+200 lbs
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$1,800	8-speed automatic transmission, reduced driveline friction, aggressive shift logic	Class 3 to Class 6 Straight Box Truck
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$15,000	Automatic Transmission	Tractor Trailer Application+200 lbs

Table 113. Reference Data for Line Haul Dual Clutch Automatic

Class 8 Dual Clutch Automatic

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$15,000 to $20,000	54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF, 10-spd MT	2011$	2014 introduction	Dual Clutch automatic tranmission with 16 gears

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 10-speed MT

Prior Technology: None additional required

Class 8 Dual Clutch Automatic

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$15,000	10-spd Automatic	+200 lbs
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$15,000	Automatic Transmission	+200 lbs

Low Rolling Resistance Tires

Table 114. Reference Data for Class 2b&3 (Gasoline, Diesel) LRR Tires

Class 2b&3 LRR Tires (G,D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$6 to $44	28, 55, 57	6.2 V-8: gasoline PFI	2011$	continuous improvement	LRR tires

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology: None additional required

Class 2b&3 Low Rolling Resistance Tires

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$180	V8 Gasoline	LRR Tires 2004 introduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$53	LRR	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$6	Level 1 LRR	40,000 Maintenance interval
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$44	Level 2 LRR	40,000 Maintenance interval

Table 115. Reference Data for Vocational (Gasoline, Diesel) LRR Tires

Class 4-6 LRR Tires (G,D)

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$6 to $44	28, 55, 57	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	continuous improvement	LRR tires

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 6-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Low Rolling Resistance Tires

Reference Number	Reference	Value from Reference	Description	Additional Notes
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$180	V8 Gasoline	LRR Tires 2004 introduction
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$53	LRR	
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$6	Level 1 LRR	40,000 Maintenance interval
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$44	Level 2 LRR	40,000 Maintenance interval

Table 116. Reference Data for Line Haul LRR Tires

Class 8 LRR Tires

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$25 to $35	28, 42, 45, 57	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	LRR tires

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Low Rolling Resistance Tires

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$30/tire	per tire price	assumes steel dualies
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$550	total incremental	assumes steel dualies
42	TIAX/UCS	$550	total incremental	assumes steel dualies
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$550		
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$6	Level 1 LRR	40,000 Maintenance interval
		$44	Level 2 LRR	40,000 Maintenance interval

Single Wide Tires

Table 117. Reference Data for Line Haul Single Wide Tires

Class 8 Single Wide Tires

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$90 to $192	7,28,42, 47, 54, 80	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Single Wide Low Rolling Resistance Tires, including compatible rims

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Single Wide Tires

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$225	per wheel and tire	Wide range of cost estimates: Freightliner has $900 per tractor; Navistar says $2,000/per vehicle; Volvo has $750/tire upcharge; Smartway claims cost-neutral compared to duals. WBS Tires, low rolling resistance
7	NESCCAF, ICCT, Southwest Research Institute, and TIAX. "Reducing Heavy-Duty Long Haul Combination Truck Fuel Consumption and CO2 Emissions." Washington, D.C.: International Council on Clean Transportation (ICCT). October 2009.	$1,120	per vehicle	16 tires and wheels become 8 (excluding the front axle).
42	TIAX/UCS	$1070 to $1210	Tractor Trailer Low-Rolling-Resistance Tires or Super Single	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$700	Super Single	Excluding the front axle.
80	National Research Council. "Reducing the Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: First Report." The National Academies Press Pre-Publication copy, 2014.	$360	Wide base single tires with Ferrous Wheel	Tandem Cost
		$768	Wide base single tires with Aluminum Wheel	Tandem Cost

Automated Tire Inflation

Table 118. Reference Data for Vocational (Gasoline, Diesel) ATI

Class 4-6 Automated Tire Inflation System

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$400 to $1200	54, 55, 57, 58	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	2014 introduction	Automated Tire Inflation systems continually monitor and adjust the level of pressurized air in tires.

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 6-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Automated Tire Inflation System

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$300 to $400	trailer only	
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$4000 to $5000	tractor	
3, 4, 5, 7	TIAX site visits during research for National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$900 to $1,000	Tire monitoring system	steel std duals
42	TIAX/UCS	$900	tractor + trailer	
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$700 to $1,000	Trailer only (700 for high volume and 1000 for low volume)	Automatic tire inflation system ($750-$1000 for tire pressure monitoring system)
77	Brady, S., D. Van Order, and A. Sharp, "Advanced Sensors and Applications: Commercial Motor Vehicle Tire Pressure Monitoring and Maintenance," US DOT Federal Motor Carrier Safety Administration report #FMCSA-RRT-13-021, February 2014	$750	Trailer only	Automatic tire inflation system ($785 for tractor tire pressure monitoring system)

Table 119. Reference Data for Line Haul ATI

Class 8 Automated Tire Inflation System

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$750 to $1535	42, 54, 76, 77	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	2014 introduction	Automated Tire Inflation systems continually monitor and adjust the level of pressurized air in tires.

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Automated Tire Inflation System

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$300 to $400	trailer only	
		$4000 to $5000	tractor	
42	TIAX/UCS	$900	tractor + trailer	
76	Sharpe, B., and M. Roeth, "Costs and Adoption Rates of Fuel-Saving Technologies for Trailers in the North American On-Road Freight Sector", International Council on Clean Transportation and North American Council for Freight Efficiency report, February 2014	$700 to $1,000	Trailer only (700 for high volume and 1000 for low volume)	Automatic tire inflation system ($750-$1000 for tire pressure monitoring system)
77	Brady, S., D. Van Order, and A. Sharp, "Advanced Sensors and Applications: Commercial Motor Vehicle Tire Pressure Monitoring and Maintenance," US DOT Federal Motor Carrier Safety Administration report #FMCSA-RRT-13-021, February 2014	$750	Trailer only	Automatic tire inflation system ($785 for tractor tire pressure monitoring system)

Weight Reduction

Table 120. Reference Data for Class 2b&3 Weight Reduction

Class 2b&3 Weight Reduction

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$1000 to $3000	28,42, 45, 58, 69	6.2 V-8: gasoline PFI	2011$	continuous improvement	Weight Reducion of 500 lbs. with the use of advanced materials

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology:

Class 2b&3 Weight Reduction

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$4,770	Material substitution—1,000 lb.	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,300	Material substitution—5% improvement	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$2,000	lightweight materials	3000 lbs reduction
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,000 - $2,000	class 2b Materials substitution - Weight Reduction - 5% , $2 to $4/lb	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$2,000 - $4,000	tractor trailer weight reduction 470- 940 lbs: $4-$8/lbs	

Table 121. Reference Data for Vocational Weight Reduction

Class 4-6 Weight Reduction

Item	Cost	Reference Number	Baseline	Cost Basis	Volume Assumptions	Technology Content
System cost	$4000 to $8000	28,42, 45, 58, 69	6.2 V-8: gasoline PFI	2011$	continuous improvement	Weight Reducion of 1000 lbs. with the use of advanced materials

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission

Prior Technology:

Class 4-6 Weight Reduction

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$4,770	Material substitution — 1,000 lb.	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$1,300	Material substitution — 5% improvement	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$2,000	lightweight materials	3000 lbs reduction
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$1,000 - $2,000	Class 2b Materials substitution - Weight Reduction - 5% , $2 to $4/lb	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$4,000 - $8,000	Class 3-6 Box and bucket reduction per 1000 lbs: $4-$8/lbs	

Table 122. Reference Data for Line Haul Weight Reduction

Class 8 Weight Reduction

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$8000 to $16000	54, 45, 58, 69	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Weight Reduction of 2000 lbs. with the use of advanced materials

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 Weight Reduction

Reference Number	Reference	Value from Reference	Description	Additional Notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$13,500	Material substitution — 2,500 lb.	
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$2,000	Lightweight materials	3000 lbs reduction
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$8,000 - $16,000	Tractor trailer weight reduction 1,000- 2,000 lbs: $4-$8/lbs	
69	"Assessment of Fuel Economy Technologies for Medium- and Heavy- Duty Vehicles", TIAX report Report to National Academy of Sciences, November 2009	$8,000 - $16,000	Tractor trailer weight reduction 1,000- 2,000 lbs: $4-$8/lbs	

6x2 Tractors

Table 123. Reference Data for Line Haul 6x2 Tractors

Class 8 6x2 Axle Configuration

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$300 to $2,000	55, 58, 67, 68	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Single drive axle instead of tandem drive, application to most applications except off-road for traction reasons. 6x2 versus 6x4 axle set-up

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology:

Class 8 6x2 Axle Configuration

Reference Number	Reference	Value from Reference	Description	Additional Notes
55	National Research Council. "Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy." 2011.	$200-$300	Single drive axle	
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$200-$300	Single drive axle	
67	North American Council for Freight Efficiency, "Confidence Report on 6x2 Axles," January 13, 2014	$1,000 - $2,000	"Dead axle" 6x2 compared to 6x4	6x2 may eventually be cost-neutral compared to 6x4 in the future.
67	North American Council for Freight Efficiency, "Confidence Report on 6x2 Axles," January 13, 2014	Late MY ($11,000), MY07-09 ($5,500), MY04-06 $700	Resale value of 6x2 tractors when compared to 6x4 tractors.	6x2 may have lower resale in many cases.
68	http://www.truckinginfo.com/channel/fuel-smarts/article/story/2013/05/rise-of-the-6x2.aspx, accessed 11/2013	($5,500)	residual value of 6x2 tractors when compared to 6x4 tractors in todays market	

Chassis Friction Reduction & Improved Lube

Table 124. Reference Data for Class 2b&3 (Gasoline, Diesel) Chassis Friction Reduction & Improved Lube

Class 2b&3 Low Friction Axles & Lubricants

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$100 to $400	45, 28, 42, 54, 57, 58	6.2 V-8: gasoline PFI	2011$	continuous improvement	Synthetic lube vs. standard, most efficient axles vs. standard

Baseline Engine: 6 to 8L gasoline engine, naturally aspirated, port fuel injection; 4-spd automatic transmission
Prior Technology: None additional required

Class 2b&3 Low Friction Axles & Lubricants

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Transmission Friction Reduction through Low-Viscosity Transmission Lubricants	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class7 & 8	Internal friction reduction through better lubricants and improved bearings.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	0 to $500	5-8L Gasoline Engine	research notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$110 to $500	Reduced Friction	Tractor Trailer
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$6	Low Friction Lub	Engine oil Only
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$110 to $500	Reduce friction - lubricants, bearings, etc	Continuous Improvement - 5-8L Gasoline Engine

Table 125. Reference Data for Vocational (Gasoline, Diesel) Chassis Friction Reduction & Improved Lube

Class 4-6 Low Friction Axles & Lubricants

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$100 to $400	45, 28, 42, 54, 57, 58	6.7L V8 Turbo Diesel, High Pressure direct inject, 6-speed AT	2011$	Continuous Improvement	Synthetic lube vs. standard, most efficient axles vs. standard

Baseline Engine: 6.7L V8 Turbo Diesel, High pressure common rail fuel injection, direct inject; multi-stage turbocharger; cooled EGR + DPF; 6-spd automatic transmission

Prior Technology: None additional required

Class 4-6 Low Friction Axles & Lubricants

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Transmission Friction Reduction through Low-Viscosity Transmission Lubricants	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class7 & 8	Internal friction reduction through better lubricants and improved bearings.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	0 to $500	5-8L Gasoline Engine	research notes
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$110 to $500	Reduced Friction	Tractor Trailer
57	National Highway Traffic Safety Administration. "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards." 49 CFR Parts 523, 531, 533, et al. and 600, final rule.	$6	Low Friction Lub	Engine oil Only
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	$110 to $500	Reduce friction - lubricants, bearings, etc	Continuous Improvement - 5-8L Gasoline Engine

Table 126. Reference Data for Line Haul Chassis Friction Reduction & Improved Lube

Class 8 Low Friction Axles & Lubricants

Item	Incremental Price	Reference Number	Baseline	Price Basis	Volume Assumptions	Technology Content
System cost	$100 to $400	11, 28, 42, 54, 58	11 to 15L diesel engine, DI; turbo; cooled EGR + SCR, DPF	2011$	continuous improvement	Synthetic lube vs. standard, most efficient axles vs. standard

Baseline Engine: 11 to 15L diesel engine, direct inject; multi-stage turbocharger; cooled EGR + SCR, DPF; 20 to 23 Bar BMEP

Prior Technology: None additional required

Class 8 Low Friction Axles & Lubricants

Reference Number	Reference	Value from Reference	Description	Additional Notes
45	Frey, Kuo, "Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation," NC State University prepared for U.S. DOT, October 2007 and references within	$500	Transmission Friction Reduction through Low-Viscosity Transmission Lubricants	
28	Vyas, A., C. Saricks, and F. Stodolsky. "The Potential Effect of Future Energy-Efficiency and Emissions-Improving Technologies on Fuel Consumption of Heavy Trucks." Argonne National Laboratory. August 2002.	$500	Class 7 & 8	Internal friction reduction through better lubricants and improved bearings.
54	National Research Council. "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles." 2010.	$100 to $400	5-8L Gasoline Engine	Packaged with all Engine Friction Reduction
		$0 to $1,000	Reduced Friction	Tractor Trailer
58	National Highway Traffic Safety Administration. "Factors and Considerations for Establishing a Fuel Efficiency Regulatory Program for Commercial Medium- and Heavy-Duty Vehicles." October 2010.	0 to $500	Reduce friction - lubricants, bearings, etc	Continuous Improvement - Same cost for 6-9 L Diesel and 11-15 L Diesel

May 2015

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

Message

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 7/14/2015 5:05:12 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]
Subject: Re: Time for a call this afternoon?

Brian,

Does 1:15 work? What number should I call you at?

Thanks
Bill

Bill Charmley
Assessment and Standards Division
Office of Transportation and Air Quality
National Vehicle & Fuel Emissions Laboratory
US Environmental Protection Agency
Ann Arbor, Michigan
Desk phone 734-214-4466
Mobile phone 734-545-0333
Email charmley.william@epa.gov

> On Jul 14, 2015, at 11:32 AM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:
>
> How about 1:00, 2:00 or 2:30 today?
>
>
> -----Original Message-----
> From: Charmley, William [mailto:charmley.william@epa.gov]
> Sent: Tuesday, July 14, 2015 10:07 AM
> To: Brian C Mormino
> Subject: Time for a call this afternoon?
>
> Brian,
>
> Do you have time for a call this afternoon to catch up on a few things?
>
> Thanks
> Bill
>
>
> Bill Charmley
> Assessment and Standards Division
> Office of Transportation and Air Quality National Vehicle & Fuel Emissions Laboratory US Environmental Protection Agency Ann Arbor, Michigan Desk phone 734-214-4466 Mobile phone 734-545-0333 Email charmley.william@epa.gov

Appointment

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 2/10/2015 3:48:13 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]

Subject: Accepted: FW: EPA & CMI Call
Location: US toll-free Conference Code / Ex. 6

Start: 2/11/2015 7:00:00 PM
End: 2/11/2015 8:00:00 PM
Show Time As: Busy

Message

From: Charmley, William [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FB1828FB00AF42FFB68B9E0A71626D95-CHARMLEY, WILLIAM]
Sent: 1/21/2015 1:53:19 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]
Subject: Re: Time for a quick chat about Friday

Brian,

I will try, but may not get to you until tomorrow morning, or perhaps this evening.

Thanks
Bill

Sent from my BlackBerry 10 smartphone on the Verizon Wireless 4G LTE network.

From: Brian C Mormino
Sent: Wednesday, January 21, 2015 8:09 AM
To: Charmley, William
Subject: Time for a quick chat about Friday

Bill, I just left you a voicemail on your cell phone. I called so that we could talk in advance of the meeting that we have in DC on Friday with Chris. Please let me know when you have a few minutes to talk today.

Thanks,

Brian

Appointment

From: EMA [ema@emamail.org]
Sent: 4/1/2016 7:31:51 PM
To: EMA [ema@emamail.org]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: EMA - April 15, 2016, Conference Call with EPA – Web Meeting Link
Attachments: 2016 04 15 AS Conference Call with EPA - Web Meeting Link.pdf
Location: Dial-In# Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 4/15/2016 6:00:00 PM
End: 4/15/2016 7:00:00 PM
Show Time As: Busy

	Aerodynamics Subcommittee
TO:	Angela Cullen, EPA Prashanth Gururaja, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	April 15, 2016
RE:	**April 15, 2016, Conference Call with EPA – Web Meeting Link**

Please join this conference call of EPA and EMA's Aerodynamics Subcommittee. Following our meeting yesterday, the purpose of the call is to review the CdA calculation elements for the GHG Phase 2 rule. In advance of the call, we will circulate a draft list of the elements to be included in a MATLAB script.

Following is the call-in information:

DATE: Friday, April 15, 2016
TIME: 1:00 p.m. (Chicago time)
DIAL IN #: Conference Code / Ex. 6
CONFERENCE ID: Conference Code / Ex. 6
CHAIR: Tim Blubaugh

To join the web meeting, please click on the link below:

Conference Code / Ex. 6

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
personal phone / Ex. 6 (312) 929-1975 fax
tblubaugh@emamail.org

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www.truckandenginemanufacturers.org

TO: Aerodynamics Subcommittee
Angela Cullen, EPA
Prashanth Gururaja, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: April 15, 2016

RE: **April 15, 2016, Conference Call with EPA – Web Meeting Link**

Please join this conference call of EPA and EMA's Aerodynamics Subcommittee. Following our meeting yesterday, the purpose of the call is to review the CdA calculation elements for the GHG Phase 2 rule. In advance of the call, we will circulate a draft list of the elements to be included in a MATLAB script.

Following is the call-in information:

DATE: Friday, April 15, 2016
TIME: 1:00 p.m. (Chicago time)
DIAL IN #: Ex. 6 Personal Privacy (PP)
CONFERENCE ID: Ex. 6 Personal Privacy (PP)
CHAIR: Tim Blubaugh

To join the web meeting, please click on the link below:

Ex. 6 Personal Privacy (PP)

If you have any questions or comments, please do not hesitate to contact me.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 2/10/2015 2:40:34 PM
To: Brian C Mormino [brian.c.mormino@cummins.com]

Subject: FW: EPA & CMI Call
Location: US toll-free Conference Code / Ex. 6

Start: 2/11/2015 7:00:00 PM
End: 2/11/2015 8:00:00 PM
Show Time As: Busy

-----Original Appointment-----
From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Tuesday, February 10, 2015 8:32 AM
To: Brian C Mormino; Jackie M Yeager; Spears, Matthew; Zhang, Houshun; Charmley, William; Gary C Salemme
Subject: EPA & CMI Call
When: Wednesday, February 11, 2015 2:00 PM-3:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: US toll-free Conference Code / Ex. 6

Appointment

From: EMA [ema@emamail.org]
Sent: 3/22/2016 9:19:23 PM
To: EMA [ema@emamail.org]; Cullen, Angela; Timothy A. Blubaugh

Subject: EMA - March 24, 2016, Web Meeting
Attachments: 2016 03 24 AS Web Meeting with EPA.pdf
Location: Dial-In# Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 3/24/2016 5:30:00 PM
End: 3/24/2016 7:00:00 PM
Show Time As: Busy

TO:	Aerodynamics Subcommittee Angela Cullen, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	March 22, 2016
RE:	**March 24, 2016, Web Meeting**

The purpose of this web meeting is to discuss aerodynamic issues with the GHG Phase 2 rule. Following is the call-in information:
DATE: Thursday, March 24, 2016
TIME: 12:30 p.m. (Chicago time)
DIAL IN #: Conference Code / Ex. 6
CONFERENCE ID: Conference Code / Ex. 6
CHAIR: Tim Blubaugh

To join the web meeting, please click on the link below:

Conference Code / Ex. 6

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
personal phone / Ex. 6 (312) 929-1975 fax
tblubaugh@emamail.org

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TO: Aerodynamics Subcommittee
Angela Cullen, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: March 22, 2016

RE: **March 24, 2016, Web Meeting**

The purpose of this web meeting is to discuss aerodynamic issues with the GHG Phase 2 rule. Following is the call-in information:

DATE:	Thursday, March 24, 2016
TIME:	12:30 p.m. (Chicago time)
DIAL IN #:	Ex. 6 Personal Privacy (PP)
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

To join the web meeting, please click on the link below:

Ex. 6 Personal Privacy (PP)

If you have any questions or comments, please do not hesitate to contact me.

91444_1

Appointment

From: EMA [ema@emamail.org]
Sent: 3/15/2016 2:50:47 PM
To: EMA [ema@emamail.org]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: EMA - March 15, 2016, Conference Call with EPA - Web Meeting
Attachments: 2016 03 15 AS Conference Call with EPA.pdf
Location: Dial-In#: Conference Code / Ex. 6 ; Chair: Tim Blubaugh

Start: 3/15/2016 3:00:00 PM
End: 3/15/2016 4:00:00 PM
Show Time As: Tentative

PLEASE NOTE:
EPA has provided the following web meeting access to today's conference call to view slides they have prepared. Please use the call-in number below for the audio connection.

Conference Code / Ex. 6

TO:	Aerodynamics Subcommittee Angel Cullen, EPA Prashanth Gururaja, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	February 25, 2016
RE:	**March 15, 2016, Conference Call with EPA**

Please join this conference call of EMA's Aerodynamics Subcommittee and EPA. Following our February 24th meeting in Ann Arbor, the primary purpose of the call is to discuss the aerodynamic baselines for the Phase 1 and Phase 2 GHG rules.

Following is the call-in information:

DATE: Tuesday, March 15, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Conference Code / Ex. 6
CONFERENCE ID Conference Code / Ex. 6
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
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tblubaugh@emamail.org

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TO: Aerodynamics Subcommittee
Angel Cullen, EPA
Prashanth Gururaja, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: February 25, 2016

RE: **March 15, 2016, Conference Call with EPA**

Please join this conference call of EMA's Aerodynamics Subcommittee and EPA. Following our February 24th meeting in Ann Arbor, the primary purpose of the call is to discuss the aerodynamic baselines for the Phase 1 and Phase 2 GHG rules.

Following is the call-in information:

DATE:	Tuesday, March 15, 2016
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Ex. 6 Personal Privacy (PP)
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

91138_1

Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/9/2016 2:30:10 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Brian C Mormino [brian.c.mormino@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Manik Narula [manik.narula@cummins.com]

Subject: Cummins/EPA call on Phase 2 cycle average map
Attachments: Joining Skype for Business Meetings (External).pdf
Location: US toll-free Conference Code / Ex. 6 r Gary's office at CTC

Start: 2/17/2016 6:00:00 PM
End: 2/17/2016 7:00:00 PM
Show Time As: Busy

Recurrence: (none)

Follow up to our cycle average map discussion on 1/29
Agenda:

1. Review of issues - Cummins
2. Testing update - Cummins, EPA
3. Generic vehicle definition - Cummins

Teleconference call-in number:

US toll-free Conference Code / Ex. 6
Access code
Skype information:
Link for non-Cummins attendees (see additional instructions in the attachment):

Join Skype Meeting (Web Guest)

Link for Cummins attendees:

Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help
Audio for this Skype for Business meeting is not available. When prompted, please select "Don't Join Audio". Use a phone to call the conference number provided in this invitation.

Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 1/29/2016 1:55:05 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Anand Puranik; Zhang, Houshun; Spears, Matthew; Sanchez, James; Brian C Mormino; Moulis, Charles; Charmley, William; Manik Narula; Gary C Salemme; Cullen, Angela

Subject: Cummins/EPA meeting
Location: 2000 Traverwood Drive, Ann Arbor, MI

Start: 1/29/2016 2:00:00 PM
End: 1/29/2016 5:00:00 PM
Show Time As: Busy

Discuss Phase 2 GHG

Appointment

From: EMA [ema@emamail.org]
Sent: 11/20/2015 10:10:45 PM
To: EMA [ema@emamail.org]; Cullen, Angela; Gururaja, Prashanth; Joshua P. Kehs - PACCAR Inc (Joshua.Kehs@PACCAR.com); Peter Kilcline (Peter.Kilcline@PACCAR.com); Hunkler, Matthew D; Cortney Guzlas (Cortney.Guzlas@Navistar.com); Raja Sengupta (raja.sengupta@volvo.com); David Kayes (david.kayes@daimler.com); Gerald Freitag (Gerald.Freitag@Daimler.com); Timothy A. Blubaugh; Jed R. Mandel

Subject: EMA - November 30, 2015, Conference Call – Aerodynamic Drag
Attachments: 2015 11 30 Conference Call - Aerodynamic Drag.pdf
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 11/30/2015 4:00:00 PM
End: 11/30/2015 5:00:00 PM
Show Time As: Busy

When: Monday, November 30, 2015 10:00 AM-11:00 AM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh
Note: The GMT offset above does not reflect daylight saving time adjustments.
~~*~*~*~*~*~*~*~*

TO:
Angela Cullen, EPA
Prashanth Gururaja, EPA
Joshua Kehs, PACCAR
Peter Kilcline, PACCAR
Matt Hunkler, Navistar
Cortney Guzlas, Navistar
Raja Sengupta, Volvo
Dave Kayes, Daimler
Gerald Freitag, Daimler

FROM: Timothy A. Blubaugh

DATE: November 20, 2015

RE: **November 30, 2015, Conference Call – Aerodynamic Drag**

Following our recent conversations, we are convening this conference call to discuss aerodynamic drag calculation methodologies. During the call, the participants will begin considering the merits of different methods of analyzing coastdown test data to determine a vehicle's C_DA.

Following is the call-in information:

DATE: Monday, November 30, 2015
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Conference Code / Ex. 6
CONFERE
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association

333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
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TO: Angela Cullen, EPA
Prashanth Gururaja, EPA
Joshua Kehs, PACCAR
Peter Kilcline, PACCAR
Matt Hunkler, Navistar
Cortney Guzlas, Navistar
Raja Sengupta, Volvo
Dave Kayes, Daimler
Gerald Freitag, Daimler

FROM: Timothy A. Blubaugh

DATE: November 20, 2015

RE: **November 30, 2015, Conference Call – Aerodynamic Drag**

Following our recent conversations, we are convening this conference call to discuss aerodynamic drag calculation methodologies. During the call, the participants will begin considering the merits of different methods of analyzing coastdown test data to determine a vehicle's C_DA.

Following is the call-in information:

DATE:	Monday, November 30, 2015
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Ex. 6 Personal Privacy (PP)
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/13/2016 7:43:53 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Draft Agenda
Attachments: 2016 04 15 AS - Draft Conference Call Agenda.pdf

Hi Angela,

During our March 31st meeting in Ann Arbor, we agreed to schedule a follow-up conference call this Friday at 1:00 p.m. (Chicago time). Attached is a draft agenda for the call with what I believe we agreed to discuss. Please let me know your thoughts about the agenda before I circulate it to my members.

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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GHG Phase 2 Aerodynamics
Conference Call
April 15, 2016
1:00 p.m. (Chicago time)

Ex. 6 Personal Privacy (PP)

DRAFT AGENDA

I. Confirm CdA Calculation Write-Up

II. High-Roof Day Cab Baseline and Bins

  A. Results of analyses of Truck 2

  B. Results of 3rd day cab tractor coastdowns

III. Mid- and Low-Roof Baselines and Bins

IV. Other Issues

V. Next Steps

91955_1

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 7/1/2016 7:17:31 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Peter Kilcline (Peter.Kilcline@PACCAR.com) [Peter.Kilcline@PACCAR.com]; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]
Subject: Coastdown Wind Limits
Attachments: EMA Coastdown Wind Limit Recommendations 01Jul16.pdf

Angela,

Following our conversation today, attached is a document with analysis and recommendations for the allowable ambient wind conditions for coastdown testing for the GHG Phase 2 rule. Considering a low-speed portion of the coastdown test being from 20 to 10 mph, we believe that during testing the longitudinal wind should not should not exceed 5 mph and the crosswind should not exceed 4 mph.

Could we have Prashanth and Peter connect first thing next week to discuss this? Additionally, we have some thoughts about the open parameters (a & b) in the SEA confidence interval equation that they should discuss.

Thanks!

Tim

Timothy A. Blubaugh
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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/30/2016 10:09:02 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: EMA Meetings
Attachments: AERO Stringency.pdf

Flag: Follow up

Hi Angela,

Attached is an updated version of the slide. The old one included C_dA numbers that were based on outdated $F_{alt\text{-}aero}$ values. Can you use this?

Additionally, I would like to talk with you to follow-up on a couple issues we discussed during our last meeting in Ann Arbor. Is there a time tomorrow when I could call you?

Thanks,

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, June 29, 2016 9:46 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Subject: FW: EMA Meetings

Tim,

May I use slide 4 from the presentation in the RIA or is this considered CBI?

Thank you,
Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Monday, July 27, 2015 2:38 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Cc: Cullen, Angela <cullen.angela@epa.gov>
Subject: EMA Meetings

Hi Matt,

Thanks again to you and your staff for such a productive meeting last week. Everyone on our end seems to be pleased with the discussions we had, and they are energized about moving forward on the issues. As we discussed, attached are the back-up slides that we used during the meeting. Also attached is an electronic version of the agenda.

Speaking of the positive energy, I wanted to try to nail down some of the logistics for the upcoming meetings. Please let me know your thoughts on the timing of the meetings on August 25th and 26th. In case you don't yet have any strong opinions, here are mine. How about if we go from 10:00 a.m. until 5:00 p.m. on Tuesday, August 25th, and from 8:00 a.m. until 3:00 p.m. on Wednesday? Additionally, my thinking is that on Tuesday we should discuss all of the "priority issues," and on Wednesday focus on the aerodynamic topics. Let me know your thoughts. Finally, let me know if we need to do anything on our end to schedule next week's WebEx on constant speed testing.

Best regards,

Tim

Timothy A. Blubaugh
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Aero Stringency

Impossible to reach Bins VI/VII with Phase 2 trailer

Truck & Engine Manufacturers Association®

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 3/30/2016 9:48:12 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Cummins N2O Data question

Thanks

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, March 30, 2016 5:11 PM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: Cummins N2O Data question

Hi Jackie,

Thank you for the feedback on the N2O data. We are in the process of correcting the data that we sent to you. I will let you know if there are any further questions after we review the corrected set of information.

I tried to get to Bill before the EMA meeting, but maybe he did not see my email since he was already on his way to California at the time.

Angela

From: Jackie M Yeager [mailto:jackie.m.yeager@cummins.com]
Sent: Wednesday, March 30, 2016 4:31 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Cc: Matthew Psota <matthew.psota@cummins.com>
Subject: RE: Cummins N2O Data question

Hi Angela,

Brian Mormino of Cummins participated in an EMA meeting with Bill Charmley yesterday where Bill mentioned EPA's need for information from manufacturers on N2O levels. I just wanted to follow up with you to check if the response we provided below is sufficient. Please let us know if you need further details.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Monday, March 28, 2016 1:44 PM
To: 'Cullen, Angela' <cullen.angela@epa.gov>
Cc: Matthew Psota <matthew.psota@cummins.com>
Subject: RE: Cummins N2O Data question

Angela,

The chart you sent is not using the same data to compare the two model years. It is showing cert results for MY 2015 and FELs for MY 2016, so it is not an "apples to apples" comparison. The MY 2015 and MY 2016 engine N2O levels are similar.

Let us know if you have further questions.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, March 16, 2016 4:27 PM
To: 'Cullen, Angela' <cullen.angela@epa.gov>
Subject: RE: Cummins N2O Data question

Hi Angela,

I'll have to check with some folks here on what changed between 2015 and 2016 and get back to you. You are correct that we are using the Phase 1 OBD-alignment provisions.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, March 16, 2016 3:57 PM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: Cummins N2O Data question

Hi Jackie,

We've been taking a closer look at N2O emissions for the final rule. Attached is a comparison of the Cummins data. We are hoping that you can help explain to us the difference that we are seeing between the 2015 and 2016 N2O emission levels. Is there some sort of technology, aftertreatment, or calibration shift with these engines that was done to help the engines meet the 2016 MY CO2 standards? If I recall correctly, Cummins used the Phase 1 OBD-alignment provision which requires the engines to meet the 2017 MY CO2 standards in 2016 MY.

We would appreciate any insight that you can provide.

Thank you,
Angela
734-214-4419

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/30/2016 2:17:01 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Aero Slides

Hi Angela,

During our meeting on June 10th, we discussed the slides Prashanth shared during our April 15th web meeting. Are you able to share those slides with us?

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
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tblubaugh@emamail.org

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Message

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 6/8/2016 4:14:56 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: EMA Meetings

Hi Tim,

This all looks good to us, thanks.

Let's talk this afternoon.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
m. Personal Address / Ex. 6

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, June 08, 2016 11:15 AM
To: Spears, Matthew <spears.matthew@epa.gov>
Cc: Cullen, Angela <cullen.angela@epa.gov>
Subject: EMA Meetings

Hi Matt,

Attached are draft agendas for our meetings this week in Ann Arbor. I trust that you will recognize most, if not all, of the issues. Please note that we haven't talked about some of the topics for some time, and others may have been closed but they are on the agenda because folks had lingering questions. The agendas include roughly all of the issues we still consider open. My hope is that we can close many of them.

I will be in my office today until about noon my time. After that, I will be available on my mobile phone during my drive to Ann Arbor. If you are having trouble deciphering my cryptic agenda item names, please don't hesitate to call me. My mobile phone number is: Ex. 6 Personal Privacy (PP)

Regarding logistics, also attached are the attendance lists for the meetings. We are planning to go from 9:00 a.m. – 4:00 p.m. Thursday, and from 8:00 a.m. – 2:00 p.m. Friday. I am planning to use my call-in number both days. We have ordered Zingerman's to be delivered both days.

Please let me know if there is anything we should discuss, substantive or otherwise.

See you tomorrow.,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
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Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 5/6/2015 4:43:41 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: Coastdown Data

Hi Angela,

During our recent discussions we have talked about compliance margins for coastdown test results and the number of $F_{alt\text{-}aero}$ values needed. As we think about these issues, it would be helpful to see EPA's data. Could you share those data sets?

Thanks and regards,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/30/2016 8:00:11 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: EMA Meeting Attendees
Attachments: 2016 03 31 GHG Phase 2 Meeting with EPA - Aero.DOCX

Angela,

Here is a list of the people from our side attending tomorrow's meeting.

Tim

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GHG Phase 2 Meeting
March 31, 2016
U.S. EPA
2000 Traverwood
Ann Arbor, Michigan

Record of Attendance

Name/Company	
Tim Blubaugh Truck and Engine Manufacturers Association	
Gerald Freitag Daimler Trucks North America	
Timothy French Truck and Engine Manufacturers Association	
Dave Gardner Navistar, Inc.	
Cortney Guzlas Navistar, Inc.	
Matthew Hunkler Navistar, Inc.	
David Kayes Daimler Trucks North America LLC	Call-in
Joshua Kehs PACCAR Inc	
Dan Kieffer PACCAR Inc	
Erin Luke PACCAR Inc	
Marc Miller Volvo Group North America	
Mark Siddall Hino Motors Manufacturing USA, Inc.	
Raja Sengupta Volvo Group North America	
Steve Yarosz Isuzu Technical Center of America, Inc.	

91458_1

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/30/2016 7:40:07 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]
Subject: EMA Meeting Agenda
Attachments: 2016 03 31 Draft Meeting Agenda GHG Phase 2.pdf

Angela, Prashanth,

Attached is a revised draft agenda for our meeting tomorrow. The only substantive changes are the addition of topics L., M. and N. under section II. Those are the topics we discussed during our March 24th web meeting. Let me know if you have any additional changes. My mobile phone number is: Conference Code / Ex. 6

See you tomorrow,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
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tblubaugh@emamail.org

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GHG Phase 2 Aerodynamics Meeting
March 31, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. EPA Input on Baselines and Bins

- A. High roof sleeper cab tractors
- B. Day cab tractors

II. Decide CdA Calculation Elements

- A. Vehicle speed data
  1. High and low ranges
  2. Pairs of data sets
- B. Yaw measurement method
- C. Yaw curve asymmetry
- D. Air speed definition
- E. Filtering
  1. Air speed
  2. Yaw angle
  3. Vehicle speed
  4. Track side wind data
- F. Calibration
- G. Discarding outliers
  1. ±X°
  2. Mean vs. median angles
- H. Yaw adjustment to 4.5°
- I. Rear axle adjustment
- J. Flatter coastdown yaw curve
- K. Rolling resistance as a function of speed
  1. EMA test data
  2. Scalar shift vs. multiplicative
- L. Bin boundaries – number of decimal places
- M. Day cab trailer gap
- N. Mid- and low-roof tractors
  1. GEM inputs
  2. Bin percentages

III. EMA Input on EPA CdA SEA and Confirmatory Testing Memorandum

IV. EMA Input on GEM Baseline Vehicle Configurations

V. Other Issues

VI. Next Steps

91459_2

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 8/27/2015 2:45:11 PM
To: Spieth, John [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7a48ef6030334c91bc8b660a14054aa0-Spieth, John]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Panelist for Technology Showcase

Hello John and Angela,

Dr. Wayne Eckerle, Vice President of Research & Technology at Cummins, will be our speaker for the panel discussion during the Oct. 13 technology showcase. Please let us know the next steps, including what the format of the panel discussion will be, whether we should prepare slides or a short speech, any pre-arranged questions, etc.

John – I am still trying to nail down our hardware display and hope to have something definite for you soon.

Thanks,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/22/2016 5:20:36 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Telephone Call

Hi Angela,

I just left you a voice message. Please call me so we can discuss aero. Try my desk: (312) 929-1972, or my cell: Personal Phone / Ex. 6

Personal Phone / Ex. 6

Thanks!

Tim

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/8/2016 3:33:46 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Timothy A. French [TFrench@clpchicago.com]
Subject: CdA Calculations
Attachments: 2016 05 27 AS CdA Calculation Recommendations DRAFT.pdf

Hi Angela,

Following our discussion last week, attached is an updated version of our document listing the CdA calculations that we agreed will reduce the variability in the results. My hope is that tomorrow we can confirm that the document represents our current consensus best practices for calculating Phase 2 CdA values form coastdown data. However, please note that we may need to put an asterisk by the low-speed range, in anticipation of possibly revisiting it after folks have gained some experience with the Phase 2 coastdown procedure and CdA calculations.

Sound good?

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
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Chicago, Illinois ▪ 60606
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tblubaugh@emamail.org

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DRAFT – June 7, 2016

Calculating C_dA from Coastdown Data

To reduce the variability associated with calculating C_dA from coastdown test data:

1. Use the largest possible amount of vehicle speed data, including the first point ≤ 72 mph and the last point ≥ 58 mph, and including the first point ≤ 22 mph and the last point ≥ 8 mph. Analyze the data from one high-speed run with the mean of a pair of low-speed runs (in opposite directions). For valid test data, the longitudinal wind must not exceed ±8 mph and the crosswind must not exceed ±5 mph.

2. Filter the following data elements with a Hampel (moving median) filter using a three-second range and three standard deviations:

   - Air speed
   - Yaw angle
   - Vehicle speed
   - Track-side wind data

   Only filter data that are within the 70 – 60 ±2 mph and 20 – 10 ±2 mph ranges.

3. Calibrate the yaw angle and air speed point-by-point using linear regression of filtered on-board data against filtered track-side wind data, using high and low-speed data separately.

4. Use total relative air speed.

5. Adjust for rear axle loses using data from a § 1037.560 rear axle efficiency test. Use zero torque data for the high and low vehicle speed ranges.

   a. Convert to vehicle speed using drive tire's rev/mile.
   b. Divide power loss by vehicle speed to get spin loss force.
   c. Use a second order curve fit to determine spin loss [N] = f(v).
   d. Apply curve fit to average vehicle speed in low and high segments.
   e. Different value for every run based on average vehicle speed.

6. Adjust for tire rolling resistance using data from an SAE J2452 test. Apply a scalar shift for the high and low vehicle speed ranges.

   a. Tire tests for tire model on each axle from SAE J2452: $P^{\alpha}L^{\beta}(a+bv+cv^2)$
   b. Assume uniform load distribution for an axle, and multiply by number of tires: $F_{RR,axle}= n[P^{\alpha}(L_{axle}/n)^{\beta}(a+bv+cv^2)]$
   c. Calculate $F_{RR,axle}$ at average vehicle speeds (v_{lo} and v_{hi}) for every run
   d. Combine RR for each axle:
      $F_{RR,veh}(v_{hi}) = F_{RR,steer}(v_{hi})+ F_{RR,drive}(v_{hi}) + F_{RR,trailer}(v_{hi})$
      $F_{RR,veh}(v_{lo}) = F_{RR,steer}(v_{lo}) + F_{RR,drive}(v_{lo}) + F_{RR,trailer}(v_{lo})$
   e. Adjust for ambient temperature (ISO 28580)
   f. For every run, calculate $\Delta F_{RR,veh}= F_{RR,veh}(v_{hi}) - F_{RR,veh}(v_{lo})$

7. Utilize the following method for discarding outlier data points:

   a. Measure data from multiples runs (which constitute one test).
   b. Discard known outliers or errors (*e.g.,* driver hit the brake during a run).
   c. Find the median angle, Θ, of all remaining runs.
   d. Draw vertical lines at $\Theta \pm 1.0°$, and discard all points outside the lines as not characteristic of the test's Θ.
   e. Find the average drag area and standard deviation, C_dA and σ, of the remaining runs' drag areas.
   f. Draw horizontal lines at $C_dA \pm 2\sigma$. Discard all points outside the lines.
   g. Take all remaining runs, average the angles to get a new mean angle Θ', and average the drag areas to get a new mean drag area C_dA'.
   h. If there are at least 24 runs remaining after all of the runs are discarded, then Θ' and C_dA' are valid for that test.

90957_7

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/21/2016 5:57:47 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Telephone Call

Hi Angela,

Thanks for your voice message. Could we talk between 3:30 and 4:00 this afternoon? I'll wait for your call.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 1/12/2016 9:37:23 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Steele, Lauren [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=a3f01d4fca2b46d49ef723223af29267-Steele, Lauren P.]
Subject: RE: Vocational Vehicle Write-Up

Thanks, Chuck.

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Tuesday, January 12, 2016 3:02 PM
To: Timothy A. Blubaugh
Cc: Cullen, Angela; Spears, Matthew; Steele, Lauren
Subject: RE: Vocational Vehicle Write-Up

Tim,

Attached are presentations outlining potential compliance structures for vocational vehicles.

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/8/2016 3:14:35 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: EMA Meetings
Attachments: 2016 06 10 GHG Phase 2 Meeting.pdf; 2016 06 09 GHG Phase 2 Meeting.pdf; 2016 06 10 Draft Meeting Agenda GHG Phase 2.pdf; 2016 06 09 Draft Meeting Agenda GHG Phase 2.pdf

Hi Matt,

Attached are draft agendas for our meetings this week in Ann Arbor. I trust that you will recognize most, if not all, of the issues. Please note that we haven't talked about some of the topics for some time, and others may have been closed but they are on the agenda because folks had lingering questions. The agendas include roughly all of the issues we still consider open. My hope is that we can close many of them.

I will be in my office today until about noon my time. After that, I will be available on my mobile phone during my drive to Ann Arbor. If you are having trouble deciphering my cryptic agenda item names, please don't hesitate to call me. My mobile phone number is: Personal Phone / Ex. 6

Regarding logistics, also attached are the attendance lists for the meetings. We are planning to go from 9:00 a.m. – 4:00 p.m. Thursday, and from 8:00 a.m. – 2:00 p.m. Friday. I am planning to use my call-in number both days. We have ordered Zingerman's to be delivered both days.

Please let me know if there is anything we should discuss, substantive or otherwise.

See you tomorrow.,

Tim

Timothy A. Blubaugh
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GHG Phase 2 Meeting
June 9, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Update on Timing

- A. Final rule
- B. Updated GEM

II. Vocational Vehicle Program

- A. Structure
- B. Baselines
  1. Vehicle configurations
  2. Engine fuel maps
  3. FELs
- C. Duty cycle changes
- D. Technology effectiveness
- E. Market penetrations
- F. Mild hybrids in GEM
- G. Idle reduction overrides
  1. Start/stop
  2. Parked idle shutdown

III. Vehicle Credit Opportunities

- A. Extend Phase 1 credit life
- B. Early adoption of Phase 2 technologies
- C. Transfer credits between Classes 2b-5 and 6/7

IV. Miscellaneous Topics

- A. Reprogrammable VSL and AES
- B. Powertrain testing
  1. Confirmatory testing
  2. Selective Enforcement Audits
  3. Idling fuel rate in GEM

C. Confidentiality
   1. Fuel maps
   2. GEM inputs
D. LHD and MHD baselines – gasoline vs. diesel
E. EPA/NHTSA credit discrepancy
F. Model Year 2017 reference engine in GEM
G. Delegated assembly – secondary manufacturer requirements
H. Engine fuel mapping
   1. Confirmatory testing
   2. Selective Enforcement Audits
   3. Predefined vehicle configurations
I. Glider kit requirements
J. Road grade profile D
K. Engine controlling vehicle class
   1. 4x2 with HHD = Class 8
   2. Class 8 with MHD = Class 7
L. Small Business Exemption
M. Alternative fuel engine in GEM

V. Other Issues

VI. June 10th Meeting

93186_2

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GHG Phase 2 Meeting
June 9, 2016
U.S. EPA
2000 Traverwood
Ann Arbor, Michigan

Record of Attendance

Name/Company	
Steve Berry Volvo Group North America	
Tim Blubaugh Truck and Engine Manufacturers Association	
Gerald Freitag Daimler Trucks North America LLC	Call-in
Timothy French Truck and Engine Manufacturers Association	
Dave Gardner Navistar, Inc.	
Cortney Guzlas Navistar, Inc.	
David Kayes Daimler Trucks North America LLC	
Don Keski-Hynnila Daimler Trucks North America LLC	
Dan Kieffer PACCAR Inc	
Erin Luke PACCAR Inc	
Marc Miller Volvo Group North America	
Mark Siddall Hino Motors Manufacturing USA, Inc.	
Jackie Yeager Cummins Inc.	

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GHG Phase 2 Meeting
June 10, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Carryover Discussions from Thursday, June 9th

II. Aerodynamic Bin Structures **(Start at 10:00 a.m.)**

- A. High-roof sleeper and day cabs
  1. Bin structure
  2. Baselines
  3. CdA results from coastdown testing of day cabs
- B. Mid- and low-roof sleeper and day cabs
  1. Bin structures
  2. Baselines

III. CdA Calculations
- A. Confirm recommendations
- B. Low-speed range

IV. Coastdown Testing
- A. Crosswind tolerance
- B. Onboard anemometer placement

V. 2027 CdA Adjustment in GEM

VI. Heavier Tractors

- A. ECCC's proposed Heavy Long Haul category
- B. Heavy haul definition
- C. Special purpose definition
- D. Nonroad exemption

VII. Additional Topics

VIII. Next Steps

93187_2

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Joshua Kehs PACCAR Inc	Call-in
Don Keski-Hynnila Daimler Trucks North America LLC	
Dan Kieffer PACCAR Inc	
Peter Kilcline PACCAR Inc	Call-in
Erin Luke PACCAR Inc	
Marc Miller Volvo Group North America	
Raja Sengupta Volvo Group North America	Call-in
Mark Siddall Hino Motors Manufacturing USA, Inc.	
Jackie Yeager Cummins, Inc.	

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/20/2016 8:22:35 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Quick Call?

Hi Angela,

Could we chat sometime Monday morning? I have something I want to quickly run past you. Let me know what time might work for you.

Thanks

Tim

Timothy A. Blubaugh
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Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
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Message

From: Moulis, Charles [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D9BA8BD68B3C4FB28B767E15AEF54D61-MOULIS, CHARLES]
Sent: 1/12/2016 9:02:09 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Steele, Lauren [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=a3f01d4fca2b46d49ef723223af29267-Steele, Lauren P.]
Subject: RE: Vocational Vehicle Write-Up
Attachments: Vocational StrawmanA_public.pptx; Strawman B for Setting Vocational Vehicle Standards.pptx

Tim,

Attached are presentations outlining potential compliance structures for vocational vehicles.

Strawman "B" for Setting Vocational Vehicle Standards

- This approach would be based on:
  - Adopting a reg structure in which manufacturers are allowed to select the duty cycle category that is most advantageous
  - Consistent with the assumption that the most advantageous duty-cycle would be the one for which the vehicle was designed and how it would be used
  - Custom-chassis applications being addressed separately

- Conceptual framework can be broken into discrete steps
  - Starting with simple one-category benchmark
  - Then adding individual elements of complexity
  - Repeat steps for each weight class and tier of standards (2021, 2024, 2027)

Step 1: Single benchmark-standard with general technology

- Assume for this step that there is one Multi-Purpose category and "benchmark standard" is based on general (non-cycle-specific) technology
  - Note: This benchmark standard would not be an actual standard – it would merely be a value used only during the standard-setting process
- Divide technology
  - Exclude cycle-specific technologies: idle controls, hybrids, 6x2 disconnect, aero, etc
  - Include as benchmark technology everything else with mid-range axle ratio
- Run vehicle through GEM to calculate benchmark standard assuming 100% of benchmark technology

Example: Medium Heavy-Duty

- Assume the following for this example:
  - Automatic transmission with 98% mechanical gear efficiency
  - 4.88 axle drive ratio with 95.5% gear efficiency
  - Drive and steer tires with 7.7 kg/t CRR
  - No idle controls, hybridization, or off-cycle controls

Cycle	GEM Result
Transient	237.7 g/ton-mile
55 Highway	174.3 g/ton-mile
65 Highway	217.3 g/ton-mile
Idle	6,946.3 g/hr
Multi-Purpose Avg*	202.3 g/ton-mile

* Based on proposed weightings

Step 2: Calculate equivalent benchmarks for Urban and Regional

- Run GEM for the *identical* vehicle using the Urban and Regional weightings
- This would isolate the *generally applicable* cycle effects

Weightings*	Benchmark
Multi-Purpose	202.3 g/ton-mile
Regional	198.3 g/ton-mile
Urban	200.1 g/ton-mile

* Based on proposed weightings

Step 3: Apply actual technology packages

- Project feasible technology packages using all available information
  (These packages would be the same for other approaches)
- Run GEM for each package, and each set of weightings
- Compare to the benchmarks in steps 1 & 2
- Assign each package to the category that provides the best delta g/ton-mile (GEM score minus benchmark)
  - Smallest positive delta, or
  - Largest negative delta
- This is the g/ton-mile delta for each *package*

Example Tech Packages

Package	Urban GEM	MP GEM	Regional GEM	Urban Delta (Urban -200.1)	MP Delta (MP-202.3)	Regional Delta (Regional-198.3)	East Delta
Benchmark	200.1	202.3	198.3	0	0	0	0
Tech Package #2	180	190	195	-20.1	-12.3	-3.3	-20.1
Tech Package #3	198	191	180	-2.1	-11.3	-18.3	-18.3
Tech Package #4	181	179	178	-19.1	-23.3	-20.3	-23.3
Tech Package #5	225	220	220	+24.9	+17.7	+21.7	+17.7

Note: actual standard-setting would involved more packages

Step 4: Calculate fleet average performance relative to the benchmarks

- Weight g/ton-mile credits by projected sales of each credit to get fleet average "credit"
  - Credit could be positive or negative
  - Sales fractions used for weighting would be the adoption rates projected by agencies in stringency analysis
- In this simplified example, the *average* vehicle would be 10.6 g/ton-mile better than the benchmarks

Package	Sales Fraction Assumed	Benefit (g/ton-mile)
Benchmark	30%	0.0 g/ton-mile
Tech Package #2	20%	-20.1 g/ton-mile
Tech Package #3	20%	-18.3 g/ton-mile
Tech Package #4	20%	-23.3 g/ton-mile
Tech Package #5	10%	+17.7 g/ton-mile
	Weighted Average	-10.6 g/ton-mile

Step 5: Calculate FRM Standards

- Apply average credit to g/ton-mile benchmark levels from steps 1 & 2
  - Should result in roughly equivalent stringency for vehicles without cycle-specific technologies
- These would be the FRM standards for the specific weight class and the specific model year
- Repeat steps 1-5 for each weight class and tier of standards (2021, 2024, 2027)

Weight Class	Benchmark	FRM Standard* (Benchmark - 10.0)
Multi-Purpose	202.3 g/ton-mile	191.7 g/ton-mile
Regional	198.3 g/ton-mile	187.7 g/ton-mile
Urban	200.1 g/ton-mile	189.5 g/ton-mile

* Strawman values based on generic technology analysis for the sole purpose of showing the calculation process

Vocational Strawman

January 2016

Strawman Overview

- Recommending primary vocational vehicle program to have three composite test cycles & three weight class groups
  - Regional, Multipurpose, Urban; HHD, MHD, LHD
- Most technology will have different effectiveness over the different cycles, as modeled in GEM.
- Technology projected at feasible adoption rates.
- Recommending unique standards for each of 7 vehicle types:
  - Motor home, Intercity bus, School bus, Transit bus, Refuse truck, Cement mixer, Emergency vehicle
  - Simplified program for these vehicles may not have as many segments or weight classes: if drivetrain not in GEM, less sensitive to test cycle
  - Option to meet primary standards, maybe a non-GEM tech option.

Staff Exploring Two Primary Program Pathways

Path A

- More prescriptive in assigning chassis to test cycles
- Numerical standards directly derived from technology performance
- Larger differences in stringency between subcategories

Path B

- Not prescriptive in assigning chassis to test cycles
- Numerical standards derived from technology performance plus weighting effects
- Smaller differences in stringency between subcategories

Strawman "A" for Segmentation

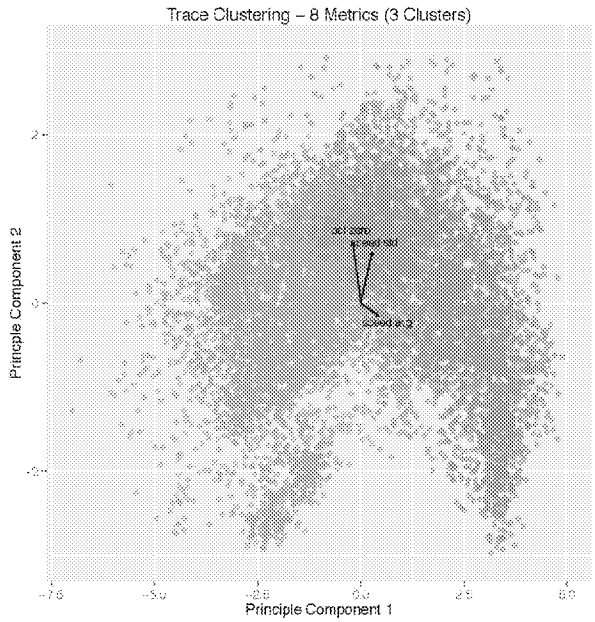
- Similar to NPRM, except no normalizing or equalizing
  - Stringency would be different for each subcategory, reflecting individual tech packages and cycle effectiveness
- EPA would define criteria for assigning vehicles to subcategories
  - NREL's predictive model has generated curves of engine rpm at 55 and 65 mph with associated probability of belonging to a subcategory. We would use these curves to locate cut-points.
  - May specify GEM as category selection tool: user would enter driveline inputs, GEM would calculate engine rpm at 55 and 65 mph, and identify subcategory based on rpm cut-points
    - Except: We would allow chassis to remain in multipurpose as default (different than NPRM which required moving chassis out of multipurpose category if met criteria to be assigned to urban or regional).

NREL's Segmentation Analysis

Two distinct clusters were identified: one with fewer stops and higher avg speeds, other with more stops and lower avg speeds. A third exhibits characteristics of each: multimodal vehicles.

Representative trips were ranked by multivariate distance from cluster centroid.

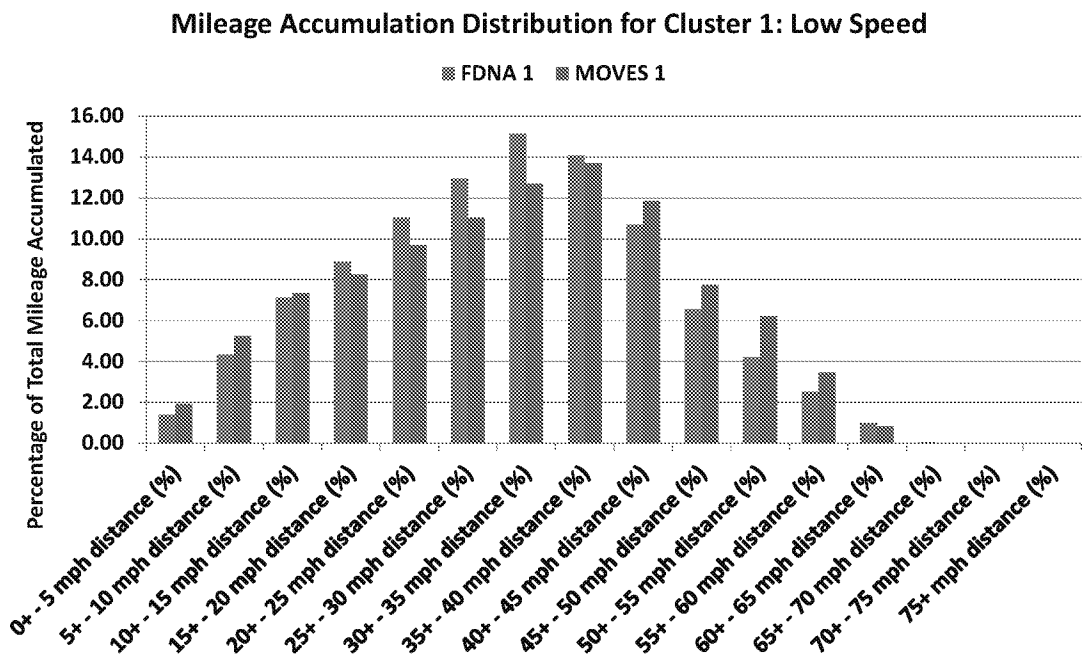
The DRIVE tool generated a single representative drive cycle for each cluster using the 50 most representative trips from each cluster.



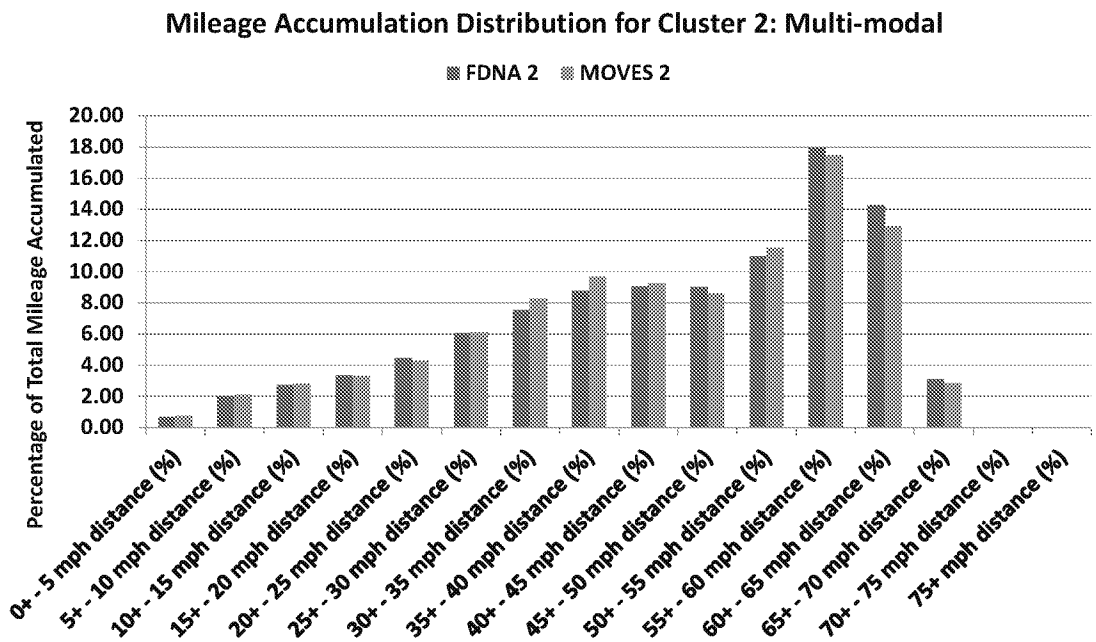
Key Cycle Metrics

- Aerodynamic speed
- Characteristic acceleration
- Percent of miles accumulated at speeds below 55 mph
- Percent of cycle time running at zero speed
- Number of stops per mile
- Average driving speed
- Maximum driving speed
- Standard deviation of driving speed

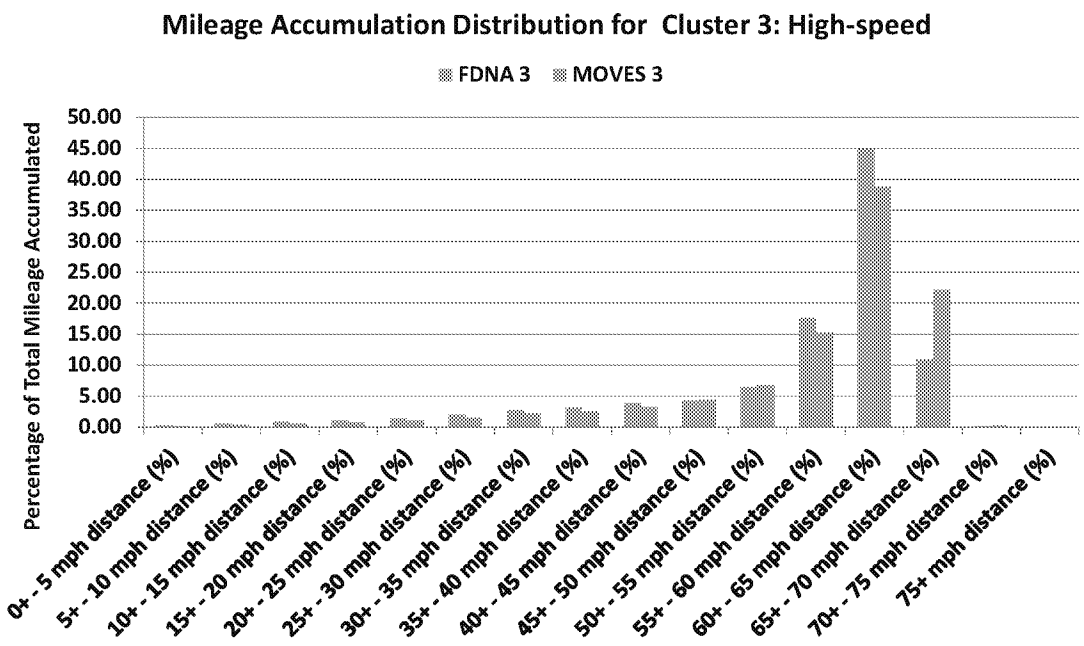
Mileage Accumulation Breakdown



Mileage Accumulation Breakdown



Mileage Accumulation Breakdown



Possible Composite Test Cycle Revisions

	Subcategory	Transient	55 mph Cruise	65 mph Cruise	Idle
NPRM	Regional	50	28	22	10
	Multi-Purpose	82	15	3	15
	Urban	94	6	0	20
		% of miles < 50 mph	% of miles 50-60 mph	% of miles > 60 mph	% of time at 0 mph
NREL Findings (December)	High Speed Cluster	20	24	56	24
	Multimodal Cluster	54	29	17	52
	Low Speed Cluster	92	7	1	47

Notes: * Day Cab Tractors have 19% weighting of transient cycle
* Weightings would change if used different speed brackets

Chassis Parameters for Logistic Regression

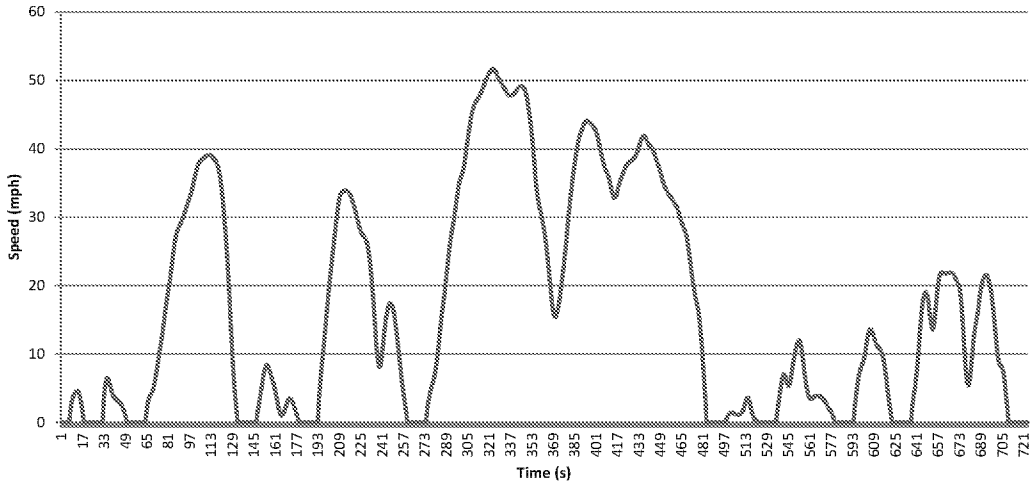
- Two parameters were observed to be highly significant predictors of cluster membership :
  - Engine speed at 55 mph
  - Engine speed at 65 mph
- Three parameters were observed to have some minor significance as predictors:
  - Conventional drivetrain (vs hybrid)
  - Fuel type
  - Transmission type (AT vs AMT)
- Others were observed to have no bearing on prediction of cluster membership at all:
  - Vehicle weight class

Vocational MOVES Population Allocation

	Subcategory	Long Haul	Short Haul	Intercity Bus	Motor Home	School Bus	Transit Bus	Refuse Truck
N	% of Total Pop.	3%	66%	0.2%	18%	8.5%	1%	3%
P	Regional	100	35	100	100	0	0	0
R	Multi-Purpose	0	60	0	0	100	75	0
M	Urban	0	5	0	0	0	25	100
	Public Comments							
	Regional	100	5	100	100	0	0	0
	Multi-Purpose	0	90	0	0	?	0	?
	Urban	0	5	0	0	0	?	?
	NREL's Predictive Model							
	High-Speed	?	20	?	?	0	0	0
	Multi-Modal	0	10	0	0	?	0	0
	Slow-Speed	0	70	0	0	0	?	?

The 35 percent Regional was selected for the NPRM specifically to accommodate CARB's desire to have lots of high-speed vehicles that could benefit from Aerodynamic devices

NREL Synthetic Transient Cycle



Max speed 52 mph, about 12 minutes total cycle duration.

Statistical Comparison of Cycles

Cycle	Aerodynamic Speed	Characteristic Accel.	% Miles accum < 55 mph	% Cycle Time at Zero Speed	# Stops Per Mile	Average Driving Speed	Maximum Driving Speed	Std Dev. Driving Speed
ARB Transient	43.36	0.49	100	15.57	1.4	18.2	47.5	13.38
World Harmonized Vehicle Cycle	61	0.28	100	13.61	1.07	25.98	54.56	19.03
Japanese HD Transient (JPJE05)	51.31	0.4	100	25.19	1.62	22.7	54.43	15.94
European HD Test Cycle (FIGE)	68.71	0.23	94.46	0	0	36.65	56.61	17.83
NREL Transient Cycle	50.99	0.59	100	21.69	2.98	21.31	51.67	16.16
NREL Target Statistics: Urban Segment	50.59	0.55	96.45	47.30	1.71	22.62	62.39	13.74
NREL Target Statistics: Multipurpose Segment	69.14	0.46	64.64	52.40	0.76	33.64	66.85	19.25
NREL Target Statistics: Regional Segment	83.40	0.29	26.47	24.50	0.21	48.57	70.81	19.17

Appendix

Other NREL Material

Fleet DNA Vehicles with Engine Data

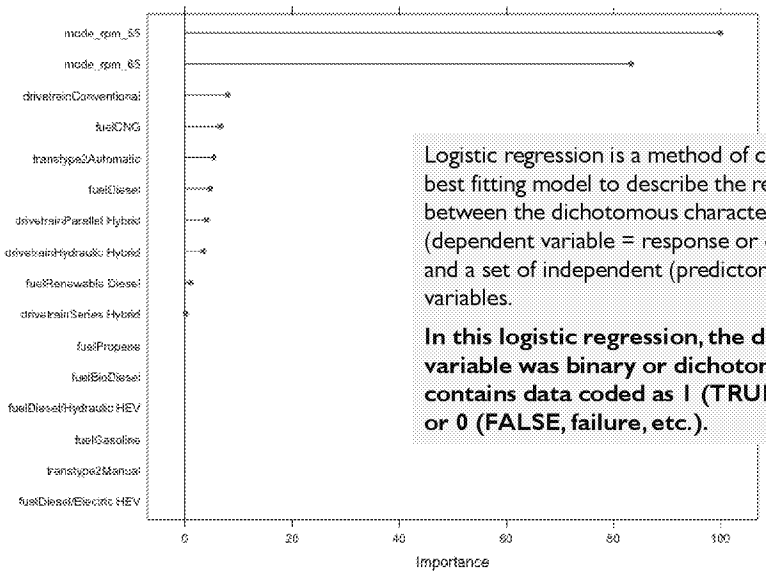
Vocation Description	Number of Vehicle	
Beverage Delivery		40
Concrete		3
Drayage		16
Dump Truck		4
Food Delivery		44
Freight		22
LINEHAUL		73
Linen Delivery		30
Local Delivery		7
Long Haul		12
Mass Transit		27
Parcel Delivery		117
Refrigerated Truck		6
Refuse Pickup		53
REGIONAL HAUL		1
School Bus		8
Snow Plow		9
Tanker		25
Telecom		17
Towing		3
Transfer truck		14
Utility		23
Warehouse Delivery		10
TOTAL	322	564

Fleet DNA vs MOVES Populations

Vehicle Type	MOVES (% of Vehicles)	Fleet DNA (% of Vehicles, (#))	Fleet DNA Resampled to Match MOVES (% (#))
Short Haul	66	59 (631)	84 (631)
School Bus	8.5	24 (254)	11 (82)
Refuse	3	5 (57)	4 (29)
Transit Bus	1	2 (23)	1 (9)
Other*	21.5	10 (108)	0
Total Number	(500,000)	(1,073)	(751)

- In MOVES, Other = Long haul straight trucks, motor homes, intercity buses
- In Fleet DNA, Other = vocational tractors, vehicles on previous slide

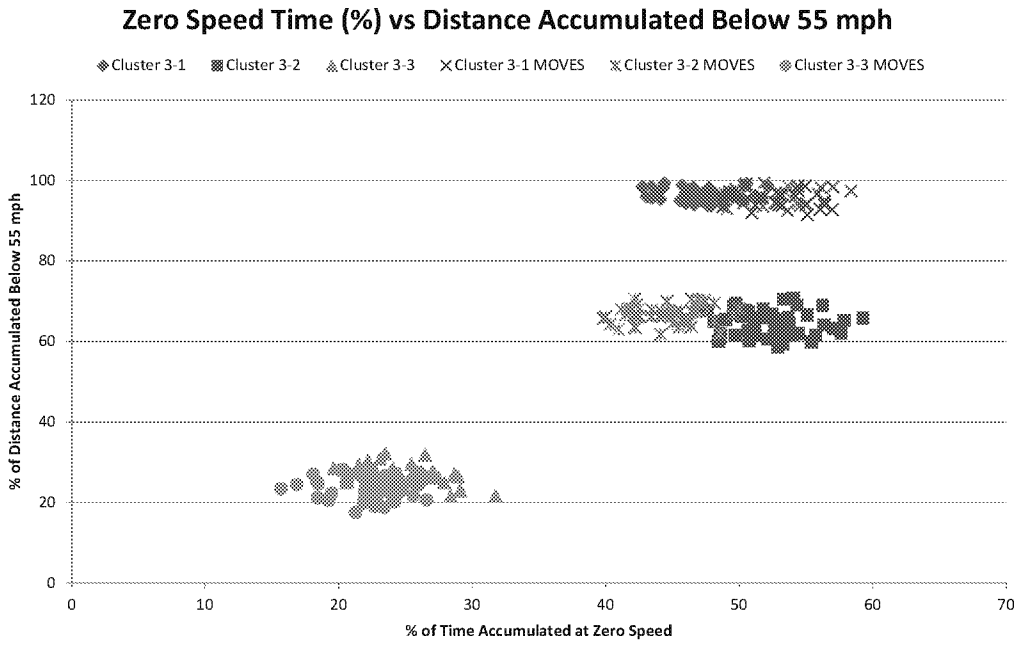
NREL's Logistic Regression model: Predicting Cluster Membership



Logistic regression is a method of constructing the best fitting model to describe the relationship between the dichotomous characteristic of interest (dependent variable = response or outcome variable) and a set of independent (predictor or explanatory) variables.

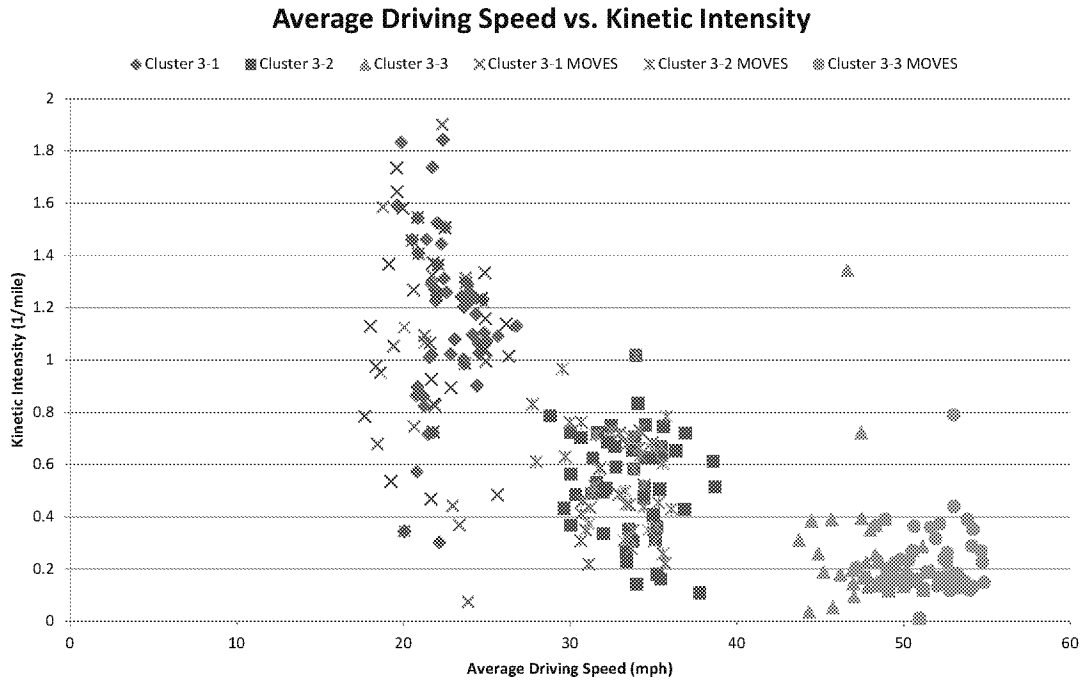
In this logistic regression, the dependent variable was binary or dichotomous, i.e. it only contains data coded as 1 (TRUE, success, etc.) or 0 (FALSE, failure, etc.).

Comparison of Source Cycle Cluster Data



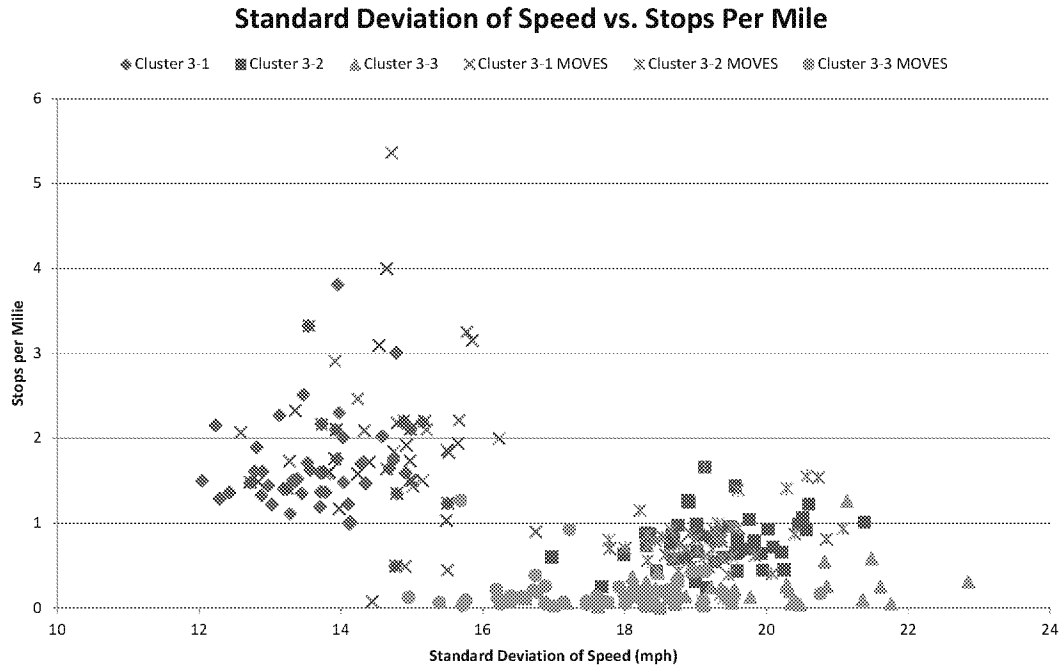
Deliberative Draft

Comparison of Source Cycle Cluster Data



Deliberative Draft

Comparison of Source Cycle Cluster Data



Deliberative Draft

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 1/12/2016 4:56:08 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Vocational Vehicle Write-Up

Hi Angela, Hi Chuck,

Could you tell me the status of the write-up of the GHG Phase 2 vocational vehicle strawmen (strawman?) that we discussed on December 16th. Please let me know.

Thanks,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Appointment

From: EMA [ema@emamail.org]
Sent: 3/15/2016 2:50:47 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: EMA - March 15, 2016, Conference Call with EPA - Web Meeting
Attachments: 2016 03 15 AS Conference Call with EPA.pdf
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh
Start: 3/15/2016 3:00:00 PM
End: 3/15/2016 4:00:00 PM
Show Time As: Tentative

Recurrence: (none)

PLEASE NOTE:
EPA has provided the following web meeting access to today's conference call to view slides they have prepared. Please use the call-in number below for the audio connection.

Conference Code / Ex. 6

TO:	Aerodynamics Subcommittee Angel Cullen, EPA Prashanth Gururaja, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	February 25, 2016
RE:	**March 15, 2016, Conference Call with EPA**

Please join this conference call of EMA's Aerodynamics Subcommittee and EPA. Following our February 24th meeting in Ann Arbor, the primary purpose of the call is to discuss the aerodynamic baselines for the Phase 1 and Phase 2 GHG rules.

Following is the call-in information:

DATE: Tuesday, March 15, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Conference Code / Ex. 6
CONFERENCE ID: Conference Code / Ex. 6
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax

tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 1/11/2016 4:53:22 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Cylce Average Variability Proposal

Hi Angela, Hi Chuck,

I wanted to follow-up on one thing we talked about last week. I understand that Chris Sharp is preparing an updated test plan to analyze the variability of the cycle average fuel mapping process. He is planning to get a proposal out this week, so the EMTC can review it during their meeting on January 19-20.

Tim

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/15/2016 1:36:18 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Voice Message + Telephone Conversation

Sounds great! I'll wait for your call. Personal Matters / Ex. 6

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Tuesday, March 15, 2016 7:40 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Subject: RE: Voice Message + Telephone Conversation

Hi Tim,

I am sorry, yesterday was full of meetings and so is this morning.

I no longer need to talk to you about vocational because Matt has been working some this week.

Prashanth has a presentation to go over in today's meeting.

How about I call you at 10:00 am EDT?

Thanks,
Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Monday, March 14, 2016 2:20 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: Voice Message + Telephone Conversation

Hi Angela,

So you and I connecting first thing on a Monday morning didn't work out so well... Is there a time when we could chat before our conference call tomorrow morning at 11:00 your time? Let me know when you can be available.

Thanks!

Tim

From: Timothy A. Blubaugh
Sent: Saturday, March 12, 2016 6:44 AM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: Voice Message + Telephone Conversation

Hi Angela,

Sorry for not responding sooner to your voice message; I was out of the country most of last week. Could we talk at some point Monday morning between 9:30 and 11:00 your time? If not, let me know when you are available Monday afternoon. In additional to your question about vocational vehicles, I would like to chat about the CdA calculations and aerodynamic baselines. Let me know what time will work for you. Thanks,

Tim

Timothy A. Blubaugh
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333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 1/7/2016 4:41:47 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: GHG Phase 2 Next Steps

Great! Talk to you then,

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, January 07, 2016 10:01 AM
To: Timothy A. Blubaugh
Subject: RE: GHG Phase 2 Next Steps

I will call you tomorrow at 11 my time. Chuck will be joining us too.

Thanks!

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Thursday, January 07, 2016 10:42 AM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: GHG Phase 2 Next Steps

Hi Angela,

How about 11:00 (your time) tomorrow morning? If it would be easier, just call me whenever your 10:00 ends – I will be here.

Sound good?

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, January 07, 2016 8:41 AM
To: Timothy A. Blubaugh
Subject: RE: GHG Phase 2 Next Steps

Hi Tim.

Happy New Year to you too.

Yesterday and today were/are pretty busy. Any chance we can talk on Friday (tomorrow)? I am free except 10-11 am.

Thank you!
Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, January 06, 2016 9:49 AM

To: Cullen, Angela <cullen.angela@epa.gov>
Subject: GHG Phase 2 Next Steps

Hi Angela,

I hope your holidays were merry, and that you are enjoying a great start to the New Year!

I wanted to see if we could arrange a time to chat today or tomorrow to compare notes on the assignments we took out of our two meetings on Dec. 15th and 16th. The best times for me are this afternoon and tomorrow morning. Is there a time that would work for you?

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 3/9/2016 4:55:50 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
CC: Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]
Subject: RE: HD chassis dyno contact?

Angela, thank you! I will pass along Maria's email address.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, March 9, 2016 11:13 AM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Cc: Peralta, Maria <Peralta.Maria@epa.gov>
Subject: RE: HD chassis dyno contact?

Hi Jackie,

Maria Peralta, who is copied on this email, is the center director responsible for our HD chassis dyno.

Angela

From: Jackie M Yeager [mailto:jackie.m.yeager@cummins.com]
Sent: Wednesday, March 09, 2016 7:30 AM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: HD chassis dyno contact?

Hi Angela,

Our Cummins China team received an inquiry from CATARC, the Chinese testing agency, about EPA's HD chassis dyno. Who would be the best contact at EPA to put CATARC in touch with?

Thanks,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 2/20/2016 5:14:39 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Draft Agendas for EMA Meetings
Attachments: 2016 02 23 Draft Meeting Agenda GHG Phase 2.pdf; 2016 02 24 Draft Meeting Agenda GHG Phase 2.pdf

Hi Matt,

As promised, attached are draft agenda for our meetings next week. Even though the topics should be very familiar, I was hoping we could run through the agendas before 11:00 you time tomorrow morning? Please let me know your availability.

Thanks,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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GHG Phase 2 Meeting
February 23, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Notice of Data Availability

- A. Data included
- B. Strategies addressed
- C. Timing

II. Vocational Vehicle Program

- A. Segmentation
  - 1. Weight class categories
  - 2. Duty cycles
  - 3. Equalization
- B. Custom chassis categories
- C. Hybrid technologies
- D. Other vocational technologies
- E. Powertrain testing
- F. Credit life and transfer

III. Engine Fuel Mapping

- A. Cycle average approach
- B. Grade Profile D
- C. SwRI test plan

IV. Additional Issues

- A. N_2O Standard
- B. NO_X measurement during engine testing
- C. Powertrain modifications in use
- D. Powertrain SEAs

V. Other Issues

91093_1

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GHG Phase 2 Meeting
February 24, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Aerodynamic Issues

- A. Baseline and bins
  1. High roof sleeper cab tractors
  2. Day cab tractors
- B. CdA Calculation Variability
  1. Draft recommendations
  2. ±X° Yaw angle for discarding outliers
- C. Coastdown data frequency
- D. Yaw curve asymmetry
- E. Tire rolling resistance as a function of speed
  1. EMA testing
  2. Scalar shift or multiplicative
- F. CdA SEA Strawman

II. GEM Inputs

- A. TPMS
- B. AES
- C. Speed limiter

III. Additional Issues

- A. In-use tractor testing
- B. 6x2 Penetrations

IV. Other Issues

V. Next Steps

91094_1

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/17/2016 4:51:51 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Brian C Mormino [brian.c.mormino@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Manik Narula [manik.narula@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]
Subject: RE: Cummins/EPA call on Phase 2 cycle average map
Attachments: CMI_EPA_Call_Feb172016_Final.pdf

All – here are some slides we would like to discuss on today's call. Talk to you soon.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

-----Original Appointment-----
From: Jackie M Yeager
Sent: Thursday, February 11, 2016 5:12 PM
To: Spears, Matthew; Zhang, Houshun; Sanchez, James; Moulis, Charles; Cullen, Angela; Brian C Mormino (brian.c.mormino@cummins.com); Gary C Salemme; Manik Narula; Jon A Dickson
Subject: Cummins/EPA call on Phase 2 cycle average map
When: Wednesday, February 17, 2016 1:00 PM-2:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: US toll-free Ex. 6 Personal Privacy (PP) or Gary's office at CTC

Follow up to our cycle average map discussion on 1/29

Agenda:

1. Review of issues – Cummins
2. Testing update – Cummins, EPA
3. Generic vehicle definition – Cummins

Teleconference call-in number:

US toll-free
Access code Conference Code / Ex. 6

Skype information:
Link for non-Cummins attendees (see additional instructions in the attachment):

→ Join Skype Meeting (Web Guest)

<< File: Joining Skype for Business Meetings (External).pdf >>

Link for Cummins attendees:

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help

Audio for this Skype for Business meeting is not available. When prompted, please select "Don't Join Audio". Use a phone to call the conference number provided in this invitation.

Cummins – EPA call on Cycle Average Map

2/17/2016

Objective:

Include Cycle Average Map for cruise cycles as an option along with the Steady State Map in the Final Rule

Analysis of Issues Requiring Use of the Steady State Fuel Map (1/29/16 meeting)

	Issue Highlighted by EPA	Cummins Conclusions
1	Cycle Average Fuel map approach for Steady State cycles is not robust for ISB child rating.	Cycle Average Fuel Map performance is as good as Steady State Fuel Map for a lower rating of a parent map.
2	~~GEM Shift Logic requires Specific Steady State Fuel Map for shift decisions.~~	~~A Generic Steady State Fuel Map performs as well as a specific Steady State Fuel Map and can be used for shift logic in GEM.~~
3	~~Steady State Fuel map would also provide NOx information.~~	~~There are other options to consider (to be discussed).~~

Not an issue

Analysis of Issues Requiring Use of the Steady State Fuel Map

	Issue Highlighted by EPA	Cummins Conclusions
1	Cycle Average Fuel map approach for Steady State cycles is not robust for ISB child rating.	Cycle Average Fuel Map performance is as good as Steady State Fuel Map for a lower rating of a parent map. <Action: EPA/SWRI to run child engine cycles using parent rating engine calibration>
2	GEM simulation @ 55 mph using EPA generic vehicle, N/V of lower axle ratio vehicle configuration overlapped with a higher axle ratio configuration.	EPA Generic Vehicle Definition can be refined to alleviate this issue. (shown in this presentation)
3	Certain vehicle specs are not geared to run 65 mph or 55 mph cycles therefore cannot follow these cycles.	There can be options to overcome this issue. (shown in this presentation)

Analysis of Issues Requiring Use of the Steady State Fuel Map

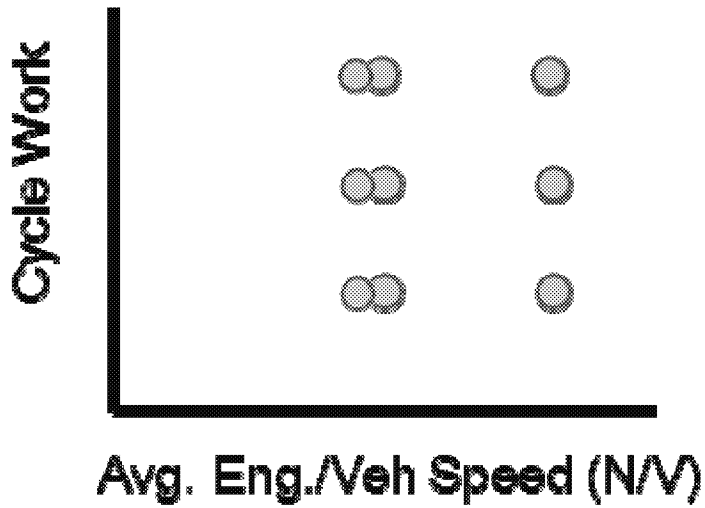
	Issue Highlighted by EPA	Cummins Conclusions
1	Cycle Average Fuel map approach for Steady State cycles is not robust for ISB child rating.	Cycle Average Fuel Map performance is as good as Steady State Fuel Map for a lower rating of a parent map. <Action: EPA/SWRI to run child engine cycles using parent rating engine calibration>
2	GEM simulation @ 55 mph using EPA generic vehicle, N/V of lower axle ratio vehicle configuration overlapped with a higher axle ratio configuration.	EPA Generic Vehicle Definition can be refined to alleviate this issue. (shown in this presentation)
3	Certain vehicle specs are not geared to run 65 mph or 55 mph cycles therefore cannot follow these cycles.	There can be options to overcome this issue. (shown in this presentation)

N/V overlap problem statement

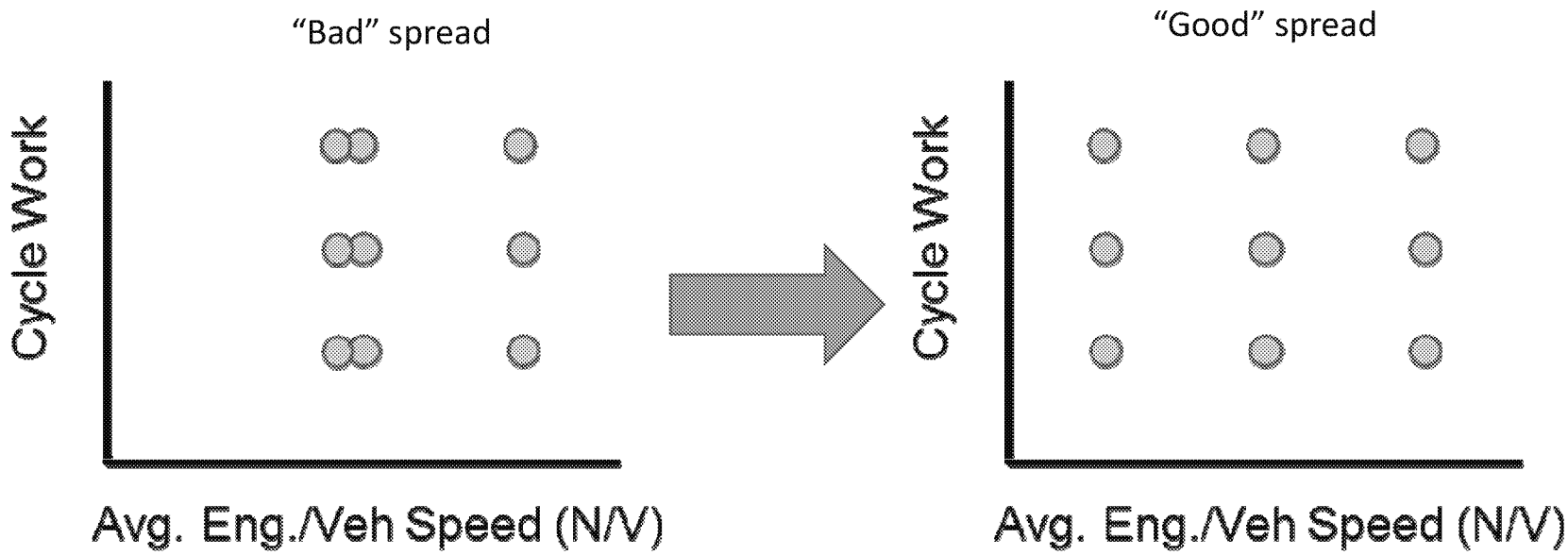
- GEM simulation @ 55 mph using EPA generic vehicle, N/V of lower axle ratio vehicle configuration overlapped with a higher axle ratio configuration.

Table 3-31 Proposed Generic Vehicle Definitions for Tractors and Class 8 Vocational Vehicles—General Purpose

	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6	TEST 7	TEST 8	TEST 9
Mass (kg)	31,978	22,679	19,051	31,978	22,679	19,051	31,978	22,679	19,051
C_dA	5.4	4.7	4.0	5.4	4.7	4.0	5.4	4.7	4.0
Tire C_{rr} (kg/ton)	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Tire Radius (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rotating Inertia (kg)	1,134	907	680	1,134	907	680	1,134	907	680
Axle Gear Efficiency (%)	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5
Accessory Power (W)	1300	1300	1300	1300	1300	1300	1300	1300	1300
Axle ratio at engine speed	Minimum NTE exclusion speed	Minimum NTE exclusion speed	Minimum NTE exclusion speed	B	B	B	Maximum engine speed	Maximum engine speed	Maximum engine speed



N/V overlap problem statement



EPA Generic vehicle definition (changing Axle Ratio) can be refined to resolve this problem

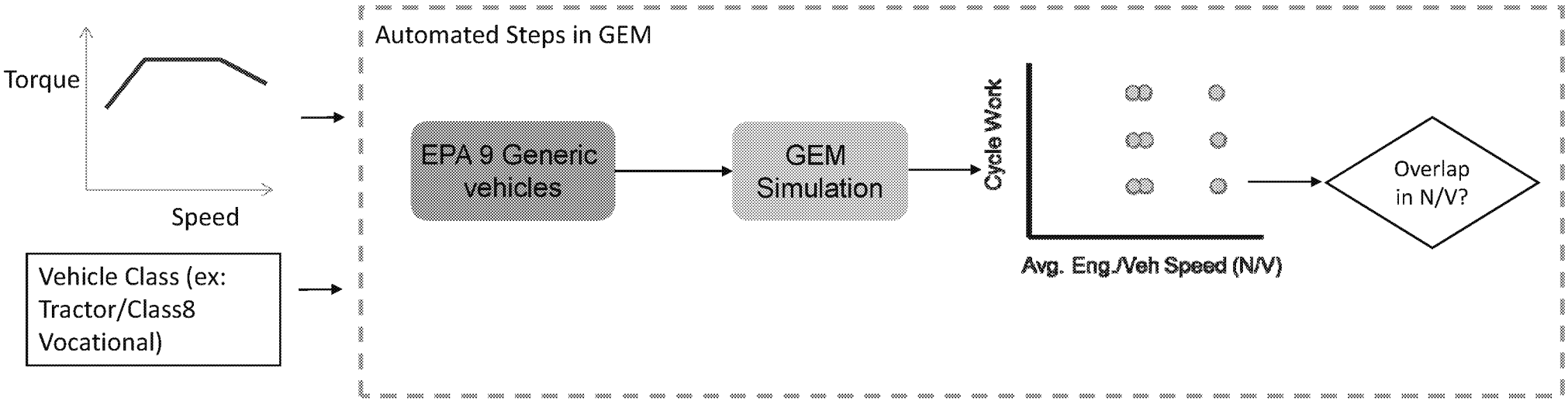
EPA Generic vehicle options – option 1

- Current:
  - Axle ratio for each Test # is calculated based on 65 mph in Top Gear @ Min NTE speed / B Speed / Max Eng Speed.
  - Same axle ratio is applied to 55 mph cycle.
- Option 1 : Separate Axle ratio calculation for 55 and 65 cycle
  - For 65 mph cycle: Axle ratio for each Test # is calculated based on 65 mph in Top Gear @ Min NTE speed / B Speed / Max Eng Speed.
  - For 55 mph cycle: Axle ratio for each Test # is calculated based on 55 mph in Top Gear @ Min NTE speed / B Speed / Max Eng Speed.

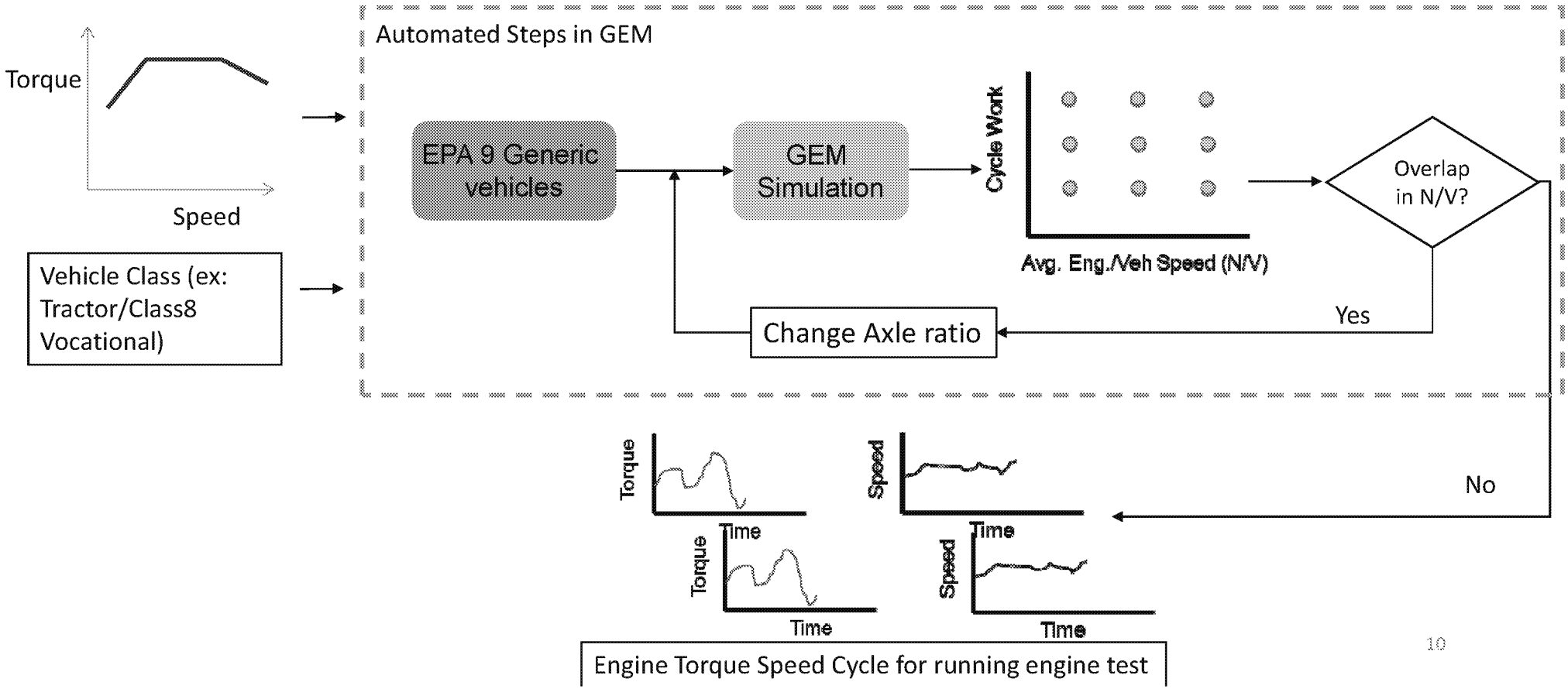
Table 3-31 Proposed Generic Vehicle Definitions for Tractors and Class 8 Vocational Vehicles—General Purpose

	TEST 1	TEST 2	TEST 3	TEST 4	TEST 5	TEST 6	TEST 7	TEST 8	TEST 9
Mass (kg)	31,978	22,679	19,051	31,978	22,679	19,051	31,978	22,679	19,051
$C_d A$	5.4	4.7	4.0	5.4	4.7	4.0	5.4	4.7	4.0
Tire C_r (kg/ton)	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Tire Radius (m)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Rotating Inertia (kg)	1,134	907	680	1,134	907	680	1,134	907	680
Axle Gear Efficiency (%)	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5	95.5
Accessory Power (W)	1300	1300	1300	1300	1300	1300	1300	1300	1300
Axle ratio at engine speed	Maximum NTE exclusion speed	Minimum NTE exclusion speed	Maximum NTE exclusion speed	B	B	B	Maximum engine speed	Maximum engine speed	Maximum engine speed

EPA Generic vehicle options – option 2



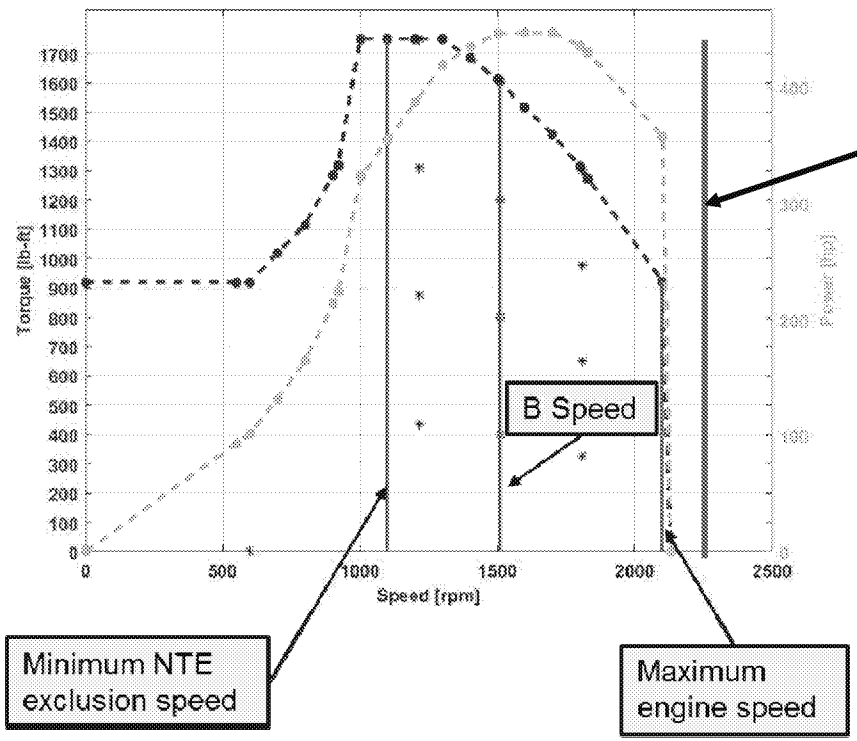
EPA Generic vehicle options – option 2



Analysis of Issues Requiring Use of the Steady State Fuel Map

	Issue Highlighted by EPA	Cummins Conclusions
1	Cycle Average Fuel map approach for Steady State cycles is not robust for ISB child rating.	Cycle Average Fuel Map performance is as good as Steady State Fuel Map for a lower rating of a parent map. <Action: EPA/SWRI to run child engine cycles using parent rating engine calibration>
2	GEM simulation @ 55 mph using EPA generic vehicle, N/V of lower axle ratio vehicle configuration overlapped with a higher axle ratio configuration.	EPA Generic Vehicle Definition can be refined to alleviate this issue. (shown in this presentation)
3	Certain vehicle specs are not geared to run 65 mph or 55 mph cycles therefore cannot follow these cycles.	There can be options to overcome this issue. (shown in this presentation)

Certain vehicle specs are not geared to run 65 mph or 55 mph cycles therefore cannot follow these cycles.



What if truck is geared such that Engine speed at 65/55 mph is > Max Engine Speed?
Example: Yard Spotter which is not geared to run at 65 mph

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Trade Secret Information Submitted Subject to the Protections of 17 CCR 91000-91022

Options

Volume of such trucks are much lower as compared to over the road tractors or vocational trucks.

1. If truck is geared not to run at 65 mph:

GHG Cycle	Cycle Average Map	Base CO2 (g/ton-mile)	Option1 (g/ton-mile)	Option2 (g/ton-mile)
ARB	ARBmap	A	A	A
55 mph	55map	B	B	B
65 mph	65map	C	B	D = 55map(@65 N/V, @65 Work)

2. If truck is not geared to run at 55 and 65, then only use ARB cycle with 100% weighting.

Cycle Average Map – Engine Testing Summary

Engine	Cycle Avg Performance (Parent)	Cycle Avg Performance (Child)	Are Steady State and Cycle Avg equivalent for 55 and 65?	Cummins Analysis
ISX 450	OK		Yes	Published in SAE paper
ISB 300 & 200 HP	OK	Re run 200 HP cycles @ SWRI	Yes	300 & 200HP calibration is different. Certain vehicles do not meet Gearing guidelines
Volvo D13	Green except 2 vehicles		Yes (except 2 vehicles)	2 vehicles with high RAR are not geared to run 65 mph therefore should not be used to judge Cycle Avg Map performance
Volvo D13 500 & 400	OK	OK		
N13 455 & 365	OK	Pending		
ISL 450 @ Cummins	Planned in Feb'16			
ISX 450 @ Eaton–New Grade, New GEM	Planned in Mar'16			

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 2/12/2016 9:51:26 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Iffland, JoNell [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=269c8731e7c6417482f8a8ddccfc4887-Iffland, JoNell]
Subject: RE: Meeting with EMA

Thanks, Chuck.

Nice weekend to all!

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Friday, February 12, 2016 3:50 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>; Spears, Matthew <spears.matthew@epa.gov>; Cullen, Angela <cullen.angela@epa.gov>; Iffland, JoNell <Iffland.JoNell@epa.gov>
Subject: RE: Meeting with EMA

I think that will work.

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Friday, February 12, 2016 4:20 PM
To: Moulis, Charles; Spears, Matthew; Cullen, Angela; Iffland, JoNell
Subject: RE: Meeting with EMA

All,

I am planning to set up our meeting on Tuesday, February 23rd to start at 10:00 a.m. and end at 4:00 p.m., and on Wednesday to start at 9:00 a.m. and end at 3:00 p.m. I trust that those times will work; let me know if they don't.

I will put together agendas, but I think we should start on Tuesday with the vocational vehicle program. Additionally, I was thinking that aero would be on Wednesday. The rest of the topics will be around those two. Sounds okay?

Tim

From: Timothy A. Blubaugh
Sent: Friday, February 5, 2016 5:28 PM
To: 'Moulis.charles@Epa.gov' <Moulis.charles@Epa.gov>; 'Spears, Matthew' <spears.matthew@epa.gov>
Cc: 'Iffland, JoNell' <Iffland.JoNell@epa.gov>
Subject: Meeting with EMA

Matt, Chuck,

Following our conversation yesterday, it looks like Tuesday and Wednesday, February 23rd & 24th, are the best days for the EMA crew to visit. I will touch base with you soon on the timing and subject matter each day. In the meantime, I wish you a pleasant weekend.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/2/2016 1:45:55 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: RE: GHG Phase 2 Aerodynamics

Sounds, great. I will call you this afternoon, hopefully at 2:00 your time.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, June 2, 2016 8:09 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>; Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>
Cc: Spears, Matthew <spears.matthew@epa.gov>
Subject: RE: GHG Phase 2 Aerodynamics

If you would call me when you are done with your meeting, then that would be great. Ex. 6 Personal Privacy (PP) (polycom in my office)

Thanks!
Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, June 01, 2016 7:38 PM
To: Cullen, Angela <cullen.angela@epa.gov>; Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>
Cc: Spears, Matthew <spears.matthew@epa.gov>
Subject: RE: GHG Phase 2 Aerodynamics

Thanks, Angela. That should work. I have something going on that should conclude by then; if it doesn't, I will shoot you a note and we can try for Friday afternoon. Do you want me to call you, or will you call me?

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, June 1, 2016 6:32 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>; Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>
Cc: Spears, Matthew <spears.matthew@epa.gov>
Subject: RE: GHG Phase 2 Aerodynamics

Hi Tim,

Would 2 pm EDT on Thursday work? If not, Friday afternoon is open.

Thanks,
Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Tuesday, May 31, 2016 8:03 PM
To: Cullen, Angela <cullen.angela@epa.gov>; Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>
Cc: Spears, Matthew <spears.matthew@epa.gov>
Subject: GHG Phase 2 Aerodynamics

Angela, Prashanth,

Could we find a time in the next day or two to chat? I would like to discuss the open issue (#1) on the attached list of calculation recommendations and our upcoming meeting in Ann Arbor. Let me know what might work on your end.

Thanks,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 6/1/2016 12:02:56 AM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: GHG Phase 2 Aerodynamics
Attachments: 2016 05 27 AS CdA Calculation Recommendations DRAFT.pdf

Angela, Prashanth,

Could we find a time in the next day or two to chat? I would like to discuss the open issue (#1) on the attached list of calculation recommendations and our upcoming meeting in Ann Arbor. Let me know what might work on your end.

Thanks,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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DRAFT – May 31, 2016

C_dA Calculation Variability

Recommendations

EMA recommends the following to reduce the variability associated with calculating C_dA values from coastdown test data.

1. Use the largest possible amount of vehicle speed data, including the first point ≤ 72 mph and the last point ≥ 58 mph, and including the first point ≤ 22 mph and the last point ≥ 8 mph. Analyze the data from one high-speed run with the mean of a pair of low-speed runs (in opposite directions). For valid test data, the longitudinal wind must not exceed ±8 mph and the crosswind must not exceed ±5 mph.

   OPTION: For comparison analysis, consider a low-speed range of 25 – 15 ±2 mph.

2. Filter the following data elements with a Hampel (moving median) filter using a three-second range and three standard deviations:

   - Air speed
   - Yaw angle
   - Vehicle speed
   - Track-side wind data

   Only filter data that are within the 70 – 60 ±2 mph and 20 – 10 ±2 mph ranges.

3. Calibrate the yaw angle and air speed point-by-point using linear regression of filtered on-board data against filtered track-side wind data, using high and low-speed data separately.

4. Use total relative air speed.

5. Adjust for rear axle loses using data from a § 1037.560 rear axle efficiency test. Use zero torque data for the high and low vehicle speed ranges.

   a. Convert to vehicle speed using drive tire's rev/mile.
   b. Divide power loss by vehicle speed to get spin loss force.
   c. Use a linear curve fit to determine spin loss [N] = f(v).
   d. Apply curve fit to average vehicle speed in low and high segments.
   e. Different value for every run based on average vehicle speed.

6. Adjust for tire rolling resistance using data from an SAE J2452 test. Apply a scalar shift for the high and low vehicle speed ranges.

   a. Tire tests for tire model on each axle from SAE J2452: $P^{\alpha}L^{\beta}(a+bv+cv^2)$
   b. Assume uniform load distribution for an axle, and multiply by number of tires: $F_{RR,axle}= n[P^{\alpha}(L_{axle}/n)^{\beta}(a+bv+cv^2)]$
   c. Calculate $F_{RR,axle}$ at average vehicle speeds (v_{lo} and v_{hi}) for every run
   d. Combine RR for each axle:
      $F_{RR,veh}(v_{hi}) = F_{RR,steer}(v_{hi})+ F_{RR,drive}(v_{hi}) + F_{RR,trailer}(v_{hi})$
      $F_{RR,veh}(v_{lo}) = F_{RR,steer}(v_{lo}) + F_{RR,drive}(v_{lo}) + F_{RR,trailer}(v_{lo})$
   e. Adjust for ambient temperature (ISO 28580)
   f. For every run, calculate $\Delta F_{RR,veh}= F_{RR,veh}(v_{hi}) - F_{RR,veh}(v_{lo})$

7. Utilize the following method for discarding outlier data points:

   a. Measure data from multiples runs (which constitute one test).
   b. Discard known outliers or errors (*e.g.,* driver hit the brake during a run).
   c. Find the median angle, Θ, of all remaining runs.
   d. Draw vertical lines at $\Theta \pm 1.0°$, and discard all points outside the lines as not characteristic of the test's Θ. When discarding a point, discard the corresponding point from the run in the opposite direction.
   e. Find the average drag area and standard deviation, C_dA and σ, of the remaining runs' drag areas.
   f. Draw horizontal lines at $C_dA \pm 2\sigma$. Discard all points outside the lines.
   g. Take all remaining runs, average the angles to get a new mean angle Θ', and average the drag areas to get a new mean drag area C_dA'.
   h. If there are at least 24 runs remaining after all of the runs are discarded, then Θ' and C_dA' are valid for that test.

90957_7

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/18/2015 8:00:08 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Aerodynamic Bin Generation Slides
Attachments: Phase 2 Aero Bin Setting - EMA Concept 12-14-15.pdf

Hi Angela, Hi Matt,

As promised, attached are the GHG Phase 2 aerodynamic bin generation slides that Dan Kieffer presented during our meeting Tuesday.

Thanks again for the two days of very productive meetings – we appreciate the time and energy that go into them, both substantively and administratively. Additionally, I would like to wish you the happiest of Holidays, and all the very best in the New Year.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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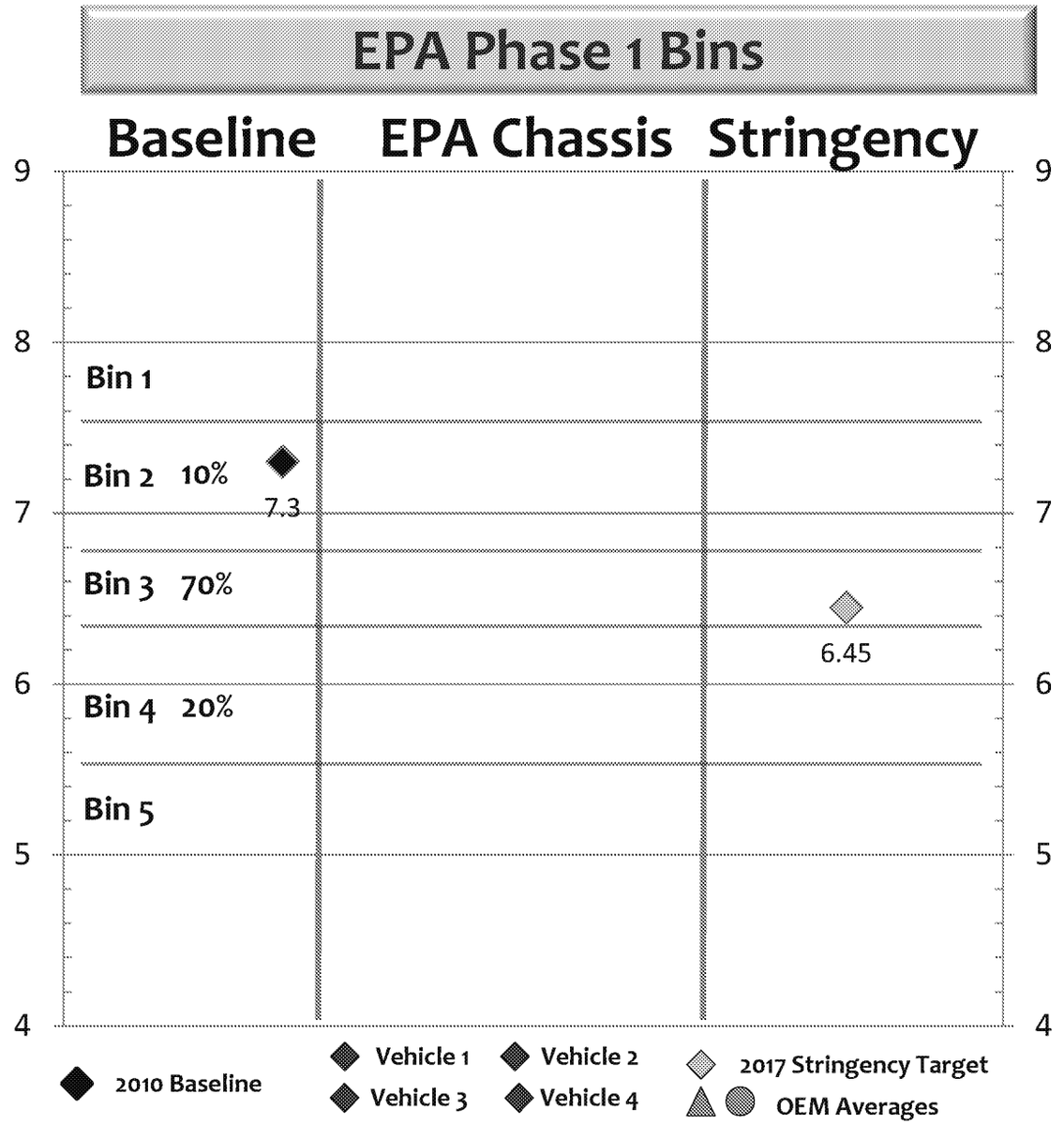
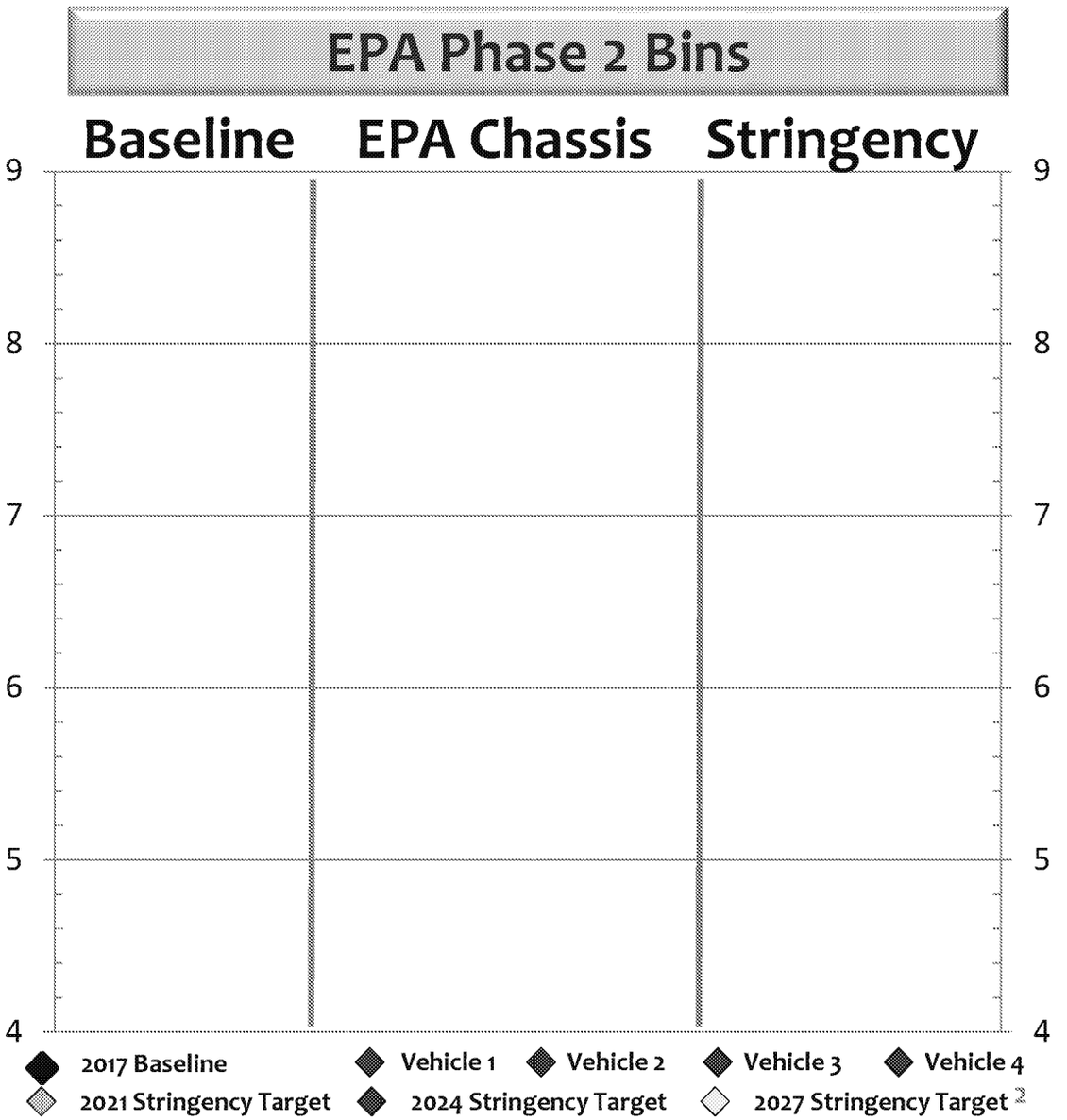
Aero Bin Generation – EMA Understanding

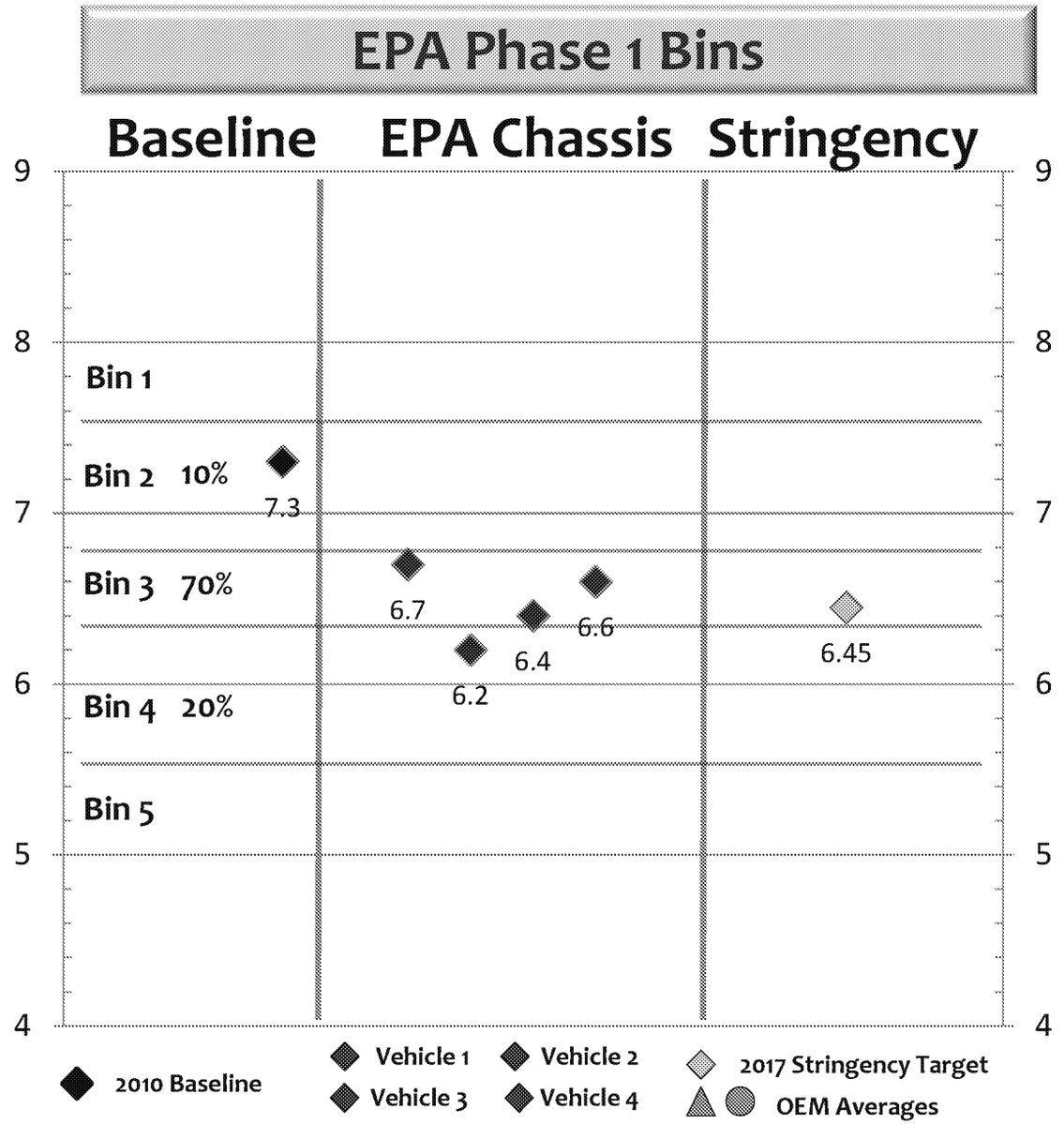
12-13-15

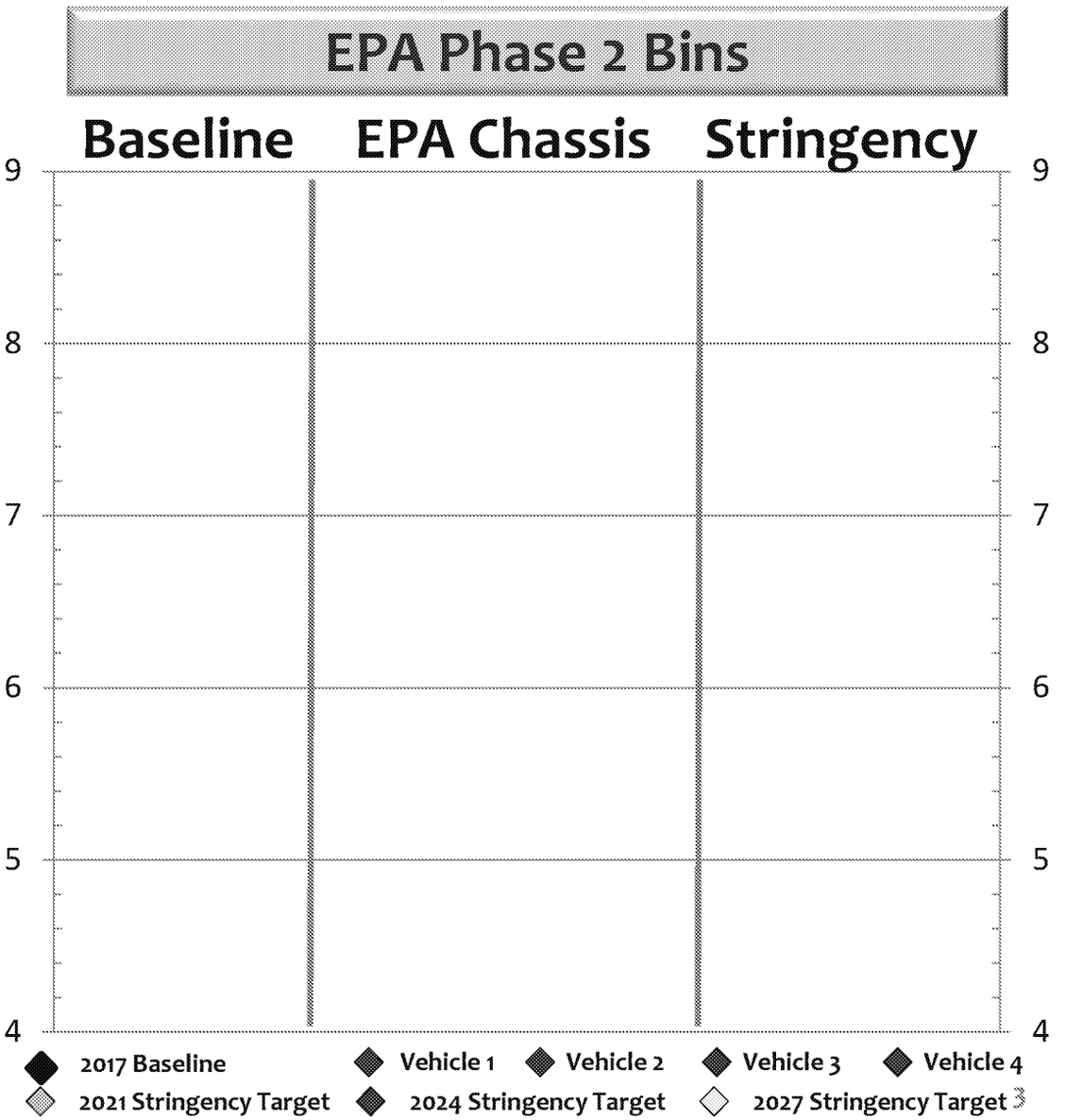
Class 8 Sleeper High Roofs – Phase 1



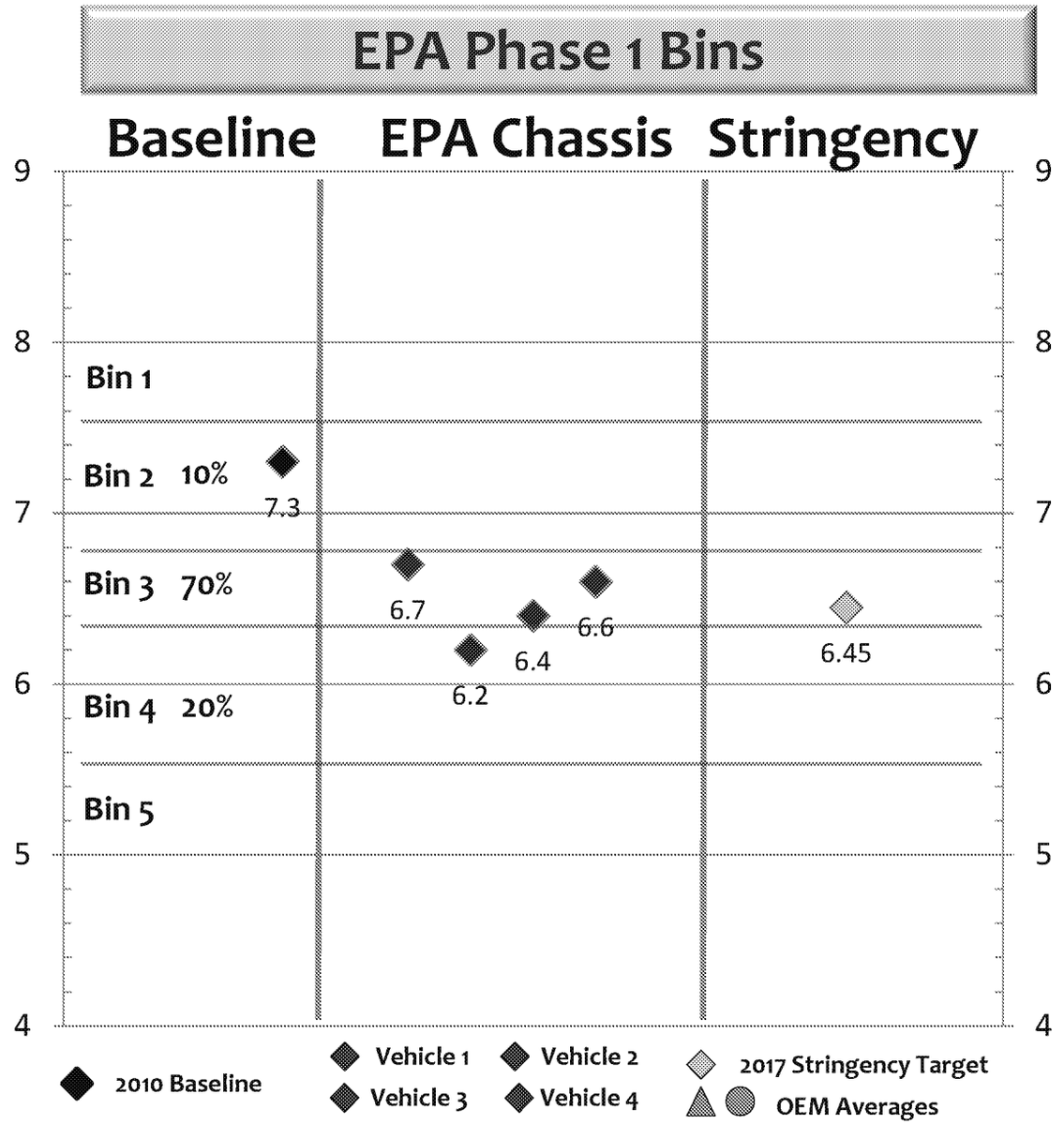


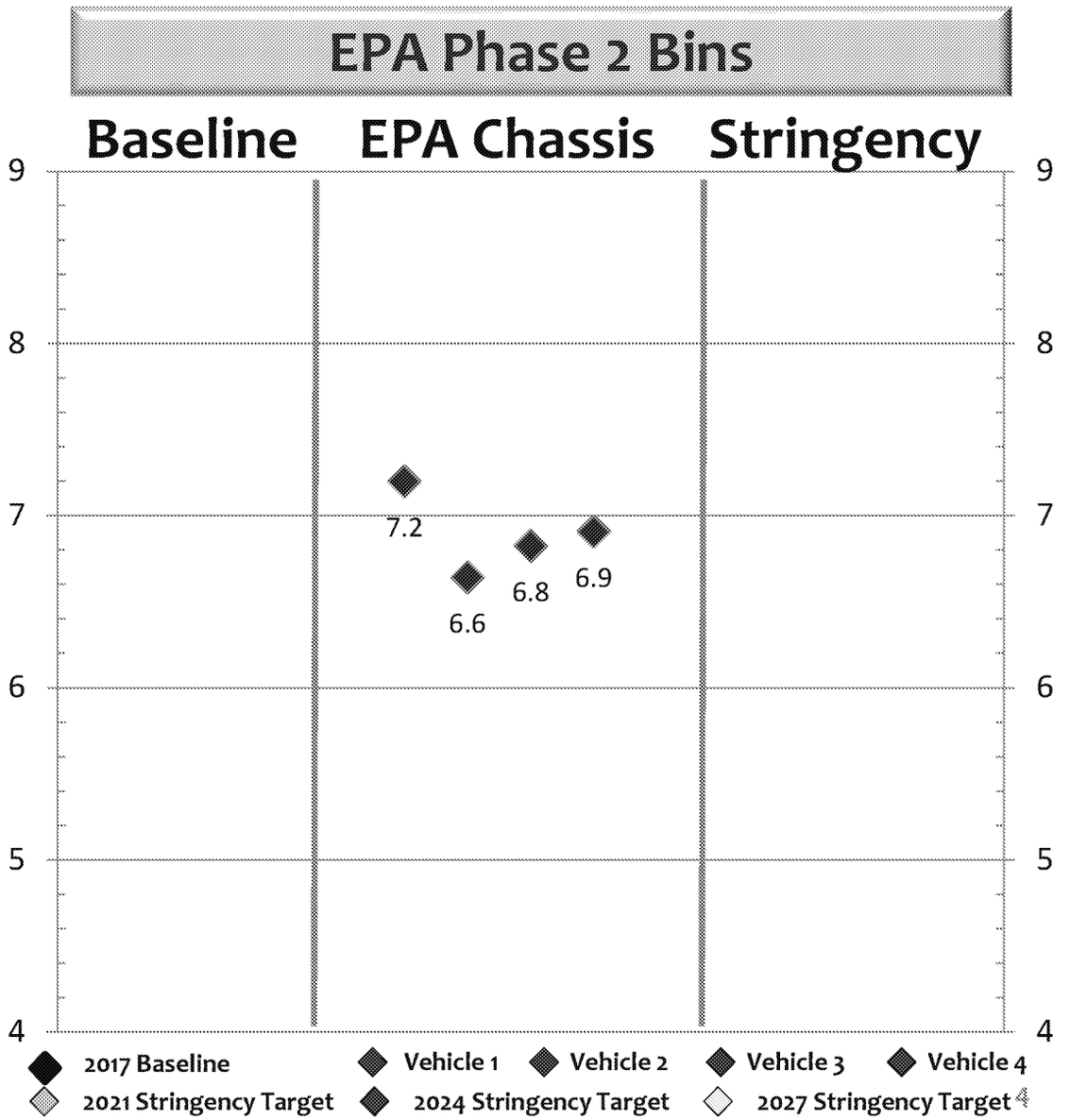
Add Vehicles – Phase 1 Trailer and Process



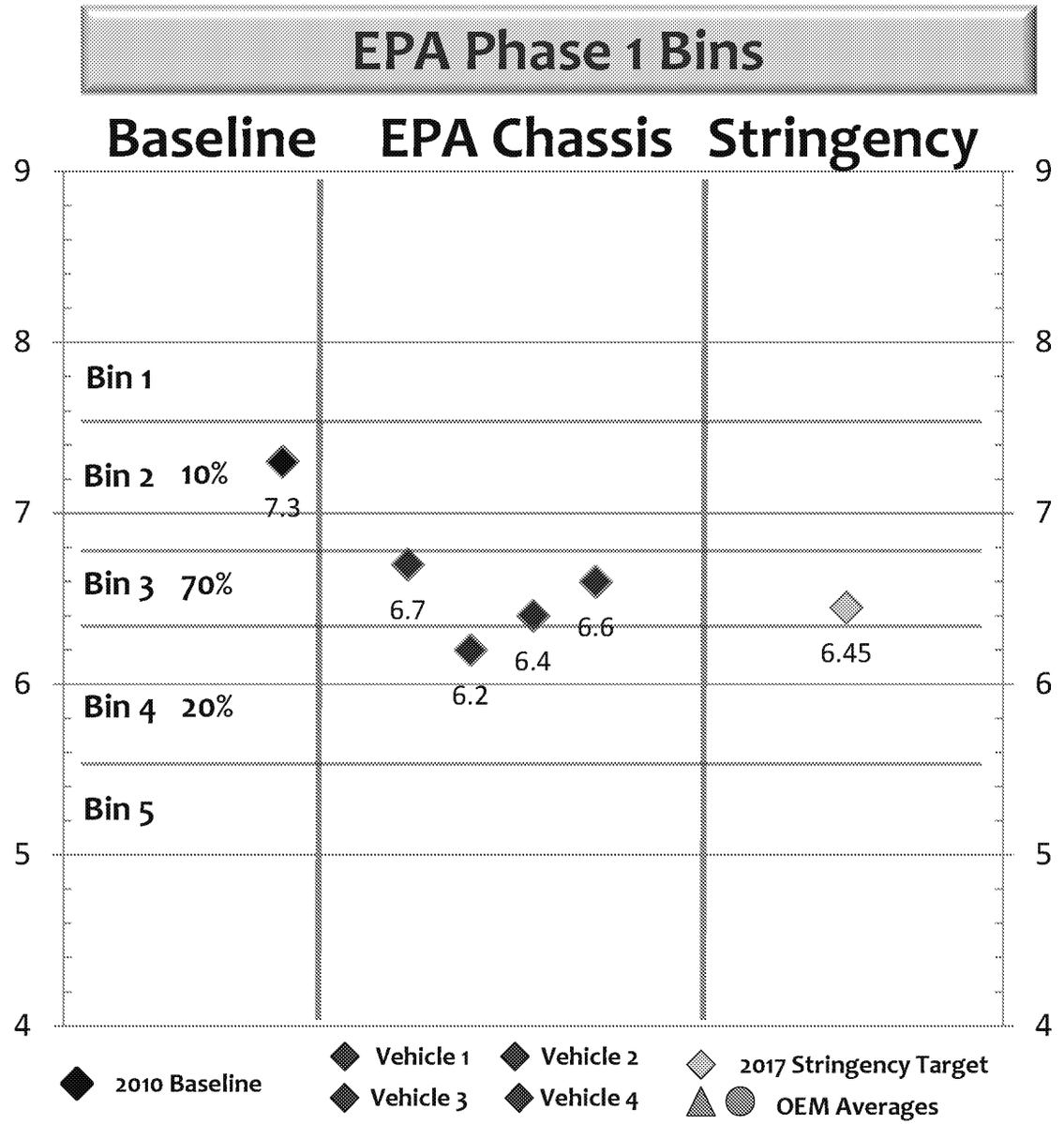


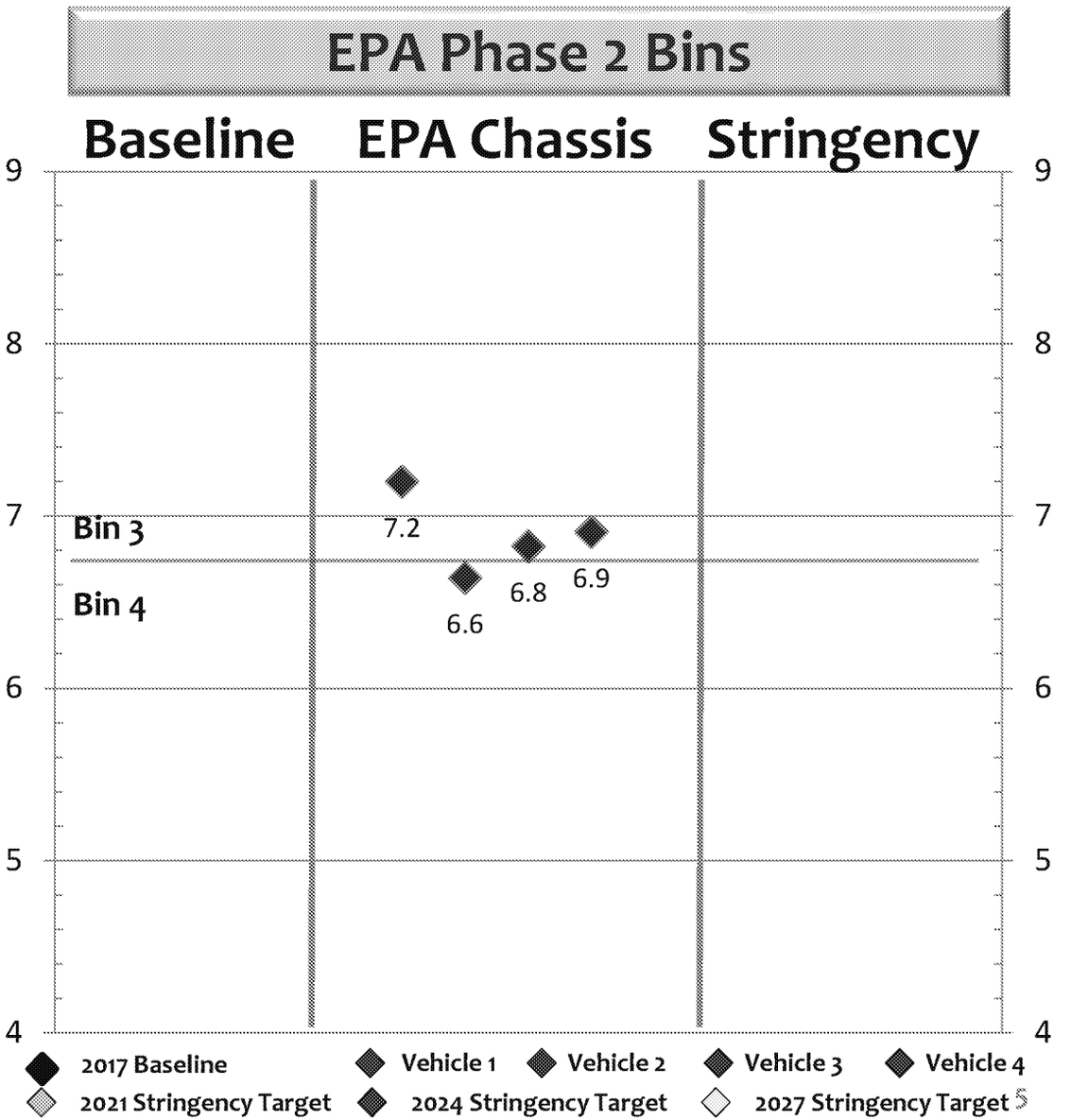
Add Vehicles – Phase 2 Trailer and Process



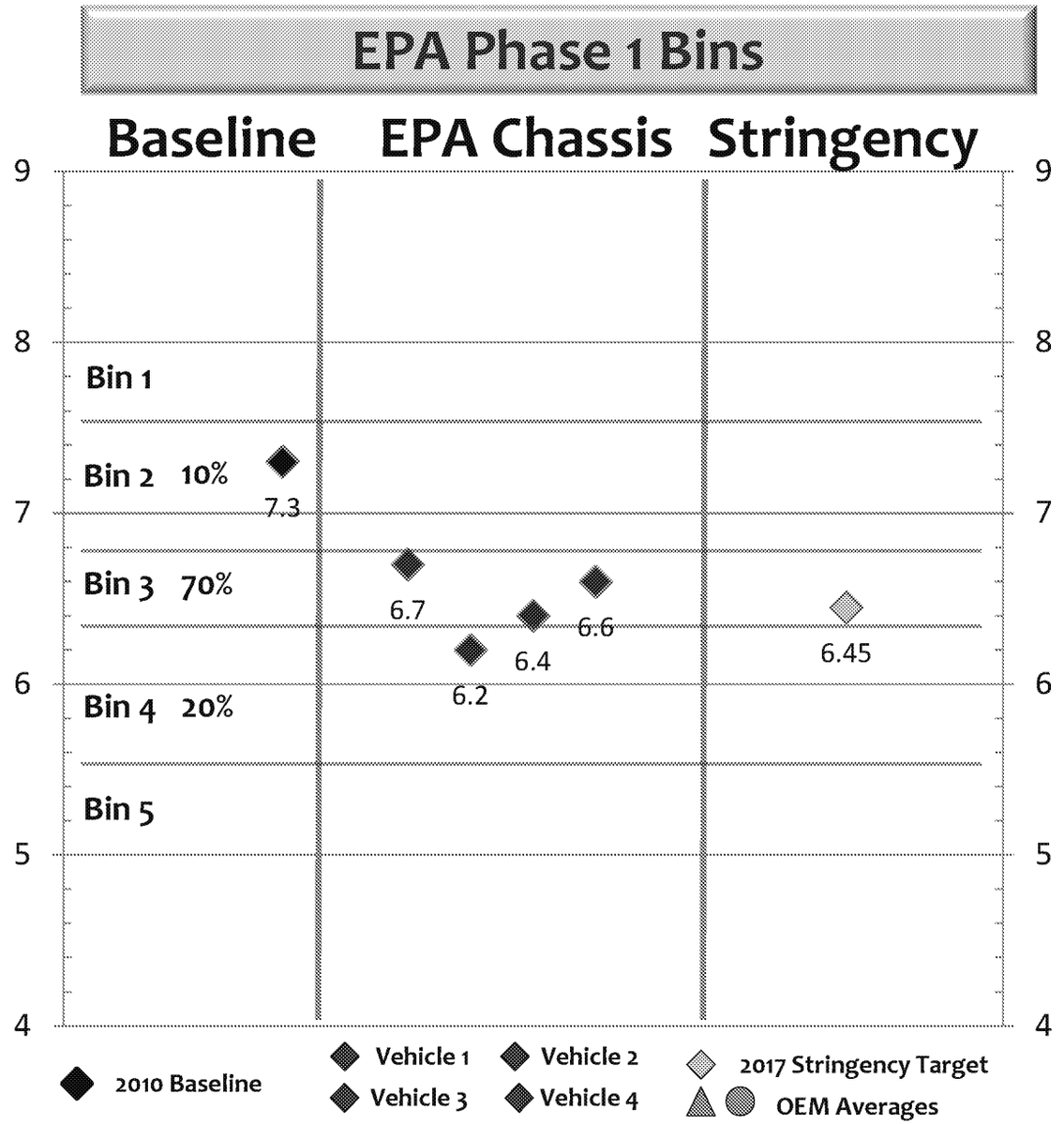


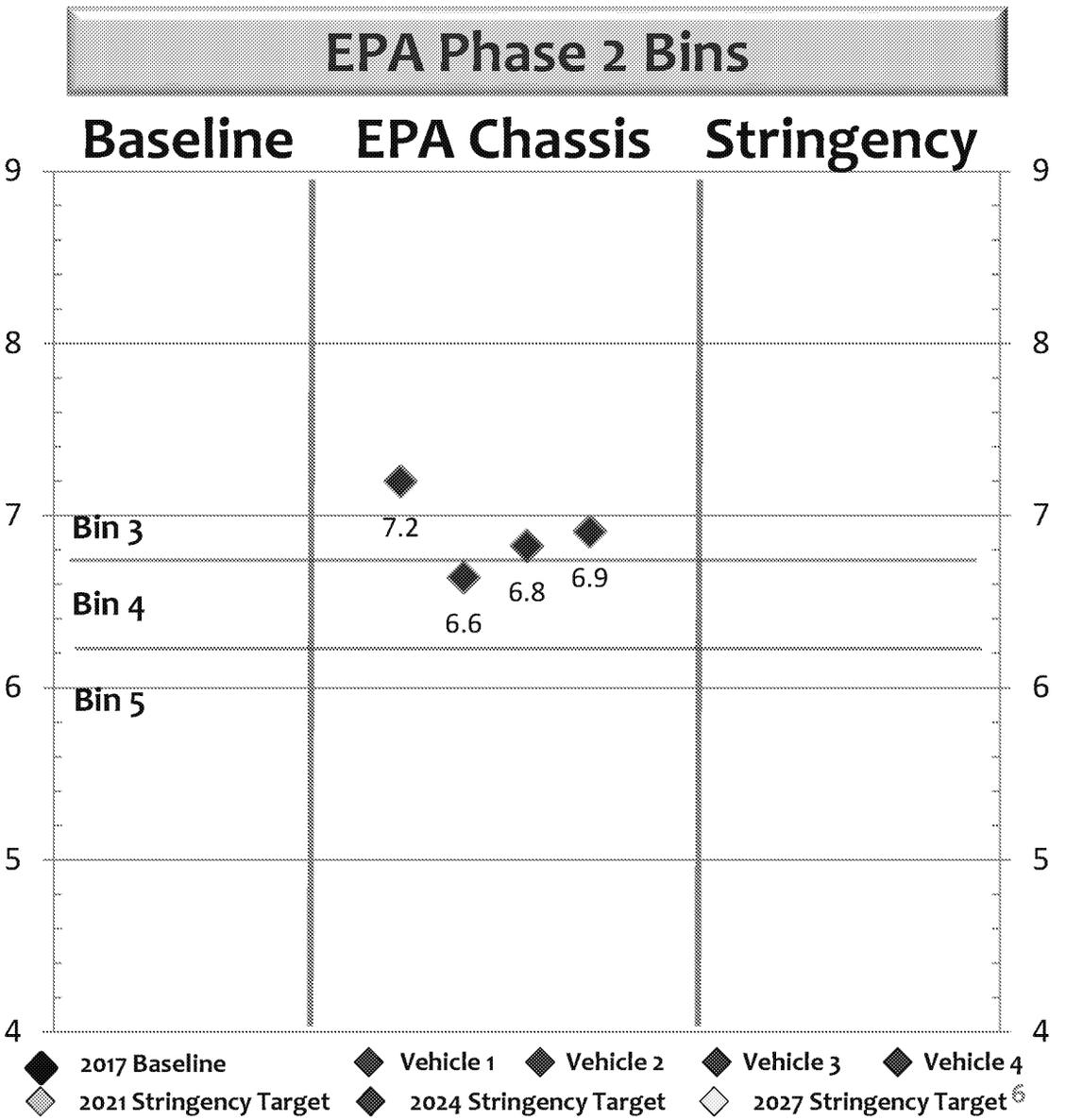
Add Bin 3 / 4 Line – Same Relative Location



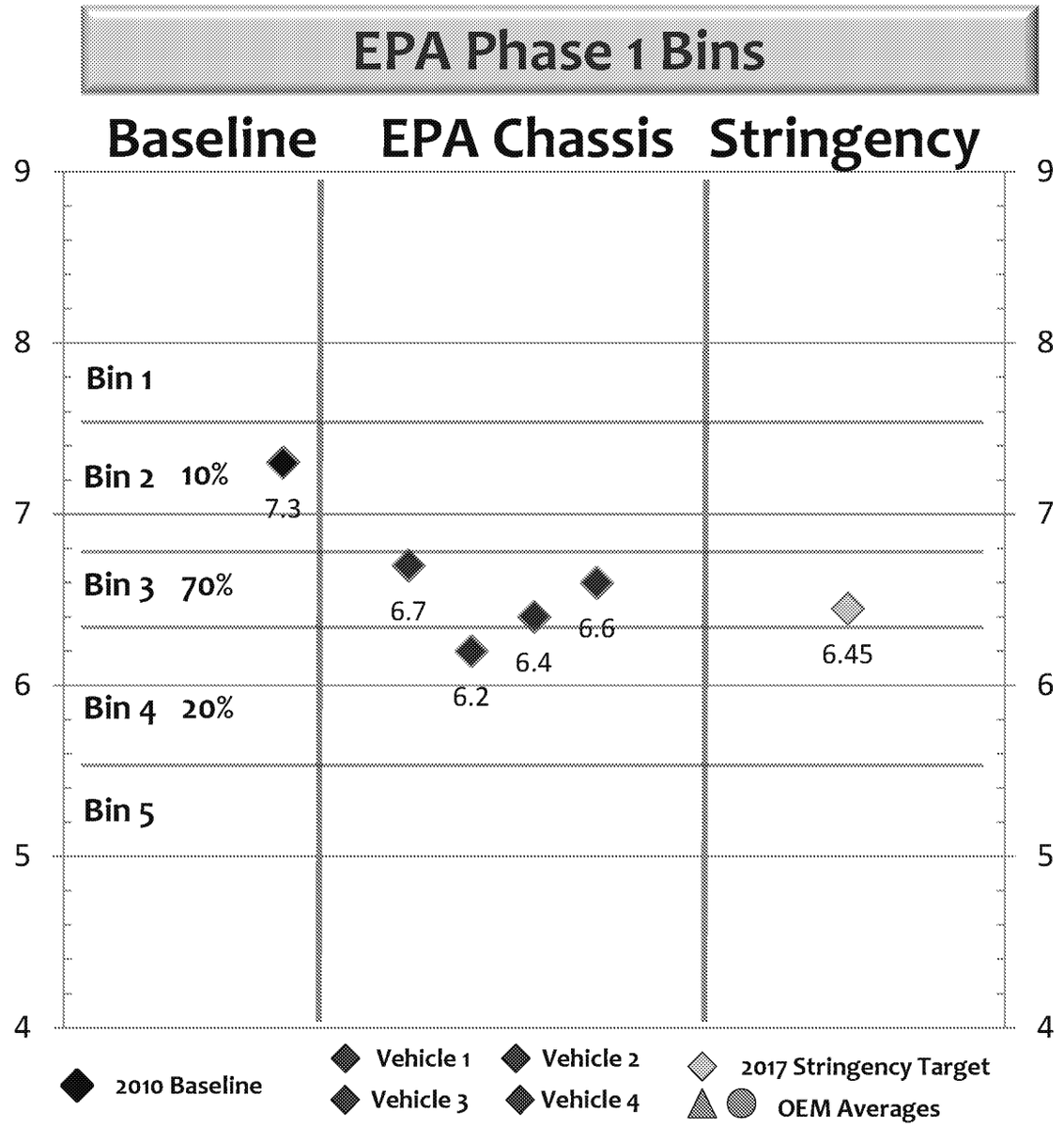


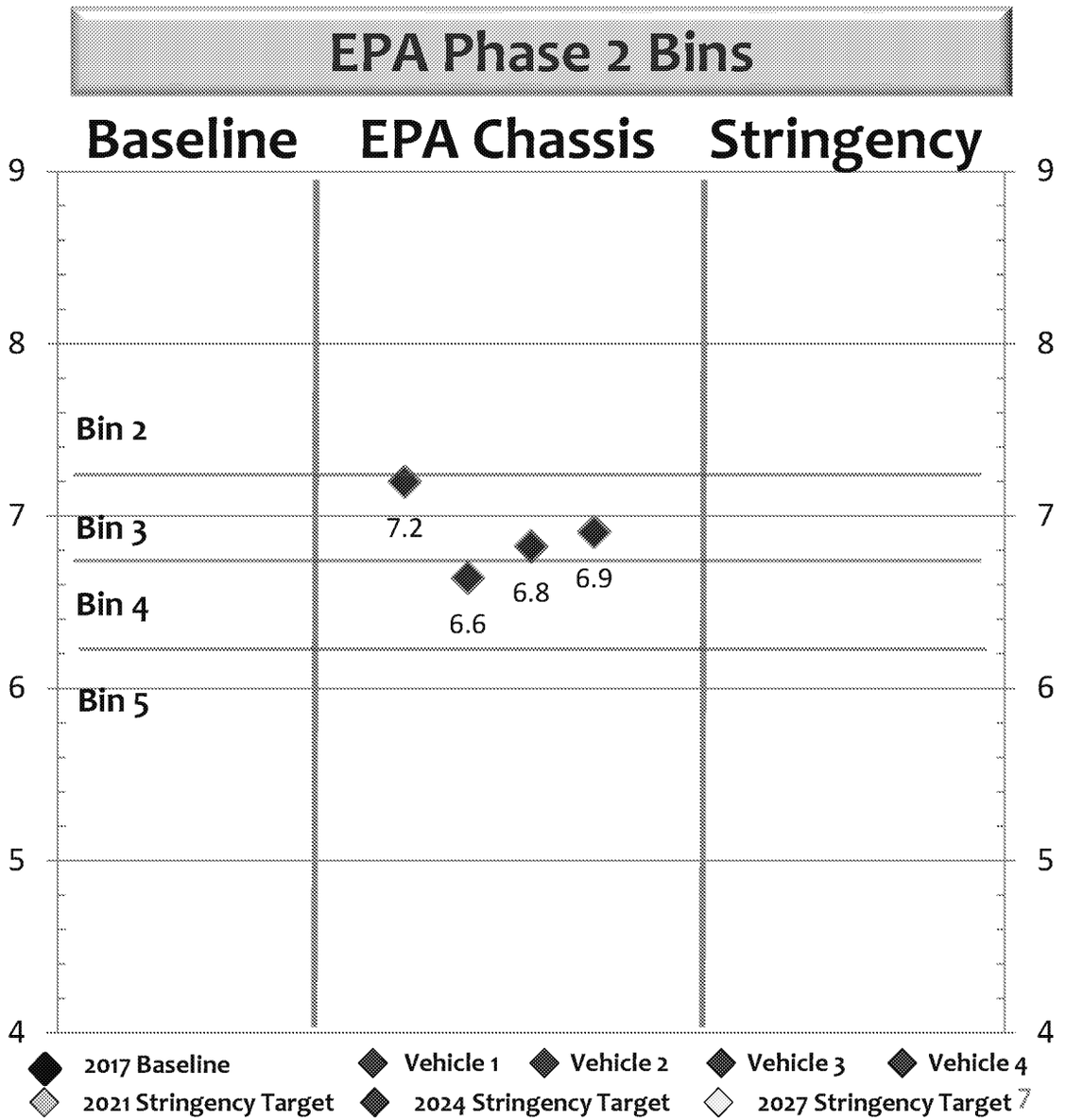
Add Bin 4 / 5 Line – Same Relative Location



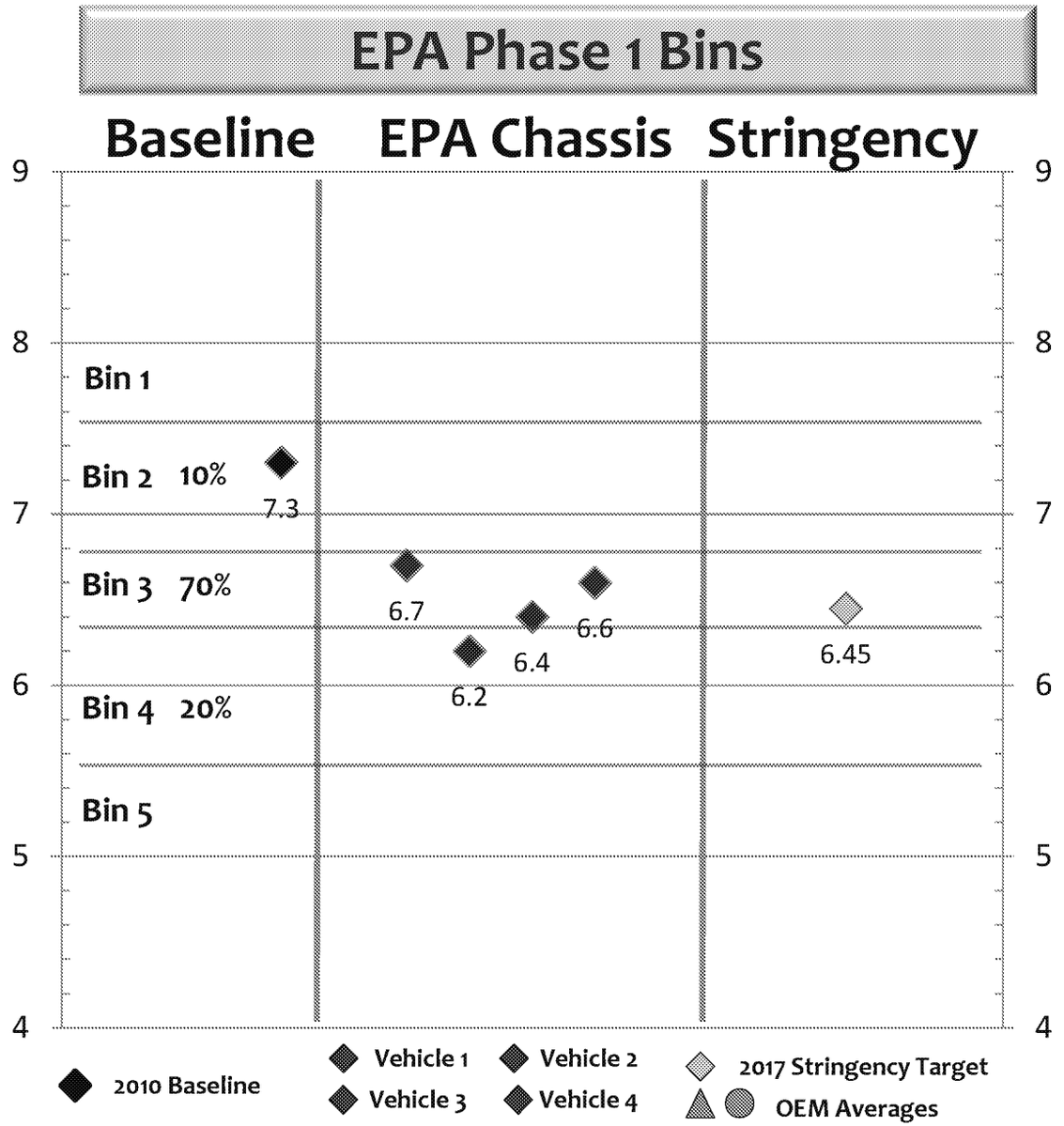


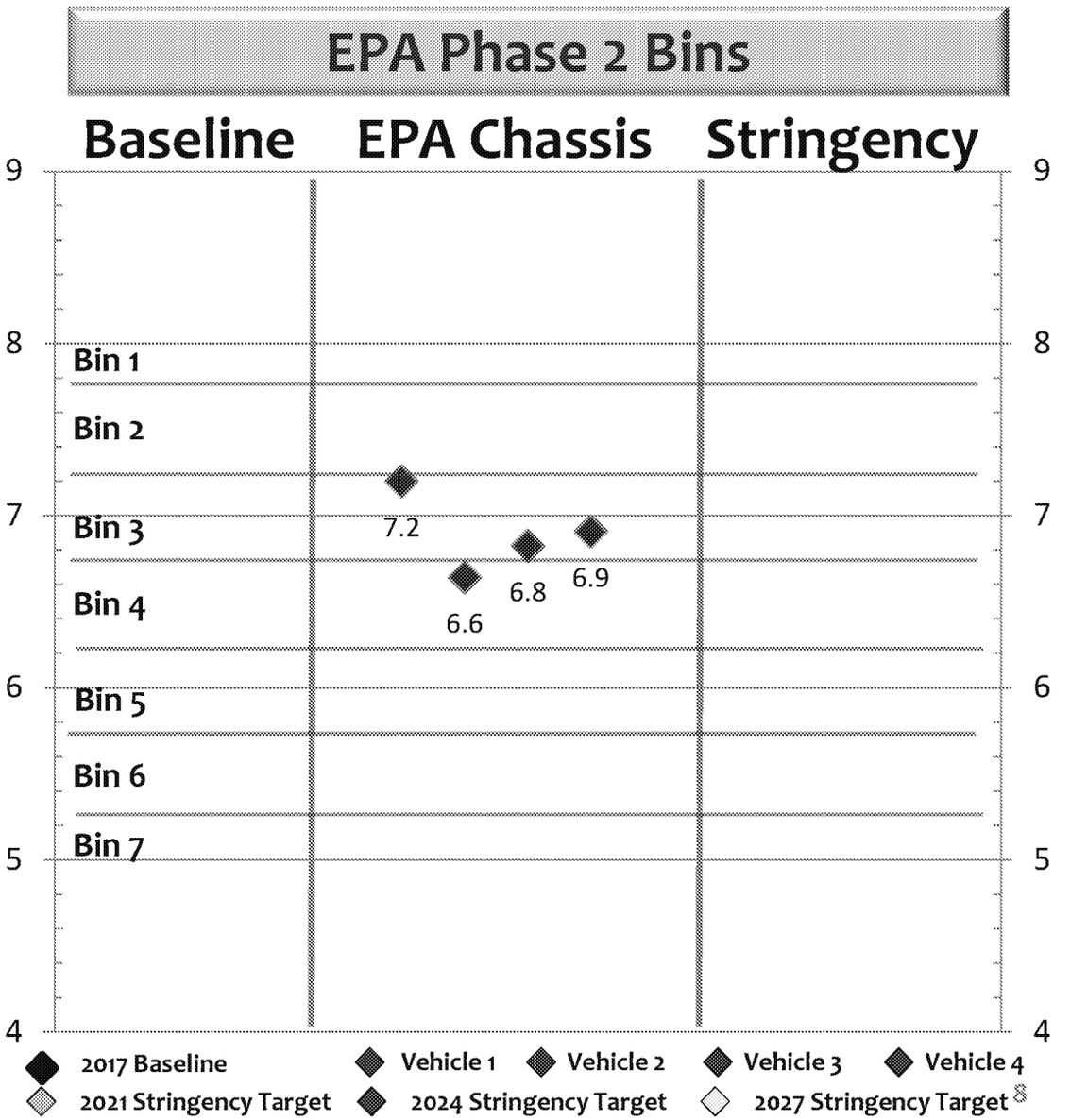
Add Bin 2 / 3 Line – Same Relative Location



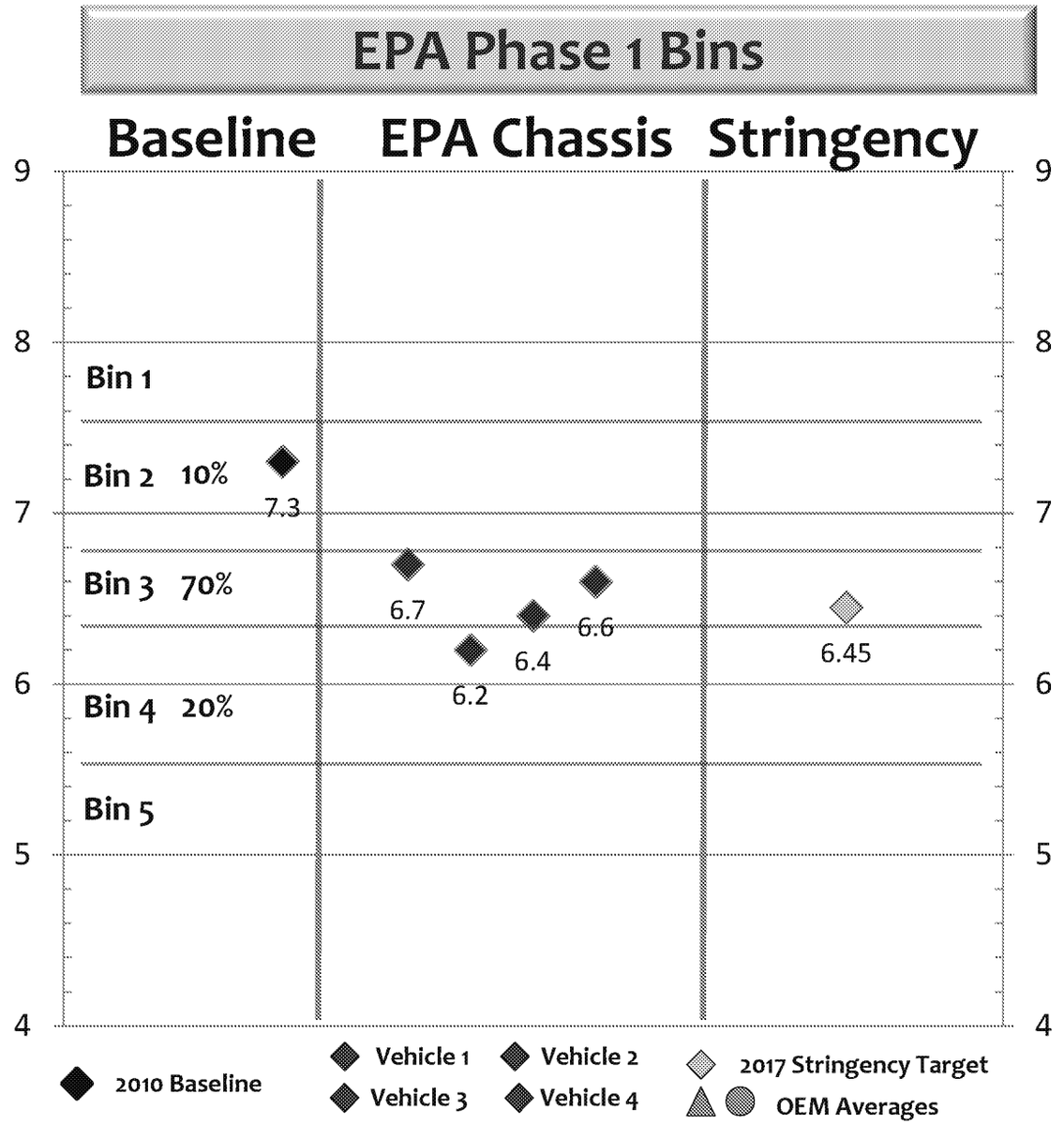


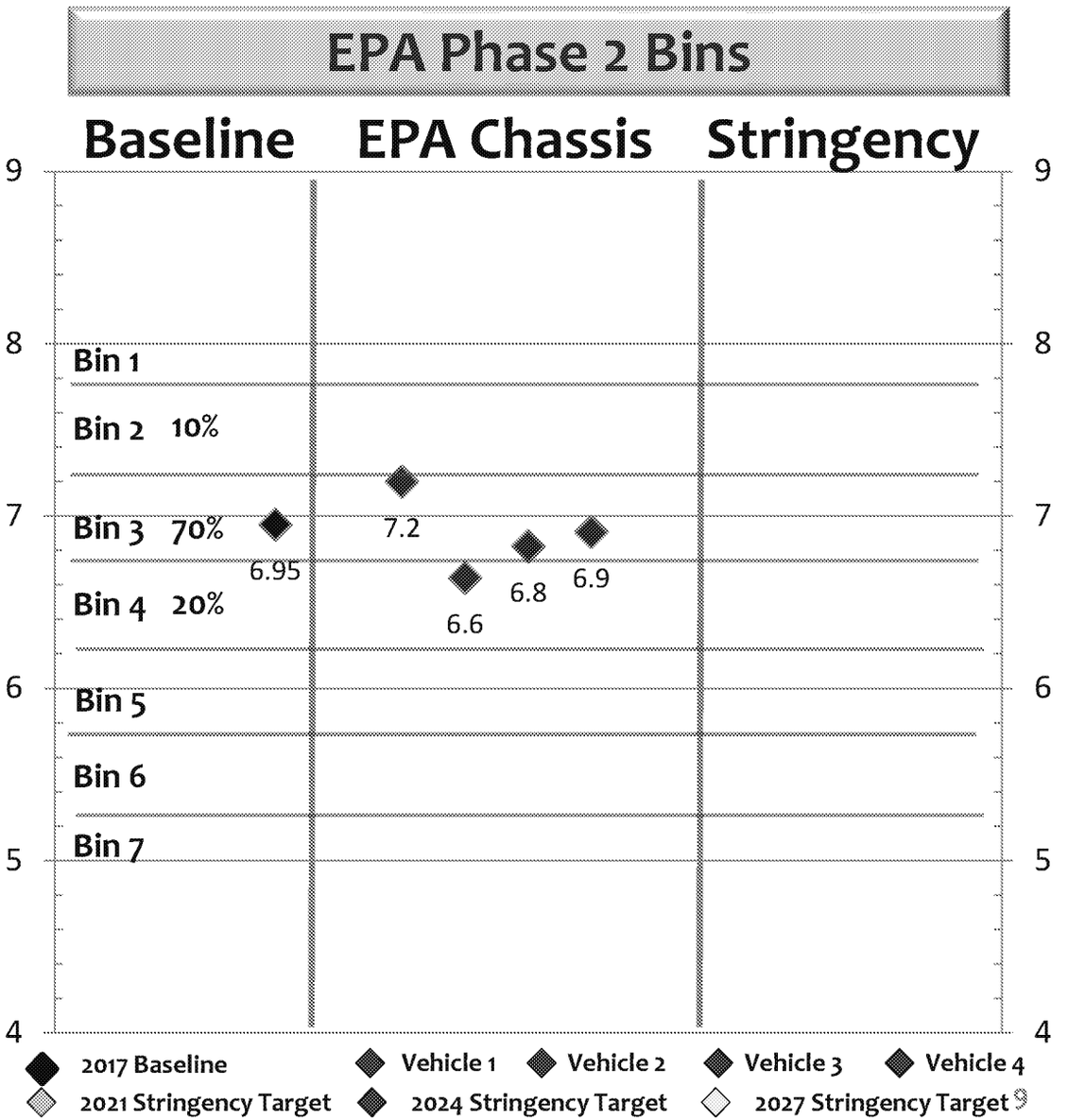
Add Other Bin Boundaries



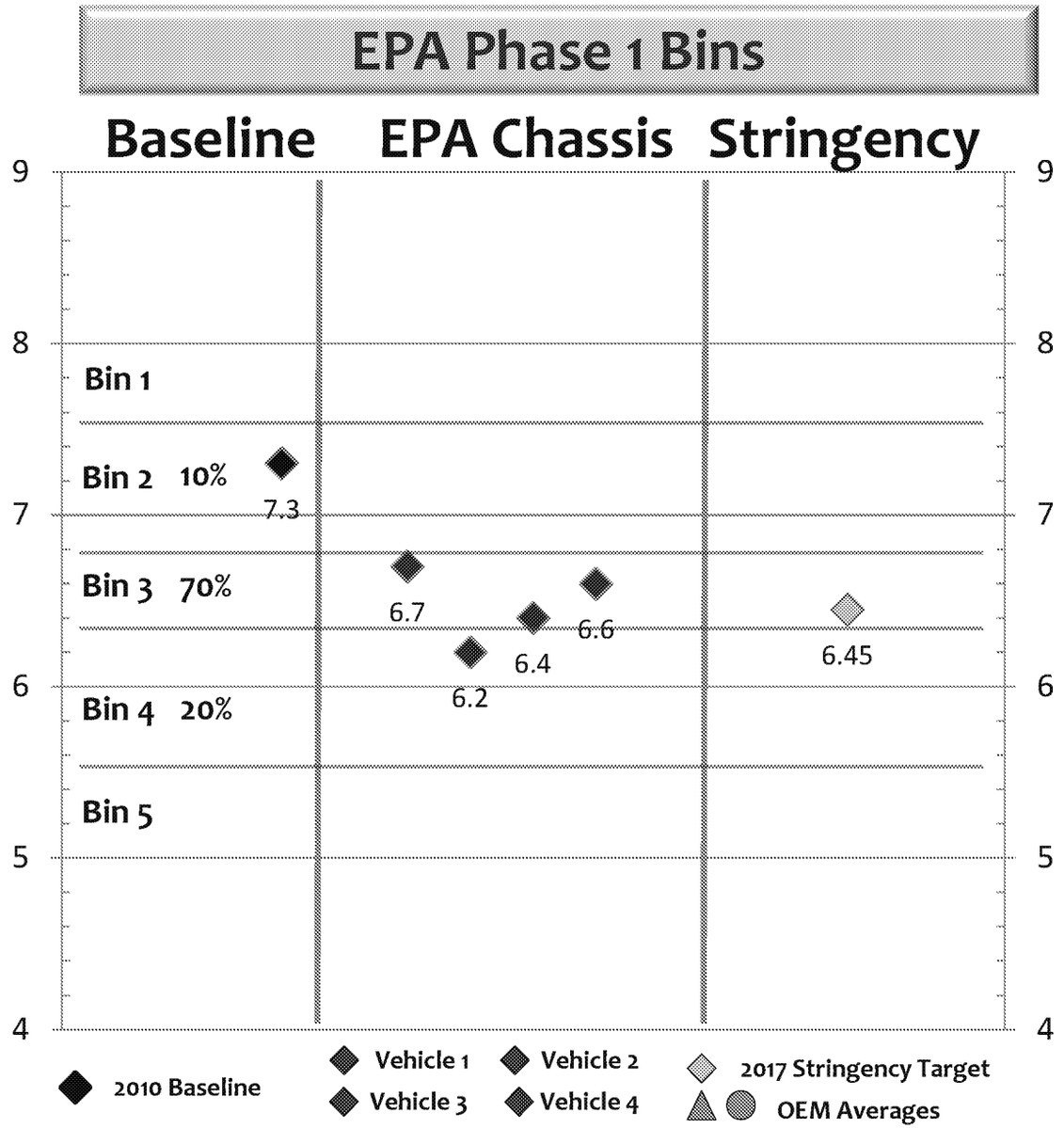


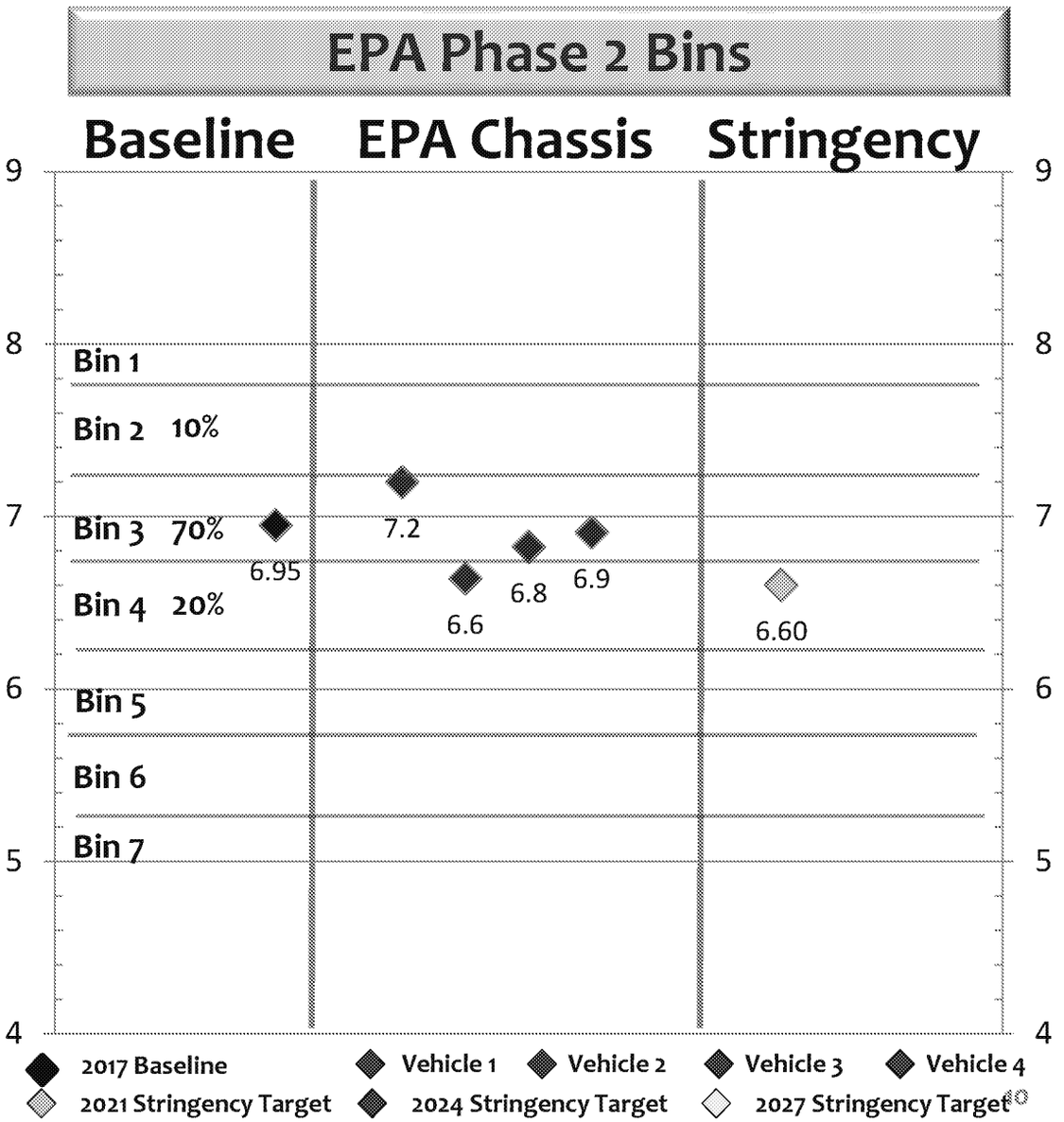
Use Phase 1 Weighting for Phase 2 Baseline



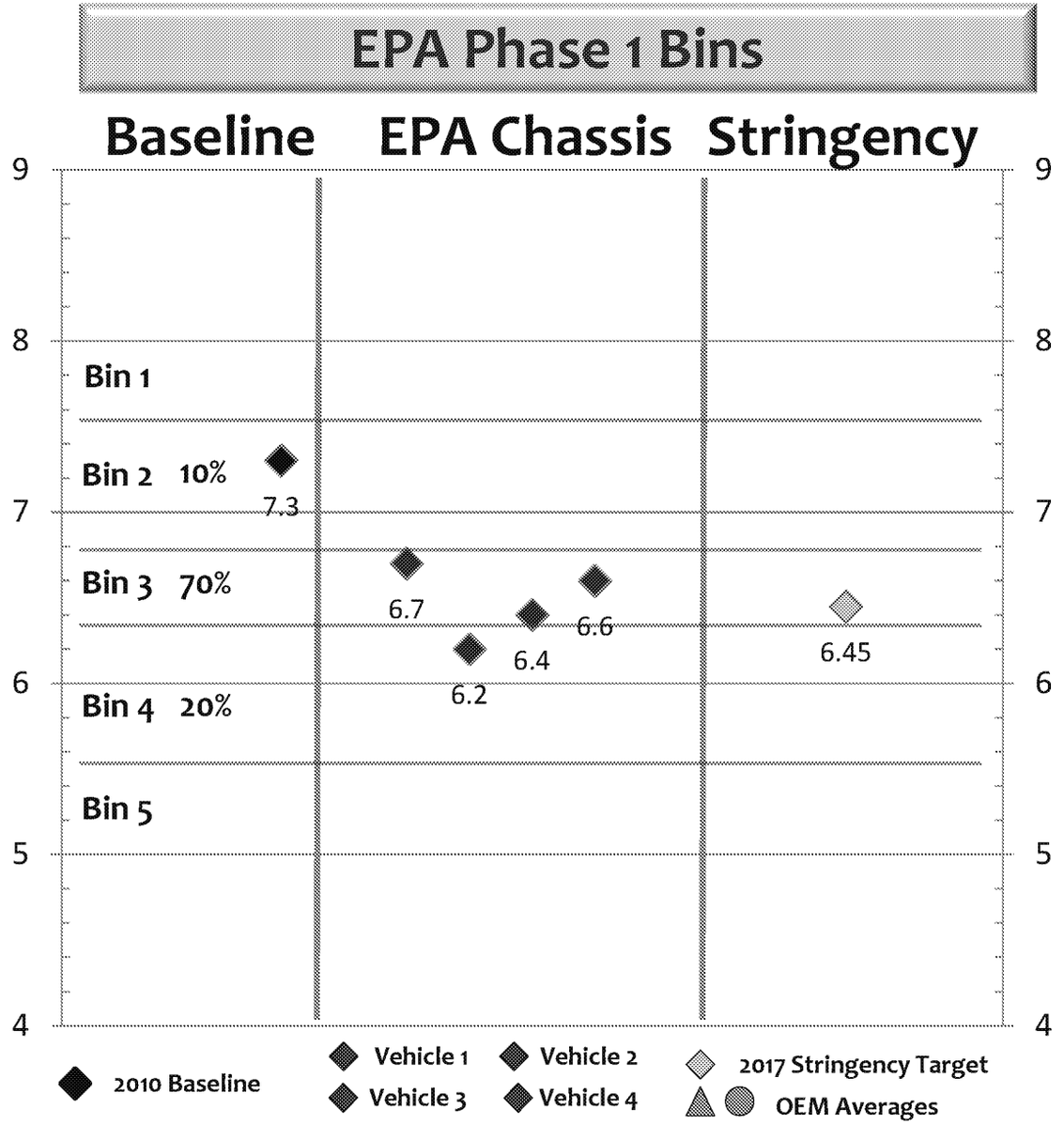


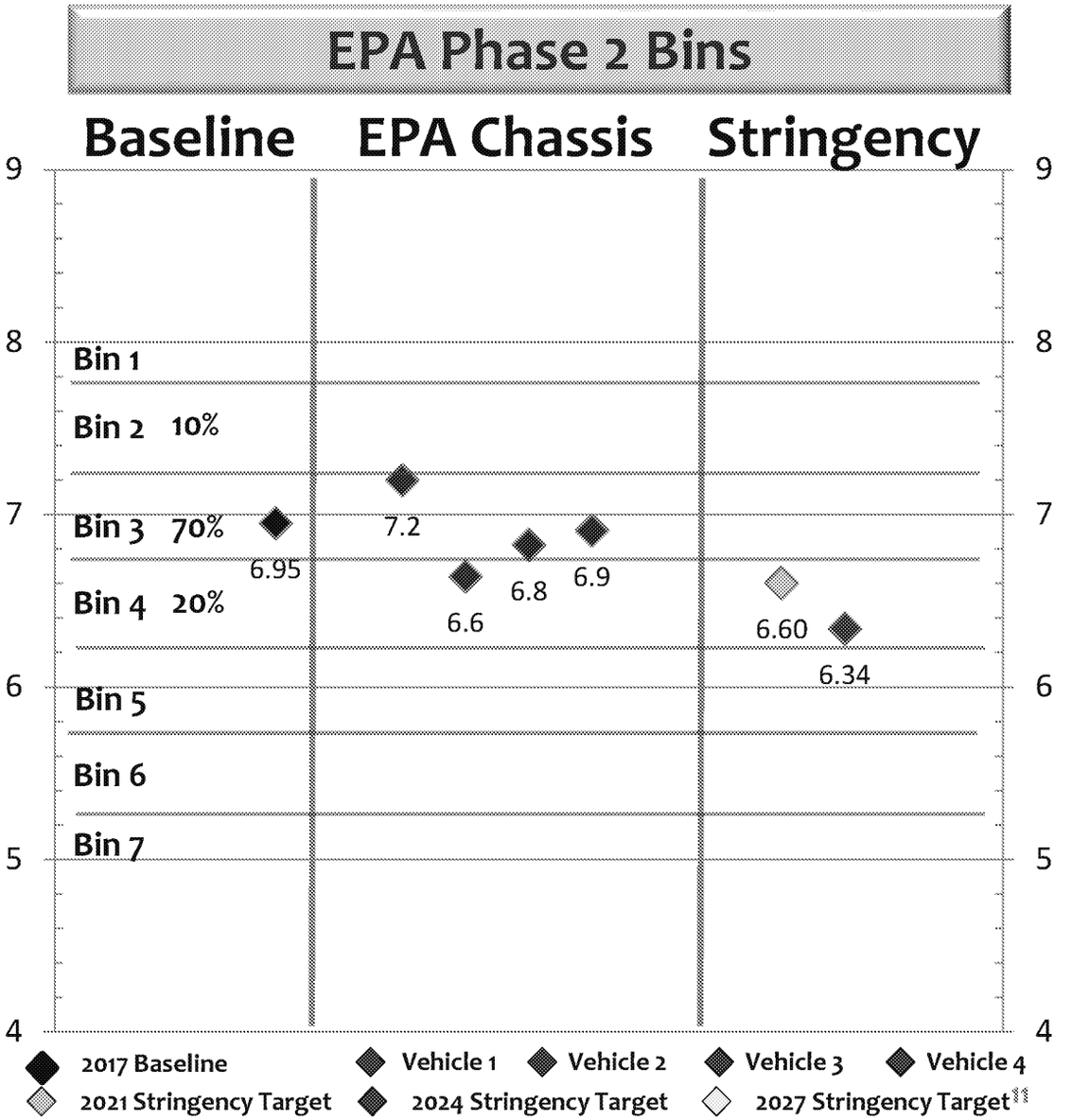
Add 2021 Average – 5% CdA Reduction



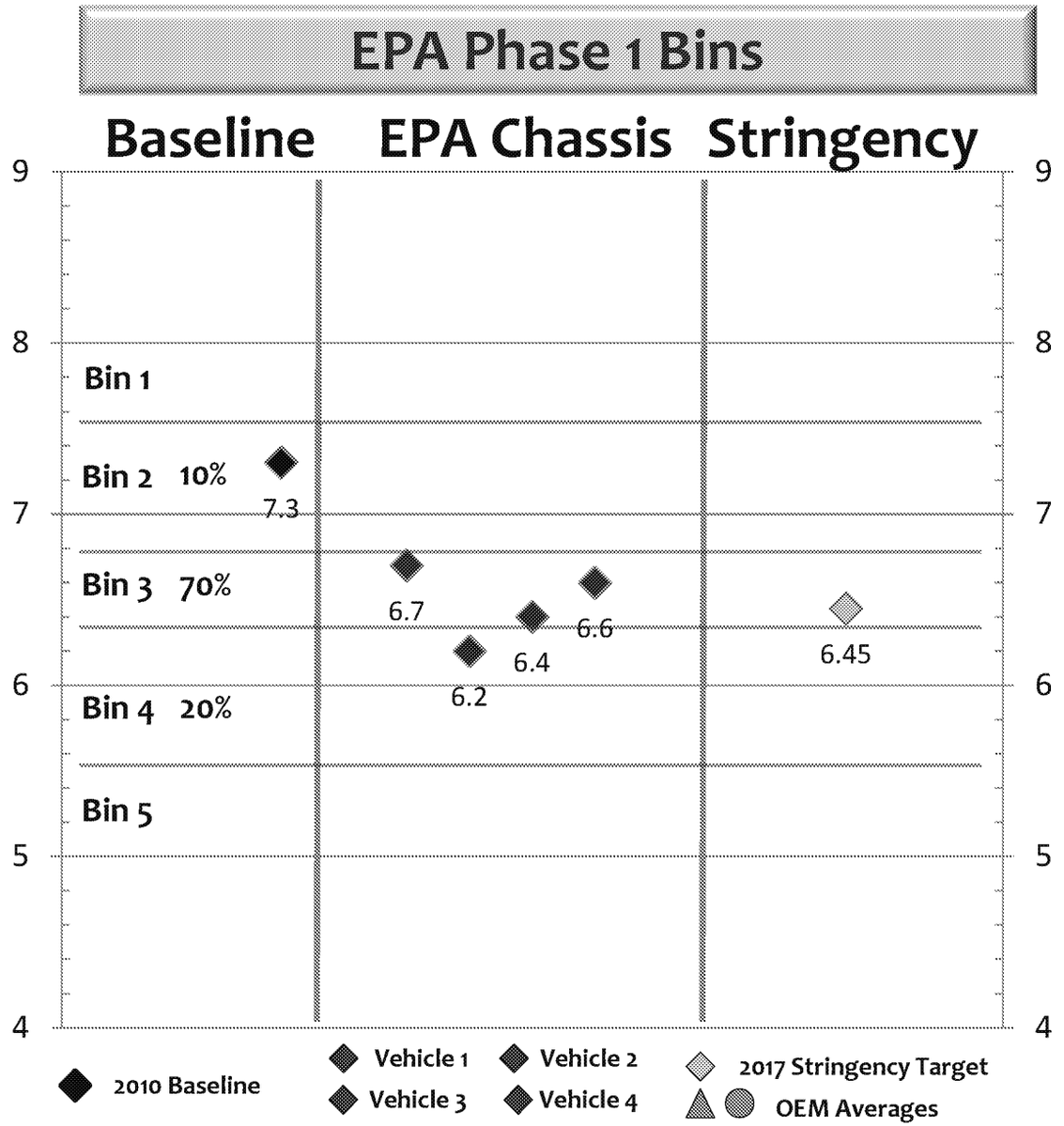


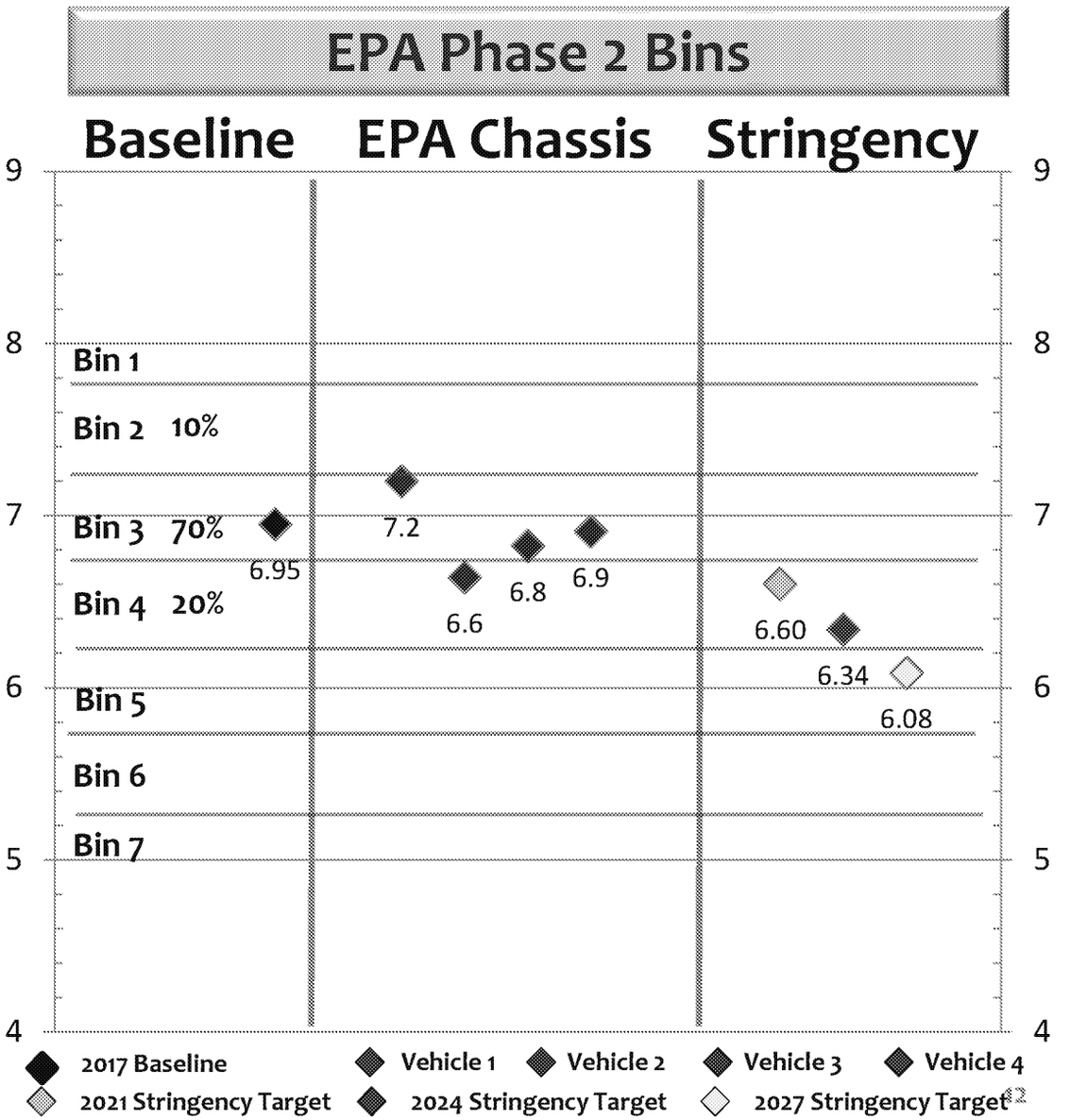
Add 2024 Average – 4% CdA Reduction



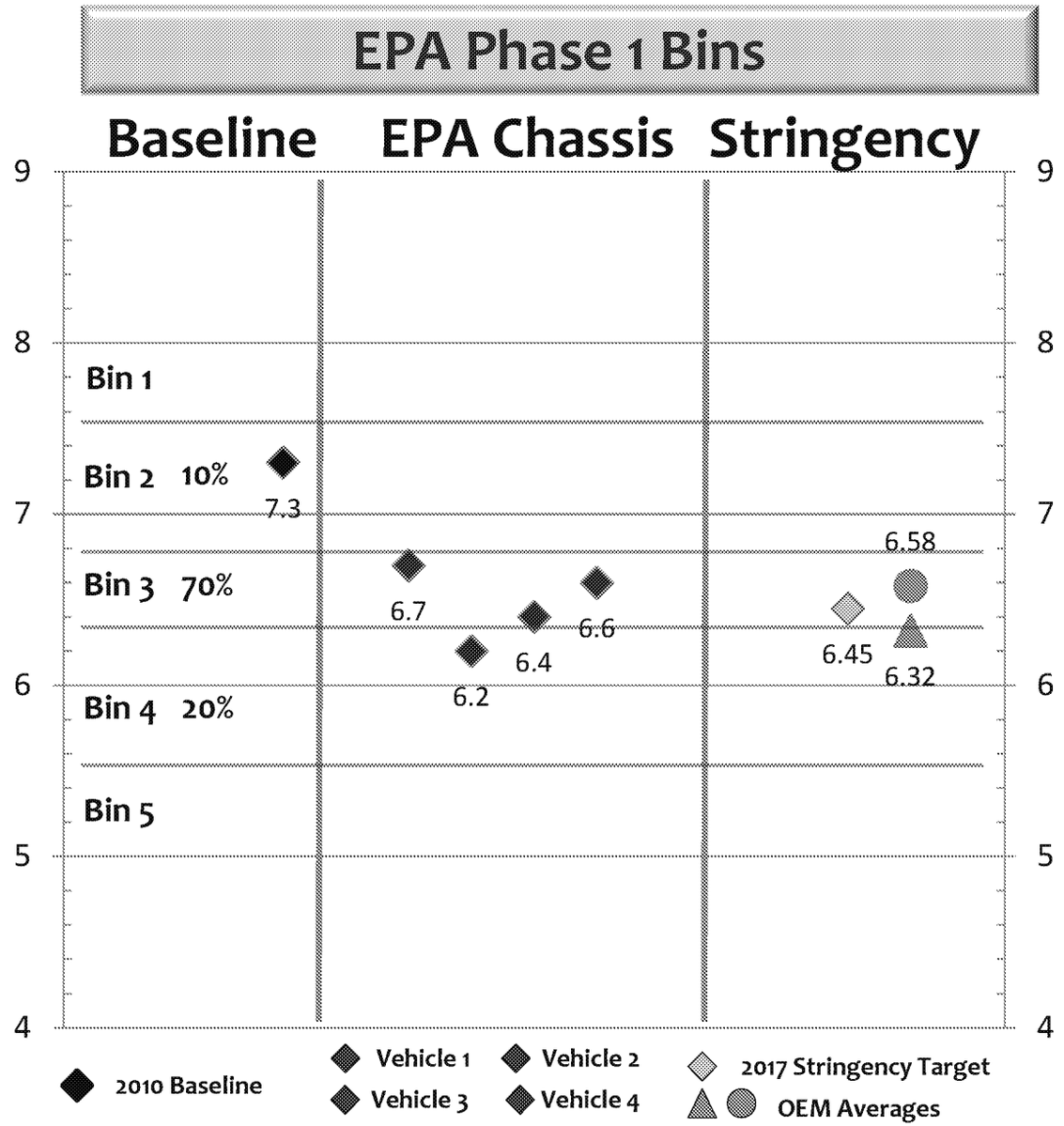


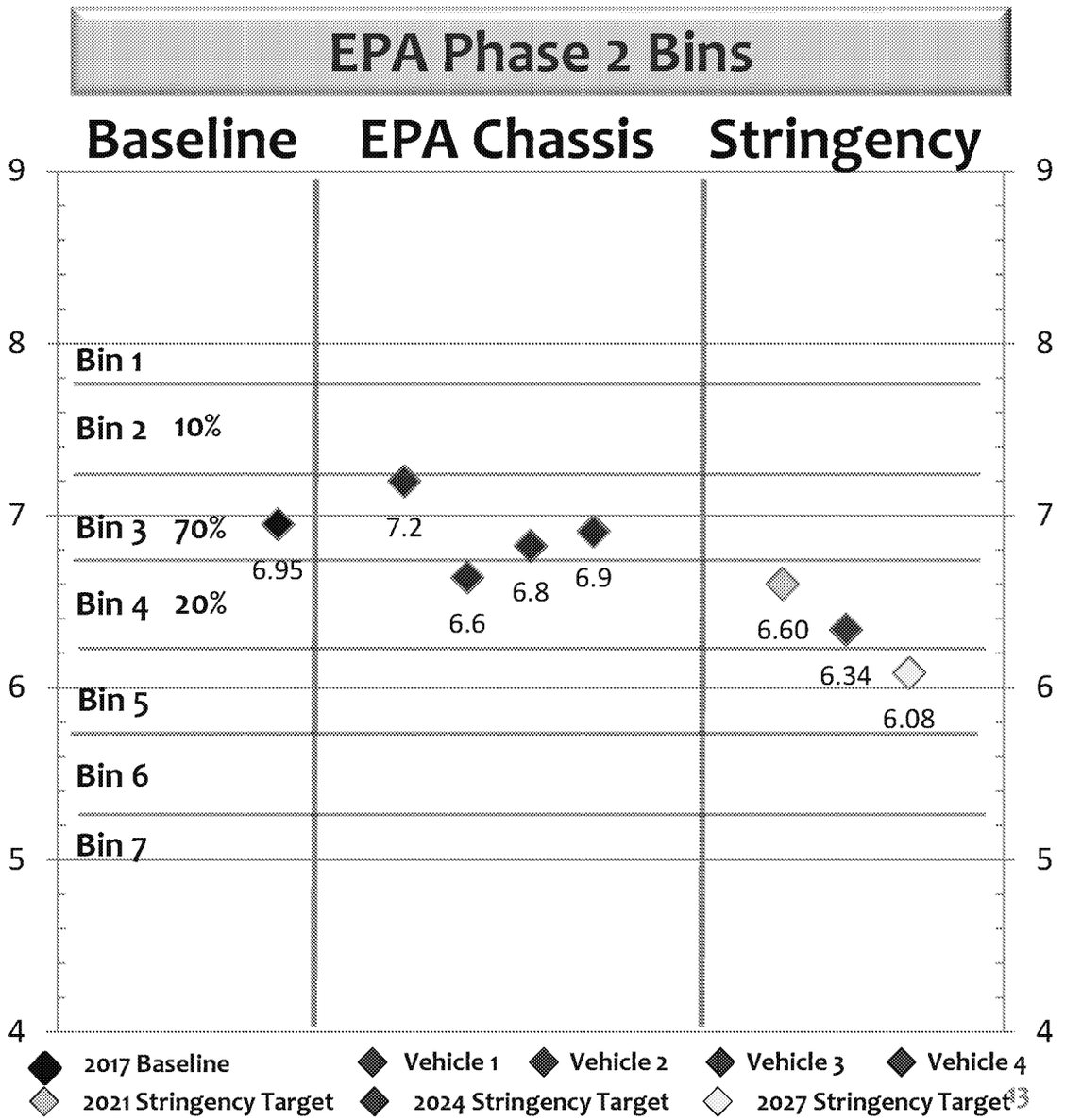
Add 2027 Average – 4% CdA Reduction





Add OEM Phase 1 CdA Average





Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/16/2015 1:20:50 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
CC: Andjelka Vujovic [avujovic@emamail.org]
Subject: More lunch...

Angela,

We missed two lunches on the list I sent you Monday. Is there any chance we could get #40 for Dan Kieffer and #81 for Marc Miler? Bottles of water for both.

Help!

Tim

Sent via my mobile device.

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 8/18/2015 5:18:45 PM
To: Iffland, JoNell [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=269c8731e7c6417482f8a8ddccfc4887-Iffland, JoNell]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Hearing audio

Hi JoNell or Angela – not sure if you are in attendance at the Long Beach Phase 2 hearing or not, but the sound on the phone line keeps dropping out. The hotel hold music is currently on again. Thought I'd let you know in case you are in a position to help fix it. Thanks!

Thanks,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/16/2015 11:50:40 AM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: Lunch

Hi Angela,

Is there any chance that at this point we could order a Zcobb Salad (#623) and a water ordered for Sean Waters?

With sincere apologies for the late notice,

Tim

Sent via my mobile device.

Message

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 8/18/2015 3:09:05 PM
To: Gary C Salemme [gary.c.salemme@cummins.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Question on Supertruck Comparison to EPA rule *from Cummins, Angela, would you be able to look into this?*
Attachments: EPA-HQ-OAR-2014-0827-0050.pdf

Hi Gary,

Houshun is not in the office today, and I might not be able to dig into the details today, but I wanted to loop Angela Cullen into this conversation now, in case she can help answer some Gary's questions more quickly than Houshun or I could.

For reference I am attaching one of our memos to the docket that at least provides some more detail on the analysis that Bill summarized to John Wall, below.

Gary, one of us will get back to you soon, thanks.

Matt

From: Gary C Salemme [mailto:gary.c.salemme@cummins.com]
Sent: Tuesday, August 18, 2015 9:58 AM
To: Zhang, Houshun; Spears, Matthew
Subject: Question on Supertruck Comparison to EPA rule

Houshun, Matt,

Bill C. sent the note below to John Wall. I assume you guys were involved in the calculation. Any chance that you can help me with the math?

My math on Supertruck goes like this.

PBI / Ex. 4

PBI / Ex. 4

Regards,

Gary

Dear John,

PBI / Ex. 4

Gary C. Salemme, P.E.
Director, Advanced Engineering Systems Integration

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gary.c.salemme@cummins.com

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
NATIONAL VEHICLE AND FUEL EMISSIONS LABORATORY
2565 PLYMOUTH ROAD
ANN ARBOR, MI 48105-2498

OFFICE OF
AIR AND RADIATION

May 27, 2015

MEMORANDUM

SUBJECT: Greenhouse Gas Emission Model (GEM) Simulation of the Best of 2027 Tractor-Trailers

FROM: Houshun Zhang, Jessica Brakora, and Angela Cullen
Mechanical Engineers, Office of Transportation and Air Quality

TO: Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 - Docket EPA-HQ-OAR-2014-0827

Background:

EPA analyzed the potential impact of the proposed Phase 2 Heavy-Duty Greenhouse Gas Emission and Fuel Efficiency Standards in terms of what we project could be the best of the tractor-trailers that would be built in 2027 and compare it to a typical tractor-trailer built in 2010.

Key Findings:

Based on the GEM simulation results detailed in the following sections, EPA projects the best tractor-trailer sold in 2027 will emit approximately 49 to 55 grams of CO_2 for every ton of payload carried per mile on the highway, which represents a 48 to 51 percent reduction in CO_2 emissions when compared to a typical tractor-trailer sold in 2010. EPA also projects the best tractor-trailer sold in 2027 will achieve 10 mpg while traveling at highway speeds. This vehicle would achieve double the fuel economy of a typical tractor-trailer sold in 2010.

Engine and Vehicle Inputs to the Simulation Model:

EPA developed the GEM inputs for two types of tractor-trailers – a typical tractor trailer built in 2010 and a tractor-trailer that represents the best of what could be built in 2027. Details of the inputs are included in the following subsections. In addition, since the Phase 1 and Phase 2 GEM models differ, details of how EPA compared vehicles across the two models are provided.

2010 Baseline Engine

EPA developed a baseline 2010 engine fuel map for the HD Phase 1 program. The engine represents a typical 15 L engine with a 455 horsepower rating built in 2010. The engine contains a selective catalytic reduction (SCR) system and a diesel particulate filter to meet the 2010 EPA standard for oxides of nitrogen (NOx) and particulate matter (PM). The 2010 engine fuel map used in simulation is shown below in Figure 1.

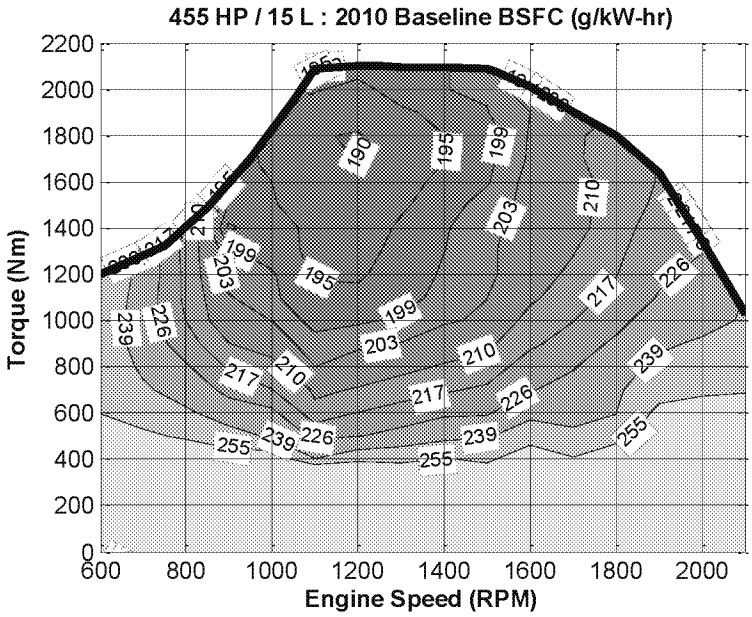

Figure 1: 2010 Engine Fuel Map

2027 Engine with Waste Heat Recovery

EPA developed a 2027 engine fuel map that included all of the technologies considered in the HD Phase 2 program, including waste heat recovery, downsizing, and improvements in parasitic loads, friction, aftertreatment backpressure, intake and exhaust flow, and combustion. The corresponding engine is a 15 L engine with 455 horsepower rating, the same displacement and output used in the 2010 baseline engine. The engine was also developed to meet the 2010 EPA standard for NOx and PM. The impact of each of these technologies relative to a 2017 MY engine over the 13 modes of the Supplementary Engine Test used in heavy-duty diesel engine certification is included in Table 1. The corresponding fuel map is shown in Figure 2.

The resulting engine has a peak brake thermal efficiency (BTE) of approximately 49.8% at 1150 rpm and 66% load. The composite BTE and CO_2 over the SET is 46.5% and 430.3 g/hp-hr with the current 13 mode weightings. With the proposed Phase 2 mode weightings, the composite BTE is 47.5% and CO_2 is 421.0 g/hp-hr. The optimal engine speed occurs between 1100 and 1250 rpm, consistent with trends in the heavy-duty engine industry.

Table 1: Impact of Engine Technologies on the 13 Modes of the Supplementary Engine Test (SET)
2017 Engine as Baseline

TECHNOLOGY	SET WEIGHTED REDUCTION (%)
WHR (RANKINE CYCLE)	3.6%
PARASITIC/FRICTION (CYL KITS, PUMPS, FIE), LUBRICATION	1.4%
AFTERTREATMENT (LOWER DP)	0.6%
EGR/INTAKE & EXHAUST MANIFOLDS/TURBO /VVT/PORTS	1.1%
COMBUSTION/FI/CONTROL	1.1%
DOWNSIZING	0.3%

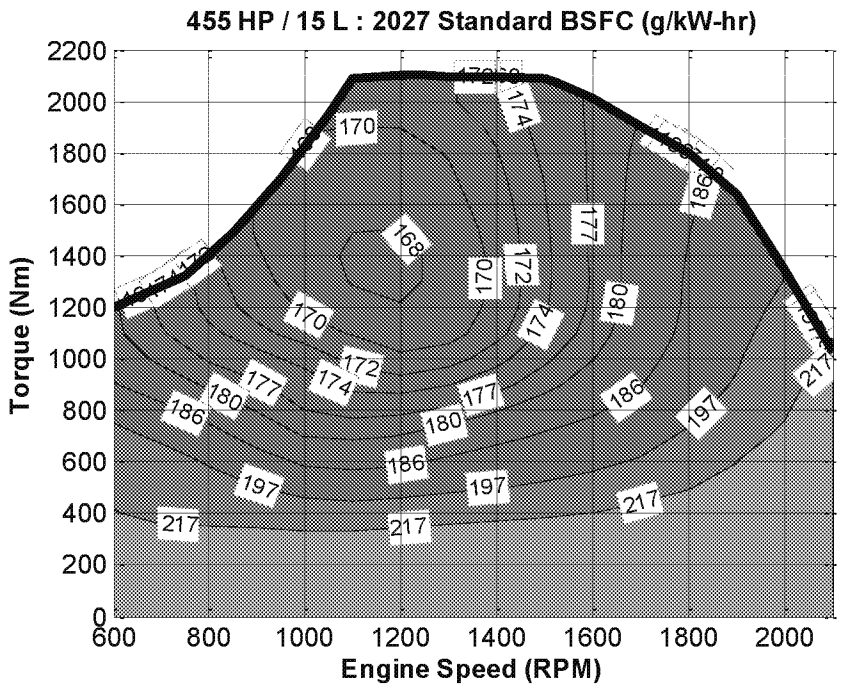

Figure 2: 2027 Engine with Waste Heat Recovery Fuel Map

2010 and 2027 Tractor-Trailer Attributes

The 2010 vehicle attributes of tire rolling resistance and coefficient of drag area were developed based on EPA's assessment of the baseline 2010 tractor-trailer in the HD Phase 1 final rule (76 FR at 57206). The tractor-trailer coefficient of drag area (CdA) value was calculated based on a 10.4 m^2 frontal area and the HD Phase 1 Cd value of 0.68, which represents a HD Phase 1 Bin II high

roof tractor with a generally aerodynamic shape pulling a box trailer with no aerodynamic devices. The GEM inputs used to derive the baseline 2010 tractor-trailer performance are listed below in Table 2.

In general, the 2027 Best Tractor-Trailer represents a combination of the best of each of the technologies that the agencies used to demonstrate feasibility of the proposed HD Phase 2 2027 MY tractor and trailer standards. The 2027 tractor steer and drive tire rolling resistance values represent the HD Phase 2 NPRM Level 3 tires. This level of rolling resistance represents the long-term rolling resistance value that Michelin predicts could be achieved in the 2025 timeframe. The agencies are proposing 2027 MY high roof sleeper cab standards premised on a 25% adoption rate of tires with rolling resistance at this level. The 2027 trailer tire coefficient of rolling resistance of 4.7 kg/metric ton represents a Level 2 tire in the HD Phase 2 NPRM. This level of trailer tire rolling resistance is available today and the agencies developed standards for long box trailers based on nearly full adoption of this level of rolling resistance by 2027. The 2027 Best Tractor-Trailer CdA value of 4.0 m^2 represents a wind averaged value and is derived from the proposed HD Phase 2 tractor Bin VI CdA value of 4.7 m^2, which is proposed at a 20% adoption level in 2027. The 4.7 m^2 tractor-trailer CdA value represents an aerodynamic tractor in combination with a box trailer with side skirts. The HD Phase 2 NPRM Trailer Aero Bin III represents a trailer with a side skirt and has a CdA delta of 0.3 m^2. The HD Phase 2 NPRM Trailer Bin VI represents a box trailer with a combination of advanced aerodynamic devices (including SmartWay Elite) and has a CdA delta equal to 1.0 m^2. The CdA delta between a trailer with only a skirt and a trailer with Bin VI advanced aerodynamics is 0.7 m^2 (equal to 1.0 – 0.3 m^2). We subtracted the trailer CdA delta of 0.7 m^2 from the tractor CdA level of 4.7 m^2 to derive the overall 2027 Best Tractor-Trailer CdA level of 4.0 m^2. In addition, we assume a slightly lower final drive ratio of 2.26 than the 2.34 (3.2 axle ratio multiplied by the 0.73 transmission top gear ratio) value used to derive the proposed HD Phase 2 2027 MY tractor standards. A 10-speed automated manual transmission (AMT) is used in the 2027 vehicle and represents a 50% adoption rate in deriving the proposed HD Phase 2 tractor standards. The GEM inputs used to derive the Best 2027 Tractor-Trailer performance are listed below in Table 2.

Table 2: 2010 and 2027 Class 8 High Roof Sleeper Cab Tractor with 53' Box Trailer GEM Inputs

Vehicle Attribute	2010 Baseline	2027 Best Tractor-Trailer
Fuel Map	2010 15L – 455HP	2027 15L - 455 HP - w/ WHR
Total weight (lb)	70500	70500
CdA (m^2)	7.2	4.0
Trailer Tire RR (kg/metric ton)	6.0	4.7
Steer Tire RR (kg/metric ton)	7.8	4.3
Drive Tire RR (kg/metric ton)	8.2	4.5
Transmission model	10 speed AMT with DD	10 speed AMT with DD
Transmission Top Gear ratio	1 .0	1 .0
Rear Axle Ratio	2.64	2.26
Axle efficiency	93.5 %	96%

The Best 2027 Tractor-Trailer also utilizes additional technologies proposed to be allowed for compliance in the HD Phase 2 NPRM, as shown in Table 3.

Table 3: 2010 and 2027 Technology Impacts

Technology	CO_2 reduction (%) in 2010	CO_2 reduction (%) in 2027
6x2 Axle	0.0%	1.5%
Low Friction Axle Lube	0.0%	0.5%
Automated manual transmission (AMT)	0.0%	2.0%
Predictive Cruise control	0.0%	1.0%
Air conditioning load reduction	0.0%	0.5%
Electric Accessories	0.0%	0.5%
Automated Tire Inflation Systems	0.0%	1.0%

The 2010 and 2027 vehicles were simulated using the 55 MPH, 65 MPH, and ARB Transient drive cycles. Two sets of runs were conducted, one without road grade in any of the cycles and the other with the proposed Phase 2 road grade in the 55 MPH and 65 MPH cycles. The weighted cycle results reflect the Phase 1 and proposed Phase 2 cycle weightings of 86% of the 65 MPH cycle, 9% of the 55 MPH cycle, and 5% of the ARB transient cycle.

Simulation Results:

The results of the GEM simulation without road grade in the cycles are shown in Table 4. The GEM simulation results of the cycles with road grade are shown in Table 5. Based on these results, EPA projects the best tractor-trailer sold in 2027 will emit approximately 50 grams of CO_2 for every ton of payload carried per mile on the highway, which represents a 50 percent reduction in CO_2 emissions when compared to a typical tractor-trailer sold in 2010. EPA also projects the best tractor-trailer sold in 2027 will achieve over 10 mpg while traveling at highway speeds. This vehicle would achieve double the fuel economy of a typical tractor-trailer sold in 2010.

Table 4: Simulation Results without Road Grade in the 55 mph and 65 mph Cycles

	2010 Baseline CO2 (g/ton-mile)	2027 CO2 (g/ton-mile)	2010 Baseline Fuel Economy (mpg)	2027 Fuel Economy (mpg)
55 MPH	81.8	40.3	6.6	13.3
65 MPH	100.2	46.9	5.4	11.4
ARB Transient	159.9	110.1	3.4	4.9
Weighted Results	101.5	49.4	5.3	10.8

Table 5: Simulation Results with Road Grade in the 55 mph and 65 mph Cycles

	2010 Baseline CO2 (g/ton-mile)	2027 CO2 (g/ton-mile)	2010 Baseline Fuel Economy (mpg)	2027 Fuel Economy (mpg)
55 MPH	85.9	46.3	6.2	11.6
65 MPH	102.7	52.1	5.2	10.3
ARB Transient	159.9	110.1	3.4	4.9
Weighted Results	104.1	54.5	5.2	9.8

The results of the GEM simulation also show that the proposed 2027 model year CO_2 emission standard for high-roof sleeper cabs is 35 percent lower than the 2010 baseline high-roof sleeper cab. The results are show below in Table 6.

Table 6: Simulation Results with Road Grade in the 55 and 65 mph Cycles Compared to the Proposed Standard

	Simulated 2010 Baseline CO2 Emissions (g/ton-mile)	Proposed 2027 MY CO2 Standards (g/ton-mile)
Weighted Results	104	67

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/14/2015 6:43:25 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: FW: Lunch Orders - Tues & Wed

Hi Angela,

Below are the lunch orders for tomorrow and Wednesday. Thanks so much for taking care of this.

See you tomorrow,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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From: Andjelka Vujovic
Sent: Monday, December 14, 2015 10:57 AM
To: Timothy A. Blubaugh
Subject: Lunch Orders - Tues & Wed

Tuesday, December 15th Lunch Order

Dan Kieffer #623 Zcobb Salad - bottle of water

Dave Kayes #20 Tom's New Job Deluxe Lunch Bag (Zzang! candy bar) - Bottle of Water

Dave Gardner #40 Siegel's Smoky Number Deluxe Lunch Bag - Bottle of Water

George Lin #19 Louie's Lunch Box Deluxe Lunch Bag (BBQ Chips) - Bottle of Water

Gerald Freitag #40 Siegel's Smoky Number Deluxe Lunch Bag - Bottle of Water

Joshua Kehs #00 d-$'s Cuban Conundrum Deluxe Lunch Bag - Bottle of Water

Marc Miller #00 d-$'s Cuban Conundrum Deluxe Lunch Bag (vinegar chips) - Coke

Raja Sengupta #23 Mary's Commute (No bacon) Deluxe Lunch Bag (Zzang! candy bar) - Coke Zero

Cortney Guzlas	#13 Sherman's Sure Choice Deluxe Lunch Bag – Diet Coke
Erin Luke	#23 Mary's Commute Deluxe Lunch Bag – Bottle of Water
Tim French	#40 Siegel's Smoky Number Deluxe Lunch Bag (with Cookie) – Diet Coke
Laura Ricart	#00 d-$'s Cuban Conundrum Deluxe Lunch Bag – Bottle of Water
Tim Blubaugh	#608 Cyprus Salad – Bottle of Water

Wednesday, December 16th

Dave Kayes	#14 Charlie's M's Tuna Deluxe Lunch Bag (Zzang! Candy Bar) – Bottle of Water
George Lin	#606 Caesar Salad (BBQ Chips & Zzang! Candy Bar)) – Bottle of Water
Steve Berry	#19 Louie's Lunch Box Deluxe Lunch Bag - Bottle of Water
Don Keski	#40 Siegel's Smoky Number Deluxe Lunch Bag–Mountain Dew
Dave Gardner	#13 Sherman's Sure Choice - bottle of water
Gerald Freitag	#40 Siegel's Smoky Number Deluxe Lunch Bag – Bottle of Water
Hideki Kato	#26 Frank & Kathy's Half-Italian Sub Deluxe Lunch Bag – Bottle of Water
Jackie Yeager	#84 Benno's Birdie Deluxe Lunch Bag - Diet Coke
Mark Siddall	#00 d-$'s Cuban Conundrum Deluxe Lunch Bag – Coke
Cortney Guzlas	#23 Mary's Commute Deluxe Lunch Bag – Diet Coke
Erin Luke	#84 Benno's Birdie Deluxe Lunch Bag – Bottle of Water
Tim French	#40 Siegel's Smoky Number Deluxe Lunch Bag (with Cookie) – Diet Coke
Laura Ricart	#623 Zcobb Salad - bottle of water
Tim Blubaugh	#84 Benno's Birdie Deluxe Lunch Bag – Bottle of Water

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/11/2015 6:54:23 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Draft Agendas
Attachments: 2015 12 15 AS - Draft Meeting Agenda GHG Phase 2 Aero.pdf; 2015 12 16 - Draft Meeting Agenda GHG Phase 2.pdf

Hi Matt,

Attached are slightly revised draft agendas for our meetings next week. Please let me know if you have any questions or concerns. If you need to reach me, I will be in the office most of the day Monday and otherwise available on my mobile phone Personal Phone / Ex. 6 look forward to seeing you next week in Ann Arbor.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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www.truckandenginemanufacturers.org

GHG Phase 2 Aero Meeting
December 15, 2015
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Baseline and Bins

- A. CdA calculation methodology
- B. Method of establishing bin boundaries

II. Coastdown Test Procedure

- A. Test variables
  1. Rolling resistance as a function of speed
  2. Yaw curve asymmetry
  3. Air speed measurement calibration
  4. Others?
- B. Data analysis and error bars

III. Audits

- A. Confirmatory tests
- B. Selective Enforcement Audits
- C. Compliance margin

IV. Potential Trailer Road Load Changes in GEM in 2027

V. Surrogate Yaw Angle for CFD and Wind Tunnel Testing

VI. Next Steps

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GHG Phase 2 Meeting
December 16, 2015
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Other Issues

- A. End of year reporting
- B. Electronic vehicle labeling
- C. Chassis dynamometer testing
- D. APU requirements
- E. Engine issues
  1. Powertrain compliance responsibility
  2. Alternative fuel engines
  3. DF for CO_2
  4. IRAFs
  5. N_2O standard
- F. Powertrain SEAs
- G. Confidential business information
  1. Fuel maps
  2. GEM inputs
- H. Technologies
  1. Start/stop
  2. Neutral idle
  3. Automatic engine shutdown
  4. 6x2 axle configuration

II. GEM Updates

III. Engine Fuel Mapping

- A. Draft test procedure
- B. SwRI test program

IV. Vocational Vehicle Program

V. Next Steps

86918_2.docx

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/18/2016 1:42:09 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: CdA Calculations

Angela,

Are you going to be able to send me the details on the tire rolling resistance and axle loses for CdA calculations that we discussed Friday? If not, it is not a big deal; I just wanted to know before I update the write-up.

Thanks!

Tim

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/10/2015 1:19:43 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Are we talking tomorrow?
Attachments: 2015 12 15 AS - Draft Meeting Agenda GHG Phase 2 Aero.pdf; 2015 12 16 - Draft Meeting Agenda GHG Phase 2.pdf

Hi Angela,

For reference, attached are the draft agendas for next week's meetings that I sent to you before we last talked (on November 20th). As of this morning, there haven't been any changes to the agenda from our side. We should talk about any topics you think we should add. Additionally, I have calls later today with my folks that may generate some changes – and of course I will let you know about those before the meetings.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Wednesday, December 09, 2015 4:01 PM
To: Timothy A. Blubaugh
Subject: Are we talking tomorrow?

Hi Tim,

I have a memory problem. I have a calendar entry for Thursday at 9:30 am EST for Matt, Chuck, and I to talk to you. I think that it is supposed to be a check in about the 12/15 and 12/16 meetings. Are you planning to talk to us tomorrow? If so, should we just call you at your desk?

Thanks!
Angela

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DRAFT - November 20, 2015

GHG Phase 2 Aero Meeting
December 15, 2015
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Baseline and Bins

   A. C_DA calculation methodology
   B. Method of establishing bin boundaries

II. Coastdown Test Procedure

   A. Test variables
   B. Data analysis

III. Audits

   A. Confirmatory tests
   B. Selective Enforcement Audits
   C. Compliance margin

IV. Potential Standard Trailer Changes

V. Surrogate Yaw Angle for Wind Tunnel Testing

VI. Next Steps

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DRAFT – November 20, 2015

GHG Phase 2 Meeting
December 16, 2015
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Other Issues

- A. End of year reporting
- B. Electronic vehicle labeling
- C. Chassis dynamometer testing
- D. APU requirements
- E. Engine issues
  1. Alternative fuel engines
  2. DF for CO_2
  3. N_2O standard
- F. Confidential business information
  1. Fuel maps
  2. GEM inputs
- G. Technologies
  1. Start/stop
  2. Neutral idle
  3. Automatic engine shutdown
  4. 6x2 axle configuration

II. GEM Updates

III. Engine Fuel Mapping

- A. Draft test procedure
- B. SwRI test program

IV. Vocational Vehicle Program

V. Next Steps

86918_1.docx

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/9/2015 10:20:18 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Are we talking tomorrow?

Hi Angela. Yes and yes. Looking forward to chatting tomorrow,

Tim

Sent via my mobile device.

-------- Original message --------
From: "Cullen, Angela"
Date:12/09/2015 5:00 PM (GMT-05:00)
To: "Timothy A. Blubaugh"
Subject: Are we talking tomorrow?

Hi Tim,

I have a memory problem. I have a calendar entry for Thursday at 9:30 am EST for Matt, Chuck, and I to talk to you. I think that it is supposed to be a check in about the 12/15 and 12/16 meetings. Are you planning to talk to us tomorrow? If so, should we just call you at your desk?

Thanks!
Angela

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 8/3/2015 8:02:21 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Steele, Lauren [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=a3f01d4fca2b46d49ef723223af29267-Steele, Lauren P.]
Subject: RE: GHG Phase 2 Cocational Vehicles

Hi Matt,

As for our conference call tomorrow, how about if at the beginning of the call I note that we would like to discuss the vocational issues after we complete the constant speed discussion. If after the constant speed discussion we find that we don't have enough time to dive into the vocational issues, we can set up a follow on conference call. I don't want to interfere with the constant speed discussion, and I suspect that the vocational issues will require significant discussion. Sound okay?

Regarding alternative mapping, I will wait to receive the test plan summary from Houshun. Additionally, I will reach out to Jackie and see what she can provide. We look forward to getting engaged in that activity -- please keep me updated.

Talk to you tomorrow,

Tim

From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Monday, August 03, 2015 11:06 AM
To: Timothy A. Blubaugh
Cc: Cullen, Angela
Subject: RE: GHG Phase 2 Cocational Vehicles

Hi Tim,

No worries, & the funny thing is that I read that as "Vocational" until you sent your second note.

We'd be happy to spend ~10 min explaining and/or answering some questions on vocational, but I'd like to not take too much time away from our constant speed discussion. If it seems like we still need to spend more time discussing vocational, then tomorrow we can also discuss setting up a separate telecon to do a deeper dive on vocational.

Also, Houshun is out today but back tomorrow. I'll ask him to write up a bullet-list summary of EPA's alternate mapping test plans & next steps. I do know that we have test matrices in place at ORNL and SwRI to conduct additional engine and powertrain tests in the next few months and that our collaboration group would like to continue our work on "default vehicle configurations" and interpolation/extrapolation schemes. We're also conducting some analysis to see if it would be possible to merge steady-state mapping and alternate mapping to decrease overall test burden. However, I do not have all the details at my fingertips. Also, Jackie Yeager at Cummins has been great at summarizing our collaboration group's meeting notes and agenda items. Therefore, I might suggest that you could reach out to Jackie for a bullet list of key work items that the group has discussed pursuing over the next few months. I hope this information helps for now.

I look forward to our discussion tomorrow.

Regards,

Matt

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Monday, August 03, 2015 9:57 AM
To: Spears, Matthew
Cc: Cullen, Angela
Subject: RE: GHG Phase 2 Cocational Vehicles

Sometimes I wish spell check worked on the Subject line...

Tim

From: Timothy A. Blubaugh
Sent: Sunday, August 02, 2015 3:59 PM
To: Spears, Matthew
Cc: Cullen, Angela
Subject: GHG Phase 2 Cocational Vehicles
Importance: High

Hi Matt,

There is a significant amount of confusion about the Agency's intent with regulating vocational vehicles in the GHG Phase 2 rule. Specifically, that confusion surrounds the different vehicle subcategories and standards. Could we get your take on vocational vehicles during our call on Tuesday? Please let me know if that would be possible, and if you and I should chat about it first. I will be in the office all day Monday.

On a separate matter, we would like to get engaged in the Agency's evaluation of the alternative engine mapping proposal. Do you have a written plan for the upcoming testing and evaluation? If so, could you share it with me?

Thanks and regards,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 11/20/2015 8:32:47 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: 12/15-16 Meeting
Attachments: 2015 12 15 AS - Draft Meeting Agenda GHG Phase 2 Aero.pdf; 2015 12 16 - Draft Meeting Agenda GHG Phase 2.pdf

Hi Angela,

I put together the attached draft agendas for our meetings in December. Let's chat about them in about 30 minutes.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, November 19, 2015 11:20 AM
To: Timothy A. Blubaugh
Subject: RE: 12/15-16 Meeting

Hi Tim,

4:00 will work. Would you like to call my desk – 734-214-4419?

Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Thursday, November 19, 2015 12:12 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: 12/15-16 Meeting

Hi Angela,

I have a conflict Friday at 2:00 your time. Could we do 11:00 your time? If not, how about 4:00 your time?

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Tuesday, November 17, 2015 9:22 AM
To: Timothy A. Blubaugh
Subject: 12/15-16 Meeting

Hi Tim,

I reserved conference rooms for 12/15 and 12/16. We may be a little crowded on 12/16 because I could not get the lobby conference room and instead have one of the bigger conference rooms in the office building.

We would like to discuss the "other" issues with you on Friday. Would 2:00 pm EST work for you?

Thanks,
Angela

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/14/2016 7:09:19 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Draft Agenda
Attachments: 2016 04 15 AS - Draft Conference Call Agenda.pdf; 2016 04 15 AS CdA Calculation Recommendations DRAFT.PDF

Hi Angela,

Attached is the draft agenda for tomorrow, with minor editorial changes. Also attached is a draft set of recommendations for reducing the variability associated with calculating CdA from coastdown data. The recommendations are intended to follow the conclusions of our March 31st meeting. Please let me know if you have any questions in advance of the call.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, April 14, 2016 8:49 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Subject: RE: Draft Agenda

Hi Tim,

The agenda is fine. Prashanth is planning to send you a WebEx invite because he has some materials to share during the meeting.

I may not have much on mid and low roof tractors, but I will try.

Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, April 13, 2016 3:44 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: Draft Agenda

Hi Angela,

During our March 31st meeting in Ann Arbor, we agreed to schedule a follow-up conference call this Friday at 1:00 p.m. (Chicago time). Attached is a draft agenda for the call with what I believe we agreed to discuss. Please let me know your thoughts about the agenda before I circulate it to my members.

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax

tblubaugh@emamail.org

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Truck & Engine Manufacturers Association®
Bringing Cleaner Power to the World Since 1968®

333 West Wacker Drive, Suite 810
Chicago, Illinois 60606
Tel: (312) 929-1970 I Fax: (312) 929-1975
www.truckandenginemanufacturers.org

GHG Phase 2 Aerodynamics
Conference Call
April 15, 2016
1:00 p.m. (Chicago time)

Ex. 6 Personal Privacy (PP)

DRAFT AGENDA

I. Confirm CdA Calculation Write-Up

II. High-Roof Day Cab Baseline and Bins

  A. Results of EPA and EMA analyses of Truck 2

  B. Results of EPA's 3rd day cab tractor coastdowns

III. Mid- and Low-Roof Baselines and Bins

IV. Other Issues

V. Next Steps

91955_1

DRAFT – April 14, 2016

C_dA Calculation Variability

Recommendations

EMA recommendas the following to reduce the variability associated with calculating C_dA values from coastdown test data.

1. Use the largest possible amount of vehicle speed data, including the first point ≤ 72 mph and the last point ≥ 58 mph, and including the first point ≤ 22 mph and the last point ≥ 8 mph. Analyze the data from one high-speed run with the mean of a pair of low-speed runs (in opposite directions). For valid test data, the longitudinal wind must not exceed ±8 mph and the crosswind must not exceed ±5 mph.

   OPTION: For comparison analysis, consider a low-speed range of 25 – 15 ±2 mph.

2. Filter the following data elements with a Hampel (moving median) filter using a three-second range and three standard deviations:

   a. Air speed
   b. Yaw angle
   c. Vehicle speed
   d. Track-side wind data

   Only filter data that are within the 70 – 60 ±2 mph and 20 – 10 ±2 mph ranges.

3. Calibrate the yaw angle and air speed point-by-point using linear regression of filtered on-board data against filtered track-side wind data, using high and low-speed data separately.

4. Use total relative air speed.

   OPTION: For comparison analysis, consider using truck axis-aligned air speed.

5. Adjust for rear axle loses using data from a § 1037.560 rear axle efficiency test. Use zero torque data for the high and low vehicle speed ranges.

6. Adjust for tire rolling resistance using data from an SAE J2452 test. Apply a scalar shift for the high and low vehicle speed ranges.

7. Utilize the following method for discarding outlier data points:

   a. Measure data from multiples runs (which constitute one test).
   b. Discard known outliers or errors (*e.g.*, driver hit the brake during a run).
   c. Find the median angle, Θ, of all remaining runs.
   d. Draw vertical lines at $\Theta \pm 1.0°$, and discard all points outside the lines as not characteristic of the test's Θ.
   e. Find the average drag area and standard deviation, C_dA and σ, of the remaining runs' drag areas.
   f. Draw horizontal lines at $C_dA \pm 2\sigma$. Discard all points outside the lines.
   g. Take all remaining runs, average the angles to get a new mean angle Θ', and average the drag areas to get a new mean drag area C_dA'.
   h. If there are at least 24 runs remaining after all of the runs are discarded, then Θ' and C_dA' are valid for that test.

90957_5

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/14/2016 2:02:53 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Draft Agenda

Thanks, Angela. Talk to you tomorrow,

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, April 14, 2016 8:49 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Subject: RE: Draft Agenda

Hi Tim,

The agenda is fine. Prashanth is planning to send you a WebEx invite because he has some materials to share during the meeting.

I may not have much on mid and low roof tractors, but I will try.

Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, April 13, 2016 3:44 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: Draft Agenda

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Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
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Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 11/19/2015 5:30:09 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: 12/15-16 Meeting

Sounds good. I will call you then.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, November 19, 2015 11:20 AM
To: Timothy A. Blubaugh
Subject: RE: 12/15-16 Meeting

Hi Tim,

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Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Thursday, November 19, 2015 12:12 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: 12/15-16 Meeting

Hi Angela,

I have a conflict Friday at 2:00 your time. Could we do 11:00 your time? If not, how about 4:00 your time?

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Tuesday, November 17, 2015 9:22 AM
To: Timothy A. Blubaugh
Subject: 12/15-16 Meeting

Hi Tim,

I reserved conference rooms for 12/15 and 12/16. We may be a little crowded on 12/16 because I could not get the lobby conference room and instead have one of the bigger conference rooms in the office building.

We would like to discuss the "other" issues with you on Friday. Would 2:00 pm EST work for you?

Thanks,
Angela

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 7/7/2016 4:18:26 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Way forward for coast down wind limits

Thanks, Matt! We sincerely appreciate your consideration of this issue.

Tim

PS: The crosswind limit will stay at 5 mph – right?

From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Thursday, July 7, 2016 11:05 AM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Cc: Cullen, Angela <cullen.angela@epa.gov>
Subject: Way forward for coast down wind limits

Hi Tim,

I wanted to let you know that I believe we've reached a good compromise solution to EMA's coast-down wind limit concern. Based on Prashanth's discussions with Peter Kilcline and with Steve Healy and me, we are agreeing to finalize for Phase 2 a 6mph head/tail wind limit versus an 8mph limit. We believe that this will modestly improve the test procedure's variability without too significant of an increase in test burden (e.g., waiting for favorable environmental conditions). Our compliance division agrees with this compromise as well.

We examined our Phase 2 coast down data and 100% of our data met the 8mph limit and 97% of the data met the 6mph limit. Therefore, this more stringent limit would not have eliminated a significant portion of the data we have used as part of our HD Phase 2 rulemaking analysis. It would also not likely create a significant additional burden for EPA to conduct confirmatory testing. Furthermore, we could not discern an appreciable improvement in variability by moving from a 6mph limit down to the 5mph limit that EMA had proposed. In other words, around this wind limit, there is a quickly diminishing return for even lower limits.

In conclusion, we believe that agreeing to finalize a 6mph limit is a reasonable compromise between additional test burden and improving test procedure variability.

Please let me know if you or your members have any questions about this way forward, thank you.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

From: Gururaja, Prashanth
Sent: Thursday, July 07, 2016 11:37 AM
To: Peter Kilcline (Peter.Kilcline@PACCAR.com) <Peter.Kilcline@PACCAR.com>
Cc: Spears, Matthew <spears.matthew@epa.gov>; Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: Coastdown Wind Limits

Hi Peter,

I spoke with our Compliance Division about the wind limit changes you and I spoke about, and they said they can work with those changes. As such, we are prepared to finalize a head/tail wind limit of 6 mph, with no change to the crosswind limit in the NPRM. Of course, this means that manufacturers should understand the implications on the test burden associated with more constrained wind conditions for whichever site they choose to test at, both for certification ($F_{alt\text{-}aero}$) testing and selective enforcement audits.

Let me know if you have any other questions/concerns.

Thanks,
Prashanth

From: Spears, Matthew
Sent: Friday, July 01, 2016 4:23 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>; Cullen, Angela <cullen.angela@epa.gov>
Cc: Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>; Peter Kilcline (Peter.Kilcline@PACCAR.com) <Peter.Kilcline@PACCAR.com>; dan.kieffer@paccar.com
Subject: RE: Coastdown Wind Limits

Hi all,

First, Tim, thank you for sending this document.

Prashanth, would you please reach out to Peter Kilcline to engage in a technical discussion with him to see if we can come to a mutual agreement on how we will move forward for the HD Phase 2 Final Rule?

Please feel free to include me in any telecon meeting invitations, but please do not try to schedule around my calendar. I will move or cancel my other meetings to attend any telecon you schedule.

Also, if it is easiest to not include me, then please feel free to reach out to Peter on your own, but either way please follow up with me to let me know how our next steps, thanks.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Friday, July 01, 2016 3:18 PM
To: Cullen, Angela <cullen.angela@epa.gov>

Cc: Spears, Matthew <spears.matthew@epa.gov>; Gururaja, Prashanth <Gururaja.Prashanth@epa.gov>; Peter Kilcline (Peter.Kilcline@PACCAR.com) <Peter.Kilcline@PACCAR.com>; dan.kieffer@paccar.com
Subject: Coastdown Wind Limits

Angela,

Following our conversation today, attached is a document with analysis and recommendations for the allowable ambient wind conditions for coastdown testing for the GHG Phase 2 rule. Considering a low-speed portion of the coastdown test being from 20 to 10 mph, we believe that during testing the longitudinal wind should not should not exceed 5 mph and the crosswind should not exceed 4 mph.

Could we have Prashanth and Peter connect first thing next week to discuss this? Additionally, we have some thoughts about the open parameters (a & b) in the SEA confidence interval equation that they should discuss.

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 7/29/2015 4:30:03 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: EMA Meetings

Hi Matt,

Can I get your thoughts on our next meetings on the Phase 2 rule?

Tim

From: Timothy A. Blubaugh
Sent: Monday, July 27, 2015 1:37 PM
To: Spears, Matthew
Cc: Cullen, Angela
Subject: EMA Meetings

Hi Matt,

Thanks again to you and your staff for such a productive meeting last week. Everyone on our end seems to be pleased with the discussions we had, and they are energized about moving forward on the issues. As we discussed, attached are the back-up slides that we used during the meeting. Also attached is an electronic version of the agenda.

Speaking of the positive energy, I wanted to try to nail down some of the logistics for the upcoming meetings. Please let me know your thoughts on the timing of the meetings on August 25th and 26th. In case you don't yet have any strong opinions, here are mine. How about if we go from 10:00 a.m. until 5:00 p.m. on Tuesday, August 25th, and from 8:00 a.m. until 3:00 p.m. on Wednesday? Additionally, my thinking is that on Tuesday we should discuss all of the "priority issues," and on Wednesday focus on the aerodynamic topics. Let me know your thoughts. Finally, let me know if we need to do anything on our end to schedule next week's WebEx on constant speed testing.

Best regards,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
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Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
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Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 11/11/2015 8:31:55 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]
Subject: GHG Phase 2 Aerodynamics

Hi Matt,

I would like to get your thoughts about some possible dates when the aerodynamics experts could come to Ann Arbor for a meeting to follow-up on our October 30th meeting. I have a conference call with them tomorrow at noon my time, and if I have some availability of the folks on your end, we may be able to lock something down. Could you give me a call or shoot me an e-mail tomorrow morning?

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 10/9/2015 8:10:28 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT
Attachments: waynebio4_10_15.docx

Angela, here is a bio that we have used for Wayne at other events. Let me know if you need anything else. Have a good weekend and see you Tuesday!

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Friday, October 9, 2015 3:46 PM
To: Spieth, John <Spieth.John@epa.gov>; Cornell.randy@conwaytruckload.com; gus.sumcad@wabashnational.com; jscarcelli@wabashnational.com; nic@theicct.org; Jackie M Yeager <jackie.m.yeager@cummins.com>; sean.waters@daimler.com; bvanamburg@calstart.org; amy.kopin@daimler.com
Subject: RE: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT

Thanks to those that joined the call today.

Panel Questions

- I will introduce the individuals on the panel at the beginning of the session. If you would like me to introduce you with more than just your name and title, then please send me a short bio.
- Based on the call today, we are not planning to change any of the questions. The questions are attached, but I expect not to use the follow-up questions because they will most likely be touched on in your responses. The intention is to have approximately a 2-5 minute response per person per question.

Tuesday Details

- Please contact me when you arrive on Tuesday. My cell is Personal Address / Ex. 6 will escort you from the lobby to the lab conference room that you will be able to use during the day. I can also escort you to your company's displays if you would like to check on them.
- If you would like to participate in the tour from noon-1:00, then please arrive at least 15 minutes early.
- There will be seats reserved for each of the panelists near the front row of the audience, so please look for those.
- After our panel concludes, Chris Grundler will make short closing remarks and then the audience will be excused. At that time, we will exit the stage and the media may approach you individually to ask questions.

I will not be in the office on Monday, so please contact me by cell if you need anything.

I look forward to seeing all of you on Tuesday!
Angela

From: Spieth, John
Sent: Wednesday, October 07, 2015 8:34 AM
To: Cornell.randy@conwaytruckload.com; gus.sumcad@wabashnational.com; jscarcelli@wabashnational.com; nic@theicct.org; jackie.m.yeager@cummins.com; sean.waters@daimler.com; bvanamburg@calstart.org
Cc: Cullen, Angela
Subject: RE: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT

Dear Panelists,

FYI, to share a few final details:

Parking is at our 2000 Traverwood Drive, Ann Arbor, MI 48105 parking lot.

I've attached our event day handout with confirmed itinerary, displayer list, building layout, etc.

Conference Room 601-B, accessible from the lab lobby, will be set aside for you throughout the day if you need a place to sit down / answer email / leave jackets.

You are invited to our VIP lab tour which begins at noon from the lab lobby. The latest is that EPA Acting Assistant Administrator Janet McCabe and NHTSA Deputy Administrator Blair Anderson will attend. Sen. Stabenow is considering.

Also repeating from my note of 9/4 in case you didn't see it; we historically ask media to withhold questions, but then do allow them 15 minutes to approach the panelists at the stage after the main audience has left (i.e. 4:30 – 4:45). AOL Automotive News and Car & Driver have confirmed. The general media announcement goes out later today, so a half dozen more are anticipated.

Thanks again--we look forward to seeing you next week.

John

From: Cullen, Angela
Sent: Friday, October 02, 2015 4:14 PM
To: Cornell.randy@conwaytruckload.com; gus.sumcad@wabashnational.com; jscarcelli@wabashnational.com; nic@theicct.org; jackie.m.yeager@cummins.com; sean.waters@daimler.com; bvanamburg@calstart.org
Cc: Spieth, John
Subject: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT

Dear panelists,

We will hold a short meeting on Friday, October 9 at 3:00 pm EDT to address anyone's concerns or questions related to the panel. Please call in to Ex. 6 Personal Privacy (PP) Please feel free to have a representative call in for you if this time is not convenient.

I would appreciate it if you would please confirm that you received this email, just to be sure that I have the correct email address for everyone.

Best regards,
Angela

From: Cullen, Angela
Sent: Tuesday, September 29, 2015 2:44 PM
To: 'Cornell.randy@conwaytruckload.com'; 'gus.sumcad@wabashnational.com'; 'jscarcelli@wabashnational.com';

'nic@theicct.org'; 'jackie.m.yeager@cummins.com'; 'sean.waters@daimler.com'; 'Bill Van Amburg'
Cc: Spieth, John
Subject: HD Technology Showcase Panel Information

Dear panelists,

The Heavy-Duty Technology Showcase is coming up on Tuesday, October 13 in Ann Arbor, MI. We would like to thank you again for your willingness to participate in the panel. As John Spieth has already shared with you, the itinerary for the day is as follows:

Itinerary: 1:00 P.M.: Doors Open
1:15 P.M. to 1:30 P.M.: NVFEL HD Chassis Dynamometer Ribbon Cutting
1:30 P.M. to 2:30 P.M.: Technology Displays
2:30 P.M. to 3:00 P.M.: Opening Keynote Remarks
3:00 P.M. to 3:30 P.M.: 2015 SmartWay Excellence Awards Presentation
3:30 P.M. to 4:30 P.M.: EPA Moderated Panel Discussion: *Progress in Heavy Duty GHG Emissions Through Technology Innovation*

Panel Information: We envision the panel to be a 60 minute discussion that will address the questions provided in the attached file. The format that we had in mind will be that I will moderate the panel and be asking these questions either to the entire panel, or as noted in the list of questions to specific panelists. We are not planning for the panelists to use presentation materials – it will only be a verbal discussion. I also am not planning to take questions from the audience, unless there is an agreement that the list of questions will not fill the entire hour and that there is a desire from the panelists to allow audience questions.

Requested Action Items: Please provide me with a few sentence bio that I can use during the panel introductions. Ideally, I would appreciate this by Friday, October 9. Also, I would like to provide the opportunity for all of you to ask questions and resolve any potential concerns during a short teleconference. I realize that many of you will be busy with COMVEC next week, so I propose a 30 minute call during the afternoon of either Friday 10/2 or 10/9. Please respond with whether you are available during either of these days and I will send a follow-up invitation.

Other Information: The dress code for the panel is expected to be business attire. We will have a conference room available for you to use in the laboratory during the day of the showcase. I can be your point of contact when you arrive at the lab. My desk number is 734-214-4419 and my cell number is Personal Phone / Ex. 6

Thank you again for your participation,
Angela Cullen
U.S. Environmental Protection Agency
Office of Transportation & Air Quality
Assessment & Standards Division
(734) 214-4419
cullen.angela@epa.gov

Dr. Wayne Eckerle

Vice President of Corporate Research and Technology, Cummins Inc.
Columbus, IN

Wayne received BS (1975) and MS (1976) degrees in Aeronautical Engineering from Purdue University and a PhD in Fluid Mechanics from the University of Connecticut in 1985. Prior to joining Cummins, Wayne worked at UTRC for 10 years on a variety of internal flow projects including chemical laser systems, scramjets, and gas turbine combustion. Wayne was also an Associate Professor at Clarkson University teaching classes in Thermal Sciences and performing research in turbulent separated flows, two-phase flow heat transfer, and supersonic combustion. Since joining Cummins in 1989 Wayne has held leadership positions in Metrology, Quality, Fuel Systems Technology, Thermal and Fluid Sciences, and Advanced Engineering. In his present position, Wayne is responsible for developing and integrating technology for Cummins' next generation of products. Wayne received the Cummins J. Irwin Miller Award of Excellence in 2005, an Honorary Doctorate from Purdue University in 2009, the Cummins Julius Perr Innovation Award in 2009, and became an SAE Fellow in 2011. Wayne is the holder of 10 US Patents.

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 10/2/2015 8:49:02 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT

Hi Angela, I plan to call in next Friday. Wayne probably won't.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Friday, October 2, 2015 4:14 PM
To: Cornell.randy@conwaytruckload.com; gus.sumcad@wabashnational.com; jscarcelli@wabashnational.com; nic@theicct.org; Jackie M Yeager <jackie.m.yeager@cummins.com>; sean.waters@daimler.com; bvanamburg@calstart.org
Cc: Spieth, John <Spieth.John@epa.gov>
Subject: HD Technology Showcase Panel Prep Mtg 10/9 at 3:00 pm EDT

Dear panelists,

We will hold a short meeting on Friday, October 9 at 3:00 pm EDT to address anyone's concerns or questions related to the panel. Please call in to Personal Phone / Ex. 6 Please feel free to have a representative call in for you if this time is not convenient.

I would appreciate it if you would please confirm that you received this email, just to be sure that I have the correct email address for everyone.

Best regards,
Angela

From: Cullen, Angela
Sent: Tuesday, September 29, 2015 2:44 PM
To: 'Cornell.randy@conwaytruckload.com'; 'gus.sumcad@wabashnational.com'; 'jscarcelli@wabashnational.com'; 'nic@theicct.org'; 'jackie.m.yeager@cummins.com'; 'sean.waters@daimler.com'; 'Bill Van Amburg'
Cc: Spieth, John
Subject: HD Technology Showcase Panel Information

Dear panelists,

The Heavy-Duty Technology Showcase is coming up on Tuesday, October 13 in Ann Arbor, MI. We would like to thank you again for your willingness to participate in the panel. As John Spieth has already shared with you, the itinerary for the day is as follows:

Itinerary: 1:00 P.M.: Doors Open

1:15 P.M. to 1:30 P.M.: NVFEL HD Chassis Dynamometer Ribbon Cutting
1:30 P.M. to 2:30 P.M.: Technology Displays
2:30 P.M. to 3:00 P.M.: Opening Keynote Remarks
3:00 P.M. to 3:30 P.M.: 2015 SmartWay Excellence Awards Presentation
3:30 P.M. to 4:30 P.M.: EPA Moderated Panel Discussion: *Progress in Heavy Duty GHG Emissions Through Technology Innovation*

Panel Information: We envision the panel to be a 60 minute discussion that will address the questions provided in the attached file. The format that we had in mind will be that I will moderate the panel and be asking these questions either to the entire panel, or as noted in the list of questions to specific panelists. We are not planning for the panelists to use presentation materials – it will only be a verbal discussion. I also am not planning to take questions from the audience, unless there is an agreement that the list of questions will not fill the entire hour and that there is a desire from the panelists to allow audience questions.

Requested Action Items: Please provide me with a few sentence bio that I can use during the panel introductions. Ideally, I would appreciate this by Friday, October 9. Also, I would like to provide the opportunity for all of you to ask questions and resolve any potential concerns during a short teleconference. I realize that many of you will be busy with COMVEC next week, so I propose a 30 minute call during the afternoon of either Friday 10/2 or 10/9. Please respond with whether you are available during either of these days and I will send a follow-up invitation.

Other Information: The dress code for the panel is expected to be business attire. We will have a conference room available for you to use in the laboratory during the day of the showcase. I can be your point of contact when you arrive at the lab. My desk number is 734-214-4419 and my cell number is Personal Phone / Ex. 6

Thank you again for your participation,
Angela Cullen
U.S. Environmental Protection Agency
Office of Transportation & Air Quality
Assessment & Standards Division
(734) 214-4419
cullen.angela@epa.gov

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 9/25/2015 9:13:25 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]
Subject: RE: Panelist information for Technology Showcase

It would be nice if we could see at least the draft questions before Tuesday. I hope to meet with Wayne on Tue/Wed sometime to discuss the event. I'm not sure of Wayne's availability on Oct. 7-9. I'll have to check – I know he is at COMVEC sometime that week. I am on vacation that week, but we will try to figure out how to cover it somehow. Thanks

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Friday, September 25, 2015 3:16 PM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: RE: Panelist information for Technology Showcase

Hi Jackie,

I have draft questions out for review with the hopes of sending them to the panelists on Tuesday.

The format at this point (though we are willing to hear what the participants would like) is that we would not have slides. I will send out the list of questions on Tuesday. The only remaining question is whether we think the list of questions will fill the full hour or if we would take questions from the audience.

I also plan to see if I can get all of the panelists on a quick phone call around Oct. 7-9 to be sure everyone is on the same page.

Does that work for you and Wayne or would you like to see the questions before Tuesday?

Angela

From: Jackie M Yeager [mailto:jackie.m.yeager@cummins.com]
Sent: Friday, September 25, 2015 2:30 PM
To: Cullen, Angela
Subject: RE: Panelist information for Technology Showcase

Hi Angela,

Do you have any more details about the panel format or questions for the panelists? Due to upcoming travel/vacation for Wayne and myself, we need to start our preparations for the discussion next week. Should we prepare any slides for his 5 minutes (there wouldn't be time but for a few!), or just a verbal message?

Thanks,

Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Spieth, John [mailto:Spieth.John@epa.gov]
Sent: Friday, September 4, 2015 3:42 PM
To: bvanamburg@calstart.org; Randy Cornell <Cornell.Randy@ConwayTruckload.com>; Jackie M Yeager <jackie.m.yeager@cummins.com>; sean.waters@daimler.com; Nic Lutsey <nic@theicct.org>; Sumcad, Gus <Gus.Sumcad@wabashnational.com>; jscarcelli@wabashnational.com
Cc: Cullen, Angela <cullen.angela@epa.gov>
Subject: Panelist information for Technology Showcase

Good Afternoon,

I wanted to share the final panelist list for our October 13th Showcase with each of you. Please let me know if you would like your name, title, or organization to appear differently on our event flyer:

From: CALSTART, Bill VanAmburg, Senior Vice President;
Conway Truckload, Randy Cornell, Vice President of Maintenance;
Cummins Inc., Dr. Wayne Eckerle, Vice President of Research & Technology;
Daimler Trucks North America LLC, Sean Waters, Director of Compliance & Regulatory Affairs;
ICCT, Nic Lutsey, Program Manager HD Vehicles;
Wabash National Corporation, Gus Sumcad, Director of Engineering, and James Scarcelli, Vice President Corporate Strategy & Governmental Affairs

We hope you will join us for the entire event, but the most critical part for your attendance is 2:30 – 4:30. In addition, after the attendees have been dismissed, we would allow media the 15 minutes immediately following (4:30 – 4:45) to approach the stage to ask any additional questions directly to individual panelists.
`

Angela Cullen is our moderator and will be sending out the panel discussion format and questions later in September. Most likely, there will be 5 minutes for each panelist at the beginning followed by questions that she will distribute in September. But we are still working out the final details.

Here is the general itinerary for the day:

1:00 P.M.: Doors Open
1:15 P.M. to 1:30 P.M.: NVFEL HD Chassis Dynamometer Ribbon Cutting
1:30 P.M. to 2:30 P.M.: Technology Displays
2:30 P.M. to 3:00 P.M.: Opening Keynote Remarks (Janet McCabe, EPA Acting Assistant Administrator for the Office of Air and Radiation)
3:00 P.M. to 3:30 P.M.: 2015 SmartWay Excellence Awards Presentation
3:30 P.M. to 4:30 P.M.: EPA Moderated Panel Discussion: Progress in Heavy Duty GHG Emissions & Fuel Economy Through Technology Innovation

Details should be up soon on our webpage: http://www.epa.gov/nvfel/showcase.htm.

If you wish to pass along the invitation to attend to any colleagues, I have attached our RSVP form.

Parking is at 2000 Traverwood Drive, Ann Arbor, MI 48105. You can name Angela Cullen as your point of contact upon check-in. Please don't hesitate to contact me with any issues or questions in the meantime.

We are looking forward to your participation. Thank you very much for making the time to join us for what should be an engaging event.

FYI--Currently confirmed manufacturer/operator participants with displays are as follows: Allison Transmission, Cummins Inc., Daimler Trucks North America, Dana, Ford Motor Co., Frito Lay, Goodyear, Honeywell, Michelin, New Eagle, SABIC, Tenneco, Wabash National, Webasto, University of Michigan. A couple others are still considering. We have positive informal responses that Michigan's Senator Peters and Representative Dingell will join us for the ribbon cutting event, but are awaiting formal confirmation. If history is any guide, we won't know the media participants until the week of the event.

Please have an enjoyable Labor Day holiday weekend.

Best regards,
John

John Spieth
Vehicle Testing Center Director
EPA, National Vehicle and Fuel Emissions Laboratory
(734) 214-4460
spieth.john@epa.gov

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 6/29/2016 2:45:38 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Subject: FW: EMA Meetings
Attachments: 2015 07 23 EMA_EPA GHG Phase 2 Meeting Agenda.DOCX; 2015 07 23 EMA Presentation on GHG Phase 2 Issues.PPTX

Tim,

May I use slide 4 from the presentation in the RIA or is this considered CBI?

Thank you,
Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Monday, July 27, 2015 2:38 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Cc: Cullen, Angela <cullen.angela@epa.gov>
Subject: EMA Meetings

Hi Matt,

Thanks again to you and your staff for such a productive meeting last week. Everyone on our end seems to be pleased with the discussions we had, and they are energized about moving forward on the issues. As we discussed, attached are the back-up slides that we used during the meeting. Also attached is an electronic version of the agenda.

Speaking of the positive energy, I wanted to try to nail down some of the logistics for the upcoming meetings. Please let me know your thoughts on the timing of the meetings on August 25th and 26th. In case you don't yet have any strong opinions, here are mine. How about if we go from 10:00 a.m. until 5:00 p.m. on Tuesday, August 25th, and from 8:00 a.m. until 3:00 p.m. on Wednesday? Additionally, my thinking is that on Tuesday we should discuss all of the "priority issues," and on Wednesday focus on the aerodynamic topics. Let me know your thoughts. Finally, let me know if we need to do anything on our end to schedule next week's WebEx on constant speed testing.

Best regards,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 4/15/2016 3:53:10 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - April 15, 2016 Conference Call with EPA – Web Meeting Link
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 4/15/2016 6:00:00 PM
End: 4/15/2016 7:00:00 PM
Show Time As: Busy

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 4/1/2016 8:03:18 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - April 15, 2016, Conference Call with EPA
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh
Start: 4/15/2016 6:00:00 PM
End: 4/15/2016 7:00:00 PM
Show Time As: Busy

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 3/30/2016 8:08:28 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Subject: RE: EMA Meeting Attendees

Thanks Tim.

We will be in the lobby conference room. See you tomorrow!

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Wednesday, March 30, 2016 4:00 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: EMA Meeting Attendees

Angela,

Here is a list of the people from our side attending tomorrow's meeting.

Tim

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 3/29/2016 5:06:15 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Subject: Ignore my last email - I talked to Angie and she has it all handled.

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Tuesday, March 29, 2016 1:04 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: Automatic reply: Draft Agenda

Out of the office until Wednesday, March 30. If urgent, contact Angie at Ex. 6 Personal Privacy (PP)

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 3/29/2016 5:04:13 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Subject: RE: Draft Agenda

Tim – I forgot to mention to you that I will need you to order lunch for your members, if EMA wants to have a working lunch. The same procedures as last time still exist and we cannot have EPA personnel ordering lunch. Any concerns?

Thanks,
Angela

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Thursday, March 24, 2016 6:05 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: Draft Agenda

Hi Angela,

Attached is a draft agenda for our meeting on Thursday, March 31st. Please note that it does not yet include the topics we discussed today. Let me know if you have any questions about the items on the agenda, or if we need to add anything. So you know, I will be out of the office tomorrow through Tuesday, March 29th. However, don't hesitate to call me on my mobile phone if there is anything we need to discuss: **Personal Phone / Ex. 6**

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 3/23/2016 1:00:27 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - March 24, 2016, Web Meeting
Location: Dial-In#: (Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 3/24/2016 5:30:00 PM
End: 3/24/2016 7:00:00 PM
Show Time As: Busy

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 3/16/2016 7:57:10 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]
Subject: Cummins N2O Data question
Attachments: Cummins Combined 2015 and 2016 N2O Cert Results.xlsx

Hi Jackie,

We've been taking a closer look at N2O emissions for the final rule. Attached is a comparison of the Cummins data. We are hoping that you can help explain to us the difference that we are seeing between the 2015 and 2016 N2O emission levels. Is there some sort of technology, aftertreatment, or calibration shift with these engines that was done to help the engines meet the 2016 MY CO2 standards? If I recall correctly, Cummins used the Phase 1 OBD-alignment provision which requires the engines to meet the 2017 MY CO2 standards in 2016 MY.

We would appreciate any insight that you can provide.

Thank you,
Angela
734-214-4419

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 2/26/2016 9:14:29 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - March 15, 2016, Conference Call with EPA
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 3/15/2016 3:00:00 PM
End: 3/15/2016 4:00:00 PM

Recurrence: (none)

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 2/26/2016 1:59:25 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - March 15, 2016, Conference Call with EPA
Location: Dial-In#: Conference Code / Ex. 6 ; Chair: Tim Blubaugh

Start: 3/15/2016 3:00:00 PM
End: 3/15/2016 4:00:00 PM
Show Time As: Busy

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 2/9/2016 5:26:33 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]

Subject: Accepted: Cummins/EPA call on Phase 2 cycle average map
Location: US toll-free Conference Code / Ex. 6 r Gary's office at CTC

Start: 2/17/2016 6:00:00 PM
End: 2/17/2016 7:00:00 PM
Show Time As: Busy

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 2/9/2016 2:38:35 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]

Subject: Accepted: Cummins/EPA call on Phase 2 cycle average map
Location: US toll-free Conference Code / Ex. 6 Brian's office COB 262 (North End)
Start: 2/16/2016 7:30:00 PM
End: 2/16/2016 8:30:00 PM
Show Time As: Busy

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 1/22/2016 10:14:04 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]

Subject: Accepted: Cummins/EPA meeting
Location: 2000 Traverwood Drive, Ann Arbor, MI

Start: 1/29/2016 2:00:00 PM
End: 1/29/2016 5:00:00 PM

Recurrence: (none)

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 12/10/2015 6:52:46 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]
Subject: Menus
Attachments: image2015-12-10-110430.pdf

Hi Tim,

Attached are the menus to both JJ and Zingerman's. If you would let me know the orders for each day by COB on Monday, that would be great.

Thanks,
Angela

DELUXE RED BAG LUNCH

Take our classic bag lunch (your choice sandwich or salad, Zapps chips, dill pickles, fresh fruit) and make it deluxe by substituting a Zingerman's Zzang! Candy Bar for the brownie and add a can of soda (Coke products) or 16 oz. bottled water.

Sandwiches & Salads to choose from:

#4 Dinty Moore: Zingerman's corned beef, lettuce, tomato & our own Russian dressing on Jewish rye bread.

#13 Sherman's Sure Choice: Corned beef with coleslaw, Switzerland Swiss cheese and Russian dressing on rye.

#19 Louie's Lunch Box: Roast beef, cheddar cheese, spicy brown mustard and lettuce on an onion roll.

#26 Frank & Kathy's Half-Italian Sub: All-beef salami, Italian mortadella, Arkansas peppered ham, provolone cheese, lettuce, tomato, onions, spicy fire-roasted New Mexico green chiles, olive oil & red wine vinegar grilled on Italian paesano roll.

#82 Don's Rhythm & Blues: Hot Zingerman's pastrami & yellow mustard on rye.

#00 d-$'s Cuban Conundrum: Roast pork, Arkansas peppered ham, Switzerland Swiss cheese, old fashioned dill pickles, mayo and hot mustard on a grilled paesano roll.

#23 Mary's Commute: Homemade chicken salad, bacon, lettuce and mayo on challah.

#84 Benno's Birdie: Amish Chicken Breast, Ligurian pesto, oven-dried tomatoes, and fresh handmade mozzarella on grilled rustic Italian bread.

#20 Tom's New Job: Turkey breast, Switzerland Swiss cheese, coleslaw, and Russian dressing on rye.

#40 Siegel's Smoky Number: Smoked turkey breast, Arkansas peppered ham, Switzerland Swiss cheese, lettuce & sweet-hot honey cup mustard on rye bread.

#42 M.J.'s Fond Farewell: Free-range turkey breast, lettuce, tomato & Hellman's mayo on double-baked, hand-sliced Jewish rye bread.

#14 Charlie's M's Tuna: Housemade tuna salad and raw milk Vermont cheddar on grilled rye.

#92 Sheila's Viva Las Vegan: Hummus, artichokes, roasted red peppers and baby spinach on grilled farm bread. **Vegan**

#5 Rodger's Big Picnic: Oven-roasted asparagus, grilled marinated portabello mushrooms raw milk Vermont cheddar cheese & dijon vinaigrette on grilled farm bread. **Vegetarian**

#94 Amazing Grace's Family Shroom: Grilled Portabello Mushrooms, carrot top spread, fresh cucumber on grilled rustic Italian bread. **Vegan**

#600 Farmer's Market Salad
A simply satisfying salad of mixed greens, red onions, cucumbers & carrots. Tossed in our own balsamic vinaigrette.

#606 Caesar Salad
Fresh romaine lettuce, Grana Padano cheese, housemade croutons & freshly ground black pepper. Tossed in our own Caesar dressing.

#608 Cyprus Salad
Grilled halloumi (a very tasty, slightly salty, soft cheese from the Mediterranean island of Cyprus), Kalamata olives, red onions, juicy tomatoes & fresh lemon zest on a bed of mixed greens. Tossed in our own Greek dressing.

#623 Zcobb Salad
Mixed greens, carrots, applewood-smoked bacon and Amish chicken tossed with our Cobb dressing, topped with a hard-boiled egg, crumbled blue cheese & a generous dollop of fresh avocado spread.

Or choose your favorite from the Deli Sandwich Menu

Price $19/person

ALLERGEN INFO

- **Vegetarian**
- **Can be made gluten-free**
- **Can be made nut free**

Food is made to order and may vary from food pictured.

Please place your catering order 48 hours or more in advance. This will help us to secure your desired delivery time and menu selection.

Need something with less notice? Check out our last minute menu.

ESTABLISHED IN CHARLESTON, IL
IN 1983 TO ADD TO STUDENTS GPA
AND GENERAL DATING ABILITY.

JIMMY JOHN'S®

Since JJ 1983

WORLD'S GREATEST GOURMET SANDWICHES

OK, SO MY SUBS REALLY AREN'T GOURMET AND WE'RE NOT FRENCH EITHER. MY SUBS JUST TASTE A LITTLE BETTER, THAT'S ALL! I WANTED TO CALL IT JIMMY JOHN'S TASTY SANDWICHES, BUT MY MOM TOLD ME TO STICK WITH GOURMET. REGARDLESS OF WHAT SHE THINKS, FREAKY FAST IS WHERE IT'S AT. I HOPE YOU LOVE 'EM AS MUCH AS I DO! PEACE!

Jimmy John

6.14

8" SUB SANDWICHES

All of my sandwiches are 8 inches of homemade French bread, fresh veggies and the finest meats & cheese I can buy! We slice everything fresh daily in this store! It tastes better that way!

#1 PEPE®
Real wood smoked ham and provolone cheese, lettuce, tomato & mayo. (The original)

#2 BIG JOHN®
Medium rare choice roast beef, mayo, lettuce & tomato.

#3 TOTALLY TUNA®
Fresh housemade tuna, mixed with celery, onions, and our tasty sauce, sliced cucumber, lettuce & tomato. (My tuna rocks! Sprouts* optional)

#4 TURKEY TOM®
Fresh sliced turkey breast, lettuce, tomato & mayo. The original (Sprouts* optional)

#5 VITO®
The original Italian sub with genoa salami, provolone, capicola, onion, lettuce, tomato & a real tasty Italian vinaigrette. (Hot peppers by request)

#6 THE VEGGIE ✌
Layers of provolone cheese separated by real avocado spread, sliced cucumber, lettuce, tomato & mayo. (Truly a gourmet sub not for vegetarians only! Sprouts* optional)

J.J.B.L.T.®
Bacon, lettuce, tomato & mayo! (My B.L.T. rocks)

THE ORIGINAL JJ'S

★ SIDES ★

- ★ Soda Pop 1.59
- ★ Chocolate chip or oatmeal raisin cookie 1.69
- ★ Real potato chips or jumbo kosher dill pickle 1.33
- ★ Extra load of meat 2.50
- ★ Extra cheese or extra avocado spread 1.00

ORDER ONLINE @ JIMMYJOHNS.COM

FREEBIES (SUBS & CLUBS ONLY)

Onion, lettuce, tomato, mayo, sliced cucumber, hot peppers, Dijon mustard, yellow mustard, oil & vinegar, oregano, sprouts*

4.87

SLIMS™

Any Sub minus the veggies and sauce

- SLIM 1 Ham & cheese
- SLIM 2 Roast beef
- SLIM 3 Tuna salad
- SLIM 4 Turkey breast
- SLIM 5 Salami, capicola, cheese
- SLIM 6 Double provolone

Low Carb Lettuce Wrap
JJ UNWICH®

Same ingredients and price of the sub or club without the bread.

mama approved Catering

★ BOX LUNCHES ★
★ PARTY PLATTERS ★
★ PARTY SUBS ★

WE PREFER 24 HOUR NOTICE, BUT IF YOU CALL, WE'LL DO WHAT WE CAN TO MAKE IT HAPPEN!

DELIVERY ORDERS will include a delivery charge per item.

9.53

THE J.J. GARGANTUAN®

The original gotbuhstuh! Genoa salami, sliced smoked ham, capicola, roast beef, turkey & provolone, jammed into one of our homemade French buns, then smothered with onions, mayo, lettuce, tomato & our homemade Italian vinaigrette.

7.94

GIANT CLUB SANDWICHES

My club sandwiches have twice the meat or cheese, try it on my fresh baked thick sliced 7-grain bread or my famous homemade French bread! Tell us when you order!

#7 SMOKED HAM CLUB
1/4 pound of real wood smoked ham, provolone cheese, lettuce, tomato & mayo!

#8 BILLY CLUB®
Choice roast beef, smoked ham, provolone cheese, Dijon mustard, lettuce, tomato & mayo.

#9 ITALIAN NIGHT CLUB®
Genoa salami, Italian capicola, smoked ham, and provolone cheese all topped with lettuce, tomato, onion, mayo & our homemade Italian vinaigrette. (Order it with hot peppers)

#10 HUNTER'S CLUB®
A full 1/4 pound of medium rare roast beef, provolone, lettuce, tomato & mayo.

#11 COUNTRY CLUB®
Sliced turkey breast, real wood smoked ham, provolone, and tons of lettuce, tomato & mayo! (A very traditional, yet always exceptional classic!)

#12 BEACH CLUB® ☮ Sprouts* optional
Fresh baked turkey breast, provolone cheese, avocado spread, sliced cucumber, lettuce, tomato & mayo!

#13 GOURMET VEGGIE CLUB®
Double provolone, real avocado spread, sliced cucumber, lettuce, tomato & mayo. (Try it on my 7-grain whole wheat bread. This veggie sandwich is really yummy! Sprouts* optional)

#14 BOOTLEGGER CLUB®
Roast beef, turkey breast, lettuce, tomato & mayo. An American classic!

#15 CLUB TUNA®
The same as our #3 Totally Tuna except this one has a lot more. Housemade tuna salad, provolone, sliced cucumber, lettuce & tomato. (Sprouts* optional)

#16 CLUB LULU®
Sliced turkey breast, bacon, lettuce, tomato & mayo. (JJ's original turkey & bacon club)

#17 ULTIMATE PORKER™
Real wood smoked ham and bacon with lettuce, tomato & mayo! (This one rocks!)

Price includes delivery Add gratuity for the driver

Appointment

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 11/23/2015 1:34:52 PM
To: EMA [ema@emamail.org]

Subject: Accepted: EMA - November 30, 2015, Conference Call – Aerodynamic Drag
Location: Dial-In#: Conference Code / Ex. 6 Chair: Tim Blubaugh

Start: 11/30/2015 4:00:00 PM
End: 11/30/2015 5:00:00 PM
Show Time As: Busy

Message

From: Cullen, Angela [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF1B7C0675434915BADE463AD4619509-CULLEN, ANGELA]
Sent: 11/20/2015 8:52:37 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]
Subject: RE: 12/15-16 Meeting

Would you please call 734-214-4919?

Thanks!

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Friday, November 20, 2015 3:33 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: 12/15-16 Meeting

Hi Angela,

I put together the attached draft agendas for our meetings in December. Let's chat about them in about 30 minutes.

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Thursday, November 19, 2015 11:20 AM
To: Timothy A. Blubaugh
Subject: RE: 12/15-16 Meeting

Hi Tim,

4:00 will work. Would you like to call my desk – 734-214-4419?

Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Thursday, November 19, 2015 12:12 PM
To: Cullen, Angela <cullen.angela@epa.gov>
Subject: RE: 12/15-16 Meeting

Hi Angela,

I have a conflict Friday at 2:00 your time. Could we do 11:00 your time? If not, how about 4:00 your time?

Tim

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Tuesday, November 17, 2015 9:22 AM
To: Timothy A. Blubaugh
Subject: 12/15-16 Meeting

Hi Tim,

I reserved conference rooms for 12/15 and 12/16. We may be a little crowded on 12/16 because I could not get the lobby conference room and instead have one of the bigger conference rooms in the office building.

We would like to discuss the "other" issues with you on Friday. Would 2:00 pm EST work for you?

Thanks,
Angela

Appointment

From: John C Wall [john.c.wall@cummins.com]
Sent: 3/16/2015 3:34:38 PM
To: John C Wall [john.c.wall@cummins.com]; Stewart, Gwen [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3f8c5838943241caadb6005ffaddd7db-gstewart]; Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]

Subject: Discussion with John Wall
Location: Teleconference

Start: 3/16/2015 8:15:00 PM
End: 3/16/2015 8:45:00 PM
Show Time As: Busy

Recurrence: (none)

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Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 11/30/2016 2:14:34 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]; Bunker, Byron [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ddf7bcf023d241a9a477a2dc75d5901c-Bunker, Byron]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: Rich S Wagner [rich.s.wagner@cummins.com]
Subject: Class Action
Attachments: ClassActionLawsuitSummary.pdf

Chris, Byron and Bill – You may have seen that a class action lawsuit was filed earlier this month against Fiat Chrysler and Cummins alleging violation of emissions regulations. We wanted to make sure you saw our response that the lawsuit has no merit: http://social.cummins.com/statement-lawsuit-fiat-chrysler-cummins/.

Additionally, attached is a summary of the case that we thought might be helpful. Please let us know if you need anything or have any questions,

Brian

Brian C. Mormino
Executive Director -- Worldwide Environmental Strategy & Compliance
Cummins Inc.
MC 60203, 500 Jackson Street
Columbus, IN 47201
Ex. 6 Personal Privacy (PP)
brian.c.mormino@cummins.com

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On Monday, November 14, a putative class comprised of the owners of certain FCA vehicles containing Cummins diesel engines filed suit against FCA and Cummins. The involved vehicles are: the MY2007-2010 Ram 2500 (2WD, 4WD) with Cummins diesel engines, MY2011-2012 Ram 2500 (non-SCR systems, 2WD, 4WD) with Cummins diesel engines, MY2007-2010 Ram 3500 (2WD, 4WD) with Cummins diesel engines, and MY2011-2012 Ram 3500 (non-SCR systems, 2WD, 4WD) with Cummins diesel engines (the "Class Vehicles"). The class alleges that FCA and Cummins deceived their customers by misrepresenting that the Class Vehicles were compliant with emissions standards. The lawsuit has no merit and contains false and exaggerated claims.

The Complaint alleges that, during unidentified on-road testing designed to simulate the federal test procedures part of the certification process, a 2012 2500 Pickup at 70,000 miles failed to meet emissions standards. The class attributes these excessive emissions to a failure of the after-treatment technology utilized in the engines.

The Complaint alleges that the high emissions observed during the unidentified tests result from excessive diesel particulate filter active regeneration in combination with a deactivated NOx Adsorber catalyst. Further, the Complaint alleges that the results from testing this one truck are "consistent" with those that led to uncovering the Volkswagen emissions "scandal." This putative class is represented by the same firm who represented the class in the action against Volkswagen.

In the Volkswagen class action, the class alleged that Volkswagen used a "defeat device" in its vehicles to fool the EPA and California ARB tests and fraudulently gain emissions certification. The defeat device worked by sensing where the vehicle was being driven and then producing lower emissions in a "testing" scenario and higher emissions under real-world operating conditions. The Complaint does not make the same allegation against Cummins – nor could it. To be clear – the Cummins diesel engines in the Class Vehicles do not contain any kind of defeat device.

The Plaintiffs allege that Cummins violated the Racketeer Influenced and Corrupt Organizations Act ("RICO"). The basis of the claim is that Cummins engaged in a pattern of misconduct by *inter alia*, making misrepresentations about emissions to regulators and to the public, for the purpose of furthering a deception that the Class Vehicles were emissions compliant in order to increase revenues. Additionally, the state subclasses bring various state law claims against Cummins including violation of various state consumer protection acts, deceptive trade practices acts, and fraudulent concealment acts. The basis of these claims is that Cummins failed to disclose, willfully concealed, and/or deliberately misrepresented the truth about emissions.

These claims are without merit and contain false and exaggerated allegations and insinuations. In particular, Cummins prohibits the use of defeat devices in all of its products. Cummins has robust certification and compliance processes and is transparent with regulating bodies throughout these processes – from disclosure of the design and operation of the emission control system, to test processes and results and later to any necessary reporting and corrective action processes as required. Cummins is deeply disappointed in this effort to tarnish its image and standing as a company and intends to combat these claims vigorously.

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 8/24/2016 10:53:42 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
CC: Stewart, Gwen [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3f8c5838943241caadb6005ffaddd7db-gstewart]
Subject: RE: Mtg on 8/30 or 9/1

Enjoy! I will reach out to you for next time.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Wednesday, August 24, 2016 6:53 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Cc: Stewart, Gwen <Stewart.Gwen@epa.gov>
Subject: Re: Mtg on 8/30 or 9/1

Sorry Brian. I am out until after Labor Day

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202/564-1682 (Washington DC)
734/214-4207 (Ann Arbor MI)

On Aug 24, 2016, at 11:25 AM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Chris, I will be in DC next Tuesday, August 30th and Wednesday, September 1st. If you will be in DC either of those days, do you have time to meet with me? I think it would be good for us to discuss moving forward on ultra-low NOx. Thanks for your consideration,
>
> Brian
>
> ---
> **Brian C. Mormino**
> *Executive Director -- Worldwide Environmental Strategy & Compliance*
> Cummins Inc.
> MC 60203, 500 Jackson Street
> Columbus, IN 47201
> Ex. 6 Personal Privacy (PP)
> brian.c.mormino@cummins.com
>
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Message

From: Alt Susan [susan.alt@volvo.com]
Sent: 8/17/2016 7:32:04 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: RE: 12:00 eastern tomorrow

OK safe travels

Susan Alt
Volvo Group North America
Senior Vice President, Public Affairs

7900 National Service Rd | Greensboro, NC 27409
Ex. 6 Personal Privacy (PP) ☎: 336-393-4500 (direct) | ✉ susan.alt@volvo.com

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Wednesday, August 17, 2016 3:08 PM
To: Alt Susan
Subject: Re: 12:00 eastern tomorrow

No. I'm happy to get together with Denny and Nicklaus when I return from vacation in September.

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202/564-1682 (Washington DC)
734/214-4207 (Ann Arbor MI)

On Aug 17, 2016, at 9:45 AM, Alt Susan <susan.alt@volvo.com> wrote:

> We will keep it short and to the point ... Any other time today?
>
> Sent from my iPhone
>
> On Aug 17, 2016, at 8:53 AM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:
>
> > Sorry Susan I am not available to talk at 12:00
> >
> > Christopher Grundler, Director
> > Office of Transportation and Air Quality
> > U.S. Environmental Protection Agency
> > 202/564-1682 (Washington DC)
> > 734/214-4207 (Ann Arbor MI)
> >
> > On Aug 17, 2016, at 6:03 AM, Alt Susan <susan.alt@volvo.com> wrote:
> >
> > > Yes
> > >
> > > Sent from my iPhone

On Aug 16, 2016, at 9:28 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:

> This will be difficult as I am leaving on vacation in 2 days and have a bunch of meetings before I take off. Is this an urgent matter?
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. Environmental Protection Agency
> 202/564-1682 (Washington DC)
> 734/214-4207 (Ann Arbor MI)
>
> On Aug 16, 2016, at 6:05 PM, Alt Susan <susan.alt@volvo.com> wrote:
>
>> OK I sent a meeting invite in hopes you can adjust
>> Susan
>>
>> ---
>>
>> *Susan Alt*
>> Volvo Group North America
>> Senior Vice President, Public Affairs
>>
>> 7900 National Service Rd | Greensboro, NC 27409
>> Ex. 6 Personal Privacy (PP)
>> (direct) | ✉ susan.alt@volvo.com
>>
>> ---
>>
>> **From:** Grundler, Christopher [mailto:grundler.christopher@epa.gov]
>> **Sent:** Tuesday, August 16, 2016 5:04 PM
>> **To:** Alt Susan
>> **Subject:** RE: 12:00 eastern tomorrow
>>
>> Hi Susan—
>> Let me see if I can re-arrange things tomorrow. I will confirm first thing in the morning
>> chris
>>
>> ---
>>
>> **From:** Alt Susan [mailto:susan.alt@volvo.com]
>> **Sent:** Tuesday, August 16, 2016 4:41 PM
>> **To:** Grundler, Christopher

<grundler.christopher@epa.gov>
Subject: 12:00 eastern tomorrow

Hi Chris
I left you a text message as well, but can you be available tomorrow at noon (eastern) for a call with me, Denny and Niklas Gustafsson?
Susan

Susan Alt
Volvo Group North America
Senior Vice President, Public Affairs

7900 National Service Rd | Greensboro, NC 27409
Ex. 6 Personal Privacy (PP)
(direct) | ✉ susan.alt@volvo.com

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 12/14/2015 6:35:13 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
CC: Stewart, Gwen [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3f8c5838943241caadb6005ffaddd7db-gstewart]
Subject: Re: Next Friday--Regrets

We are staying at the courtyard convention center marriott at 900 f street nw.

Sent from my iPhone

On Dec 14, 2015, at 1:03 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:

> I am happy to meet you for breakfast or coffee. Let me know where you are staying and we can find a place and agree on time
>
> **From:** Brian C Mormino [mailto:brian.c.mormino@cummins.com]
> **Sent:** Monday, December 14, 2015 10:02 AM
> **To:** Grundler, Christopher; Stewart, Gwen
> **Subject:** RE: Next Friday--Regrets
>
> Chris, we are going to come in on Thursday night so that we can meet with you early. We have our first meeting at 9:30 am at DOT. What time and what location can we arrange for us to meet in the morning and allow us to still get across town for that meeting? We can come to your office, but I wonder if meeting for coffee or breakfast might be better. Please let me know.
>
> **From:** Grundler, Christopher [mailto:grundler.christopher@epa.gov]
> **Sent:** Sunday, December 13, 2015 3:25 PM
> **To:** Brian C Mormino <brian.c.mormino@cummins.com>
> **Subject:** Re: Next Friday--Regrets
>
> I appreciate it. The conflict concerns a meeting about a major enforcement matter I am managing. I am free before 9am, and am flexible between 9:30 and 11:30
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. Environmental Protection Agency
> 202.564.1682 (Washington)
> 734.214.4207 (Ann Arbor)
> www.epa.gov/otaq
>
> On Dec 13, 2015, at 2:59 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:
>
> > Chris, I will see if we can move other meetings to still find time with you in the morning. Give me a day or two.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Friday, December 11, 2015 5:31 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: Next Friday--Regrets

Brian—an unavoidable conflict has come up and I am unable to have lunch with you and Jennifer next Friday. I do have flexibility in the morning, but I know you were scheduling other meetings. If we can't find time in the morning to chat I will see you with Janet in the afternoon. I'm really sorry about this but there is nothing that can be done

Chris

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 4/8/2015 2:44:18 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
CC: Jerry Z Liu [jerry.z.liu@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Jennifer Rumsey [jennifer.rumsey@cummins.com]; Rich S Wagner [rich.s.wagner@cummins.com]; Carol Henry [carol.henry1@verizon.net]
Subject: Follow up on Tier-4F DPF DOC emissions
Attachments: Cummins Liu Tier IV-F DOC DPF PAH Presentation 10-14-2014.pdf; Cummins -- Liu et al EST PAH 2015.pdf; Cummins -- Liu et al EST PAH 2015 Supplemental Info.pdf

Chris – This is a follow up to our discussion about health effects, Tier-4F DOC and DPF emissions. Sorry for the delay, but I wanted to be sure our paper had been officially published before I sent it along.

This is probably way more information than you're looking for, but I do want to reinforce that we take all this very seriously. We embarked on a comprehensive study of PAH and nitro-PAH emissions from Tier-4F engines so *WE* would know the story, and we have made the data public. We have published similar studies comparing on-highway engine emissions with various aftertreatment configurations in the past.

Emissions testing was done over the Non-Road Steady Cycle (NRSC) and Non-Road Transient Cycle (NRTC).

The PowerPoint presentation is probably more digestible. It is focused on the DOC+SCR system through slide 16, but begins some comparisons with DPF systems at slide 17. The "money slide" is no. 20 in the PowerPoint. As you will see, n-PAH toxicity as measured by potency-equivalency factors (PEF) is down two orders of magnitude from the engine-out levels with the DOC system and another order of magnitude with the DPF. You will also see that the DOC system actually increased two-ring n-PAH emissions slightly (slide 10). Some nitration mechanisms are postulated in the PowerPoint and paper. Occasionally we see similar nitration as a sampling artifact, and we see similar effects with a DPF and even with SCR. Nonetheless, thanks to reduction in higher ring n-PAH species, total n-PAH PEF is reduced significantly with both the DOC and the DPF systems as noted above.

The PEF for PAH doesn't drop much with any system since it is dominated by 7,12 dimethylbenz(a)anthracene (DMBA), and immunosuppressant, which none of the systems with the exception of vanadia SCR reduce to any degree. (DMBA makes up less than 0.5% of the total PAH but accounts for more than 50% of the PEF!).

You'll see in Figs 9-11 of the PowerPoint and Fig. 5 of the paper that with the exception of the noted increase in 2-ring n-PAH, the DOC based system produces significant reductions in all the hydrocarbon species we care about the most from a health effects standpoint, and is quite comparable to the DPF in most cases.

Figures 1 in the paper are also a good comparison across the various systems studied. Figure 1 shows that the DOC and DPF based systems are equivalent in reducing PAH and n-PAH mass emissions with the exception of n-PAH on the steady state cycle. Both aftertreatment configurations reduced combined PAH + n-PAH by two orders of magnitude.

I thought this might be useful perspective for you as you raise the subject at HEI. It turns out that the DOC+SCR based systems are generally comparable to DOC+DPF+SCR systems from a health-effects standpoint, and both are way better than engine-out.

You'll see that key members of your staff have been engaged and briefed (also CARB staff, including Alberto Ayala, who also publishes in this area). They know our expert, Jerry Liu, very well.

If you'd like to discuss any of this in greater detail, we'd be more than happy to set up a call.

All the best,

John

Dr. John C. Wall, NAE
Vice President - Chief Technical Officer
Cummins Inc.
Mailcode 60912
500 Jackson Street
Columbus, IN 47201
tel: 1-812-377-7344
fax: 1-812-377-2731
e-mail: john.c.wall@cummins.com

Supplemental Materials

Mitigation of PAH and Nitro-PAH Emissions from Nonroad Diesel Engines

Z. Gerald Liu,* John C. Wall, Nathan A. Ottinger, Dana McGuffin

Cummins Inc.
1801 US Highway 51, Stoughton, WI 53589

*Corresponding author contact information: email: jerry.z.liu@cummins.com

Number of Figures: 2
Number of Tables: 3

Figures:
S.1 – Sampling portion of the source dilution system.
S.2 – Emissions of parent PAH compounds corresponding to nitro-PAH species with increased emissions during NRTC (a) and NRSC (b) cycles.

Tables:
S.1 – Engine properties
S.2 – Brake-specific emissions of PAH and nitro-PAH compounds during NRTC testing with engine-out, DOC+SCR, V-SCR, and DOC+DPF+SCR configurations.
S.3 – PEFs proposed by California EPA and IARC classifications for all measured compounds. Number of benzene rings for each compound is shown in parentheses.

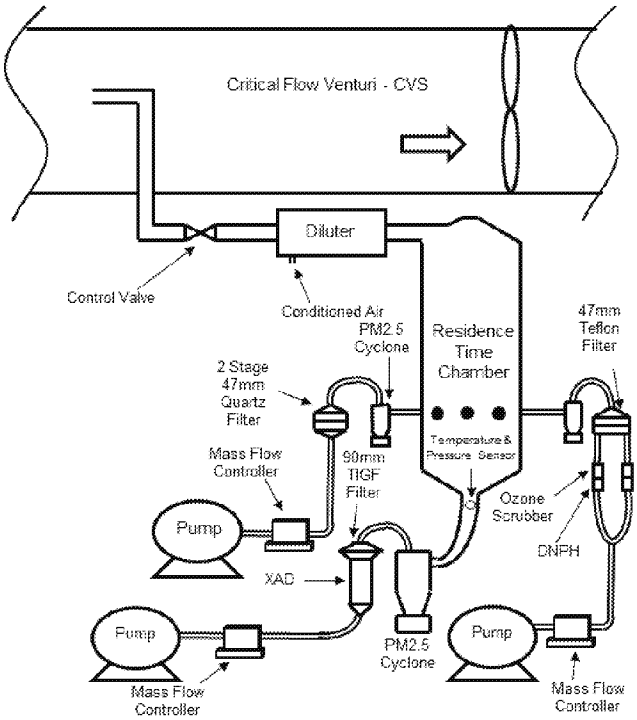

Figure S.1 Sampling portion of the source dilution system.

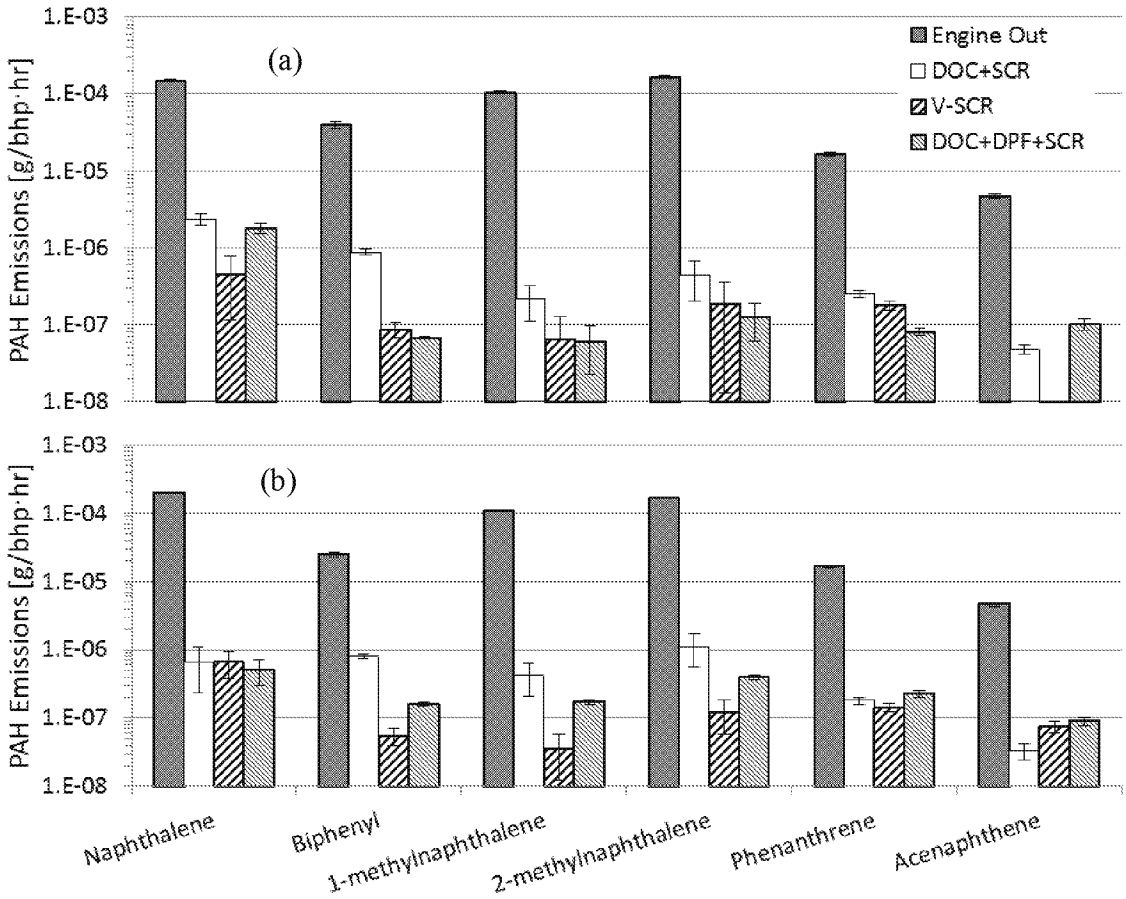

Figure S.2 Emissions of parent PAH compounds corresponding to nitro-PAH species with increased emissions during NRTC (a) and NRSC (b) cycles.

Table S.1. Engine properties

Configuration	Inline-6
Displacement	8.9 liter
Bore	4.49 in (114 mm)
Stroke	5.69 in (145 mm)
Max. Power at rpm	400 hp (298 kW) at 1900
Max. Torque at rpm	1200 ft-lb (1627 N-m) at 1500

Table S.2. Brake-specific emissions of PAH and nitro-PAH compounds during NRTC testing with engine-out, DOC+SCR, V-SCR, and DOC+DPF+SCR configurations.

	Compound	Emissions [g/bhp·hr] NRTC (Standard Error)				Compound	Emissions [g/bhp·hr] NRTC (Standard Error)			
		Engine Out	*DOC+SCR*	*V-SCR*	*DOC+DPF+SCR*		*Engine Out*	*DOC+SCR*	*V-SCR*	*DOC+DPF+SCR*
	Non-Detected species (ND) show the lab minimum detection limit in units of [g/bhp ·hr]									
PAH	Naphthalene	**1.48E-04**	**2.34E-06**	**4.51E-07**	**1.80E-06**	1,7-dimethylphenanthrene	**1.80E-06**	**2.02E-08**	**9.32E-08**	**1.94E-08**
		5.14E-06	*4.02E-07*	*3.35E-07*	*2.62E-07*		*1.50E-07*	*2.43E-09*	*2.77E-08*	*8.23E-09*
	Quinoline	**5.78E-06**	**1.98E-08**	**ND**	**ND**	3,6-dimethylphenanthrene	**2.13E-06**	**9.87E-09**	**5.64E-08**	**4.21E-09**
		1.43E-07	*1.76E-09*	*3.45E-08*	*3.45E-08*		*1.85E-07*	*6.56E-10*	*1.36E-08*	*2.00E-09*
	2-methylnaphthalene	**1.68E-04**	**4.38E-07**	**1.86E-07**	**1.27E-07**	D-dimethylphenanthrene	**1.03E-06**	**2.24E-08**	**1.14E-07**	**1.34E-08**
		6.31E-06	*2.32E-07*	*1.73E-07*	*6.60E-08*		*1.42E-08*	*1.77E-09*	*2.91E-08*	*3.32E-09*
	1-methylnaphthalene	**1.06E-04**	**2.17E-07**	**6.54E-08**	**6.06E-08**	E-dimethylphenanthrene	**2.01E-06**	**4.06E-09**	**1.26E-08**	**6.06E-09**
		4.16E-06	*1.05E-07*	*6.54E-08*	*3.78E-08*		*8.84E-08*	*8.77E-10*	*3.96E-09*	*1.99E-09*
	2,6+2,7-dimethylnaphthalene	**1.25E-04**	**1.44E-07**	**6.41E-08**	**4.22E-08**	C-dimethylphenanthrene	**5.46E-06**	**4.21E-08**	**2.18E-07**	**2.34E-08**
		3.39E-06	*3.65E-08*	*5.90E-08*	*1.27E-08*		*3.87E-07*	*1.04E-08*	*6.50E-08*	*2.18E-09*
	1,3+1,6+1,7dimethylnaphth	**1.29E-06**	**6.22E-08**	**9.24E-08**	**4.96E-08**	Fluoranthene	**1.45E-06**	**1.27E-07**	**5.92E-08**	**5.83E-09**
		1.04E-07	*3.42E-08*	*9.24E-08*	*2.57E-08*		*1.01E-07*	*1.50E-08*	*1.70E-08*	*2.00E-09*
	1,4+1,5+2,3-dimethylnaphth	**1.02E-04**	**4.77E-08**	**2.41E-08**	**2.04E-08**	Pyrene	**6.09E-06**	**3.63E-08**	**2.50E-07**	**2.38E-08**
		3.29E-06	*1.59E-08*	*2.41E-08*	*4.18E-09*		*3.22E-07*	*3.36E-09*	*7.98E-08*	*5.93E-09*
	Acenaphthylene	**2.18E-05**	**1.03E-08**	**2.63E-09**	**ND**	9-Anthraaldehyde	**5.39E-08**	**1.70E-10**	**2.35E-09**	**1.73E-09**
		8.78E-07	*2.14E-09*	*1.65E-09*	*3.45E-08*		*2.61E-08*	*1.38E-10*	*1.75E-09*	*8.67E-10*
	1,2-dimethylnaphthalene	**2.96E-05**	**1.44E-08**	**ND**	**1.04E-08**	Retene	**1.59E-09**	**6.44E-10**	**2.69E-09**	**ND**
		9.72E-07	*3.64E-09*	*3.45E-08*	*6.10E-09*		*5.26E-12*	*8.52E-11*	*6.45E-10*	*3.45E-08*
	Acenaphthene	**4.71E-06**	**4.84E-08**	**3.19E-09**	**1.02E-07**	benzo(a)fluorene	**1.52E-07**	**5.21E-10**	**8.06E-09**	**4.76E-11**
		3.17E-07	*7.15E-09*	*1.84E-09*	*1.78E-08*		*1.33E-08*	*4.96E-11*	*2.16E-09*	*4.13E-11*
	Dibenzofuran	**6.62E-06**	**1.68E-07**	**ND**	**1.68E-08**	benzo(b)fluorene	**4.04E-09**	**ND**	**1.73E-09**	**ND**
		1.00E-06	*2.68E-08*	*3.45E-08*	*7.99E-09*		*1.16E-09*	*3.45E-08*	*3.25E-10*	*3.45E-08*
	1,8-dimethylnaphthalene	**ND**	**ND**	**ND**	**ND**	B-MePy/MeFl	**2.78E-08**	**3.45E-09**	**2.05E-08**	**ND**
		3.45E-08	*3.45E-08*	*3.45E-08*	*3.45E-08*		*6.41E-09*	*7.58E-10*	*1.20E-08*	*3.45E-08*
	1-ethyl-2-methylnaphthalene	**9.89E-06**	**1.68E-08**	**7.20E-09**	**7.12E-09**	1-MeFl+C-MeFl/Py	**1.75E-08**	**ND**	**ND**	**ND**
		5.14E-07	*4.95E-09*	*7.20E-09*	*8.81E-10*		*4.22E-09*	*3.45E-08*	*3.45E-08*	*3.45E-08*
	2,3,5+I-trimethylnaphthalene	**2.40E-05**	**5.55E-08**	**3.16E-08**	**3.00E-08**	1+3-methylfluoranthene	**4.22E-07**	**7.47E-10**	**3.53E-08**	**1.18E-09**
		6.47E-07	*5.75E-09*	*1.58E-08*	*4.51E-09*		*1.49E-08*	*7.20E-10*	*1.06E-08*	*3.56E-10*
	B-trimethylnaphthalene	**3.46E-05**	**2.85E-09**	**5.19E-08**	**3.34E-08**	4-methylpyrene	**2.24E-06**	**9.87E-09**	**1.36E-07**	**7.26E-09**
		1.20E-06	*2.85E-09*	*3.31E-08*	*6.16E-09*		*4.45E-08*	*4.14E-10*	*3.52E-08*	*2.03E-09*
	A-trimethylnaphthalene	**4.43E-05**	**1.11E-07**	**9.12E-08**	**3.12E-08**	C-MePy/MeFl	**1.04E-08**	**7.48E-11**	**4.44E-09**	**8.27E-10**
		1.88E-06	*1.75E-08*	*4.81E-08*	*1.94E-09*		*4.19E-09*	*7.48E-11*	*8.85E-10*	*8.27E-10*
	C-trimethylnaphthalene	**2.96E-05**	**8.74E-08**	**1.17E-07**	**3.21E-08**	D-MePy/MeFl	**1.48E-06**	**1.47E-08**	**1.53E-07**	**7.52E-09**
		8.26E-07	*1.25E-08*	*5.57E-08*	*3.31E-09*		*7.40E-07*	*9.66E-10*	*3.77E-08*	*3.15E-09*
	1+2ethylnaphthalene	**2.56E-05**	**5.08E-07**	**7.40E-08**	**3.35E-07**	1-methylpyrene	**1.12E-06**	**6.96E-09**	**6.52E-08**	**3.08E-09**
		1.12E-06	*3.14E-08*	*5.54E-08*	*2.64E-08*		*4.27E-09*	*2.92E-10*	*1.50E-08*	*9.58E-10*
	2-ethyl-1-methylnaphthalene	**1.54E-06**	**2.08E-08**	**1.25E-08**	**2.91E-09**	Benzonaphthothiophene	**7.44E-09**	**9.56E-10**	**3.52E-09**	**3.21E-09**
		8.86E-07	*1.76E-09*	*7.80E-09*	*2.48E-09*		*2.41E-09*	*7.46E-10*	*2.36E-09*	*3.21E-09*
	E-trimethylnaphthalene	**2.14E-05**	**1.25E-07**	**6.90E-08**	**1.24E-08**	benzo(c)phenanthrene	**1.97E-07**	**1.85E-09**	**1.48E-08**	**3.29E-10**
		2.52E-07	*2.96E-08*	*7.77E-09*	*7.97E-09*		*1.34E-08*	*7.20E-10*	*3.92E-09*	*1.22E-10*
	2,4,5-trimethylnaphthalene	**4.22E-06**	**3.52E-08**	**1.45E-08**	**1.65E-08**	Benzo(ghi)fluoranthene	**7.25E-07**	**5.59E-09**	**3.65E-08**	**4.94E-09**
		3.03E-07	*1.12E-08*	*4.38E-09*	*6.73E-09*		*1.81E-08*	*2.43E-10*	*1.07E-08*	*4.55E-09*
	F-trimethylnaphthalene	**1.80E-05**	**ND**	**2.85E-08**	**1.89E-08**	9-phenylanthracene	**1.07E-08**	**ND**	**4.55E-10**	**ND**
		7.41E-07	*3.45E-08*	*1.47E-08*	*3.06E-09*		*5.95E-09*	*3.45E-08*	*1.33E-10*	*3.45E-08*
	Fluorene	**6.56E-06**	**2.90E-07**	**1.21E-07**	**1.45E-07**	Cyclopenta(c,d)pyrene	**7.20E-08**	**9.48E-10**	**2.28E-09**	**1.21E-09**
		6.60E-07	*2.13E-08*	*1.09E-08*	*2.22E-08*		*2.02E-09*	*3.22E-11*	*7.79E-10*	*1.21E-09*
	1,4,5-trimethylnaphthalene	**7.37E-06**	**ND**	**3.31E-08**	**ND**	Benz(a)anthracene	**2.03E-07**	**2.11E-09**	**1.02E-08**	**ND**
		5.35E-07	*3.45E-08*	*1.89E-09*	*3.45E-08*		*3.31E-09*	*1.30E-09*	*1.25E-09*	*3.45E-08*
	J-trimethylnaphthalene	**1.45E-05**	**3.63E-08**	**2.67E-08**	**1.22E-08**	Chrysene	**2.54E-07**	**4.84E-09**	**1.86E-08**	**ND**
		3.86E-07	*8.06E-09*	*2.67E-08*	*7.05E-09*		*5.21E-09*	*2.01E-10*	*2.56E-09*	*3.45E-08*
	A-Methylfluorene	**1.34E-05**	**2.25E-08**	**1.04E-08**	**5.64E-09**	Triphenylene	**6.22E-08**	**5.88E-10**	**3.71E-09**	**4.65E-09**
		4.93E-07	*2.13E-09*	*4.87E-09*	*2.27E-09*		*1.87E-08*	*3.56E-10*	*3.76E-10*	*5.95E-10*
	B-Methylfluorene	**5.10E-06**	**8.08E-09**	**ND**	**ND**	3-methylchrysene	**3.35E-08**	**1.01E-09**	**3.86E-09**	**1.43E-10**
		1.99E-07	*9.88E-10*	*3.45E-08*	*3.45E-08*		*4.46E-10*	*9.46E-11*	*4.23E-10*	*2.85E-11*
	1-Methylfluorene	**7.71E-06**	**5.91E-08**	**2.75E-08**	**1.73E-09**	5-methylchrysene	**N/A***	**N/A***	**ND**	**ND**
		1.41E-07	*5.29E-09*	*6.21E-09*	*8.66E-10*				*3.45E-08*	*3.45E-08*
	Dibenzothiophene	**8.57E-08**	**2.19E-08**	**1.44E-08**	**ND**	6-methylchrysene	**N/A***	**N/A***	**1.28E-09**	**ND**
		2.63E-08	*2.31E-09*	*4.00E-09*	*3.45E-08*				*1.86E-10*	*3.45E-08*
	Phenanthrene	**1.64E-05**	**2.55E-07**	**1.81E-07**	**8.18E-08**	Dibenzo(ah)anthracene	**2.75E-09**	**8.20E-10**	**1.82E-09**	**ND**
		9.24E-07	*2.68E-08*	*2.53E-08*	*7.98E-09*		*2.75E-09*	*6.13E-10*	*9.10E-10*	*3.45E-08*
	Anthracene	**3.18E-06**	**5.86E-09**	**2.68E-08**	**2.49E-09**	7H-dibenzo[c,g]carbazole	**ND**	**4.50E-09**	**1.79E-08**	**ND**
		8.45E-08	*1.03E-09*	*4.89E-09*	*2.07E-09*		*3.45E-08*	*9.36E-10*	*5.33E-09*	*3.45E-08*
	3-methylphenanthrene	**9.21E-06**	**5.80E-08**	**1.33E-07**	**2.88E-08**	Benzo(ghi)perylene	**7.32E-08**	**7.80E-09**	**2.98E-08**	**1.11E-10**
		5.79E-07	*5.57E-09*	*2.56E-08*	*2.37E-09*		*5.54E-09*	*2.01E-09*	*2.14E-09*	*1.65E-11*
	2-methylphenanthrene	**9.09E-06**	**6.90E-08**	**1.91E-07**	**3.77E-08**	Dibenzo(a,i)pyrene	**ND**	**1.70E-09**	**ND**	**ND**
		2.97E-07	*7.28E-09*	*3.19E-08*	*4.01E-09*		*3.45E-08*	*1.70E-09*	*3.45E-08*	*3.45E-08*
	2-methylanthracene	**1.58E-06**	**2.43E-09**	**2.00E-08**	**1.64E-09**	Coronene	**4.81E-09**	**2.08E-09**	**1.92E-08**	**3.40E-10**
		4.31E-08	*1.15E-09*	*7.71E-09*	*1.64E-09*		*4.81E-09*	*2.08E-09*	*3.78E-09*	*2.54E-10*
	4,5-methylenephenanthrene	**4.78E-07**	**1.32E-08**	**2.40E-08**	**4.91E-09**	Dibenzo(a,e)pyrene	**ND**	**ND**	**5.40E-08**	**ND**
		7.64E-08	*1.51E-09*	*4.18E-09*	*1.21E-09*		*3.45E-08*	*3.45E-08*	*5.40E-08*	*3.45E-08*

PAH	9-methylphenanthrene	**5.97E-06**	**4.34E-08**	**7.68E-08**	**1.47E-08**	Dibenzo(a,i)pyrene	**ND**	**ND**	**ND**	**ND**
		3.72E-07	*6.44E-09*	*1.85E-08*	*1.03E-09*		*3.45E-08*	*3.45E-08*	*3.45E-08*	*3.45E-08*
	1-methylphenanthrene	**3.98E-06**	**2.70E-08**	**7.94E-08**	**1.85E-08**	Dibenzo(a,h)pyrene	**ND**	**ND**	**ND**	**ND**
		2.20E-07	*4.01E-09*	*1.44E-08*	*4.45E-09*		*3.45E-08*	*3.45E-08*	*3.45E-08*	*3.45E-08*
	9-methylanthracene	**2.90E-07**	**1.16E-09**	**3.95E-09**	**1.15E-09**	Dibenzo(b,k)fluoranthene	**ND**	**ND**	**ND**	**ND**
		8.50E-08	*7.12E-10*	*1.98E-09*	*1.15E-09*		*3.45E-08*	*3.45E-08*	*3.45E-08*	*3.45E-08*
	2-phenylnaphthalene	**6.16E-07**	**9.19E-09**	**2.09E-08**	**3.13E-09**	Anthraquinone	**7.67E-07**	**9.76E-08**	**3.21E-07**	**3.55E-08**
		1.50E-07	*1.27E-09*	*3.87E-09*	*1.27E-09*		*6.51E-08*	*1.30E-08*	*6.02E-08*	*4.96E-09*
	A-dimethylphenanthrene	**3.93E-06**	**2.74E-08**	**1.46E-07**	**1.41E-08**	Picene	**4.56E-08**	**9.38E-09**	**3.03E-08**	**1.28E-11**
		3.84E-07	*2.61E-09*	*3.59E-08*	*2.24E-09*		*7.45E-09*	*3.33E-09*	*7.70E-09*	*1.28E-11*
	B-dimethylphenanthrene	**1.73E-06**	**1.70E-08**	**7.70E-08**	**9.94E-09**	Benzo(b)chrysene	**ND**	**1.06E-10**	**ND**	**ND**
		7.71E-08	*1.04E-08*	*1.86E-08*	*2.13E-09*		*3.45E-08*	*1.06E-10*	*3.45E-08*	*3.45E-08*
	7-methylbenz(a)anthracen	**3.78E-09**	**8.55E-10**	**5.19E-09**	**ND**	Perinaphthenone	**1.27E-05**	**9.80E-08**	**2.04E-06**	**4.46E-08**
		1.80E-09	*7.07E-10*	*5.19E-09*	*3.45E-08*		*1.56E-06*	*1.38E-08*	*6.96E-07*	*2.66E-08*
	7,12-dimethylbenz(a)anthrace	**1.62E-08**	**8.37E-09**	**ND**	**1.56E-08**	9-fluorenone	**4.01E-06**	**7.60E-07**	**1.50E-07**	**8.49E-08**
		2.02E-09	*4.12E-09*	*3.45E-08*	*8.30E-09*		*4.40E-07*	*9.11E-08*	*2.68E-08*	*1.38E-08*
	Benzo(b)fluoranthene	**9.62E-08**	**2.66E-09**	**7.32E-09**	**ND**	Acenaphthenequinone	**ND**	**3.58E-10**	**1.07E-08**	**ND**
		2.44E-09	*2.36E-10*	*7.24E-10*	*3.45E-08*		*3.45E-08*	*1.52E-10*	*2.38E-09*	*3.45E-08*
	Benzo(k)fluoranthene	**3.93E-08**	**1.15E-09**	**3.42E-09**	**ND**	Xanthone	**1.59E-05**	**9.72E-09**	**6.95E-09**	**8.28E-09**
		9.79E-10	*2.21E-10*	*5.21E-10*	*3.45E-08*		*1.46E-06*	*9.69E-10*	*3.37E-09*	*4.68E-09*
	Benzo(j)fluoranthene	**6.67E-08**	**2.43E-09**	**5.85E-09**	**ND**	Benzanthrone	**8.08E-07**	**7.49E-09**	**7.55E-08**	**1.20E-09**
		8.30E-10	*2.41E-10*	*6.83E-10*	*3.45E-08*		*3.47E-08*	*8.83E-10*	*9.94E-09*	*9.76E-11*
	Benzo(a)fluoranthene	**1.76E-08**	**1.03E-09**	**6.53E-09**	**ND**	Benz(a)anthracene-7,12-dione	**3.93E-08**	**2.85E-10**	**7.54E-09**	**ND**
		1.04E-10	*6.20E-10*	*5.20E-09*	*3.45E-08*		*2.26E-09*	*2.22E-10*	*5.87E-09*	*3.45E-08*
	BeP	**7.40E-08**	**2.27E-09**	**7.80E-09**	**ND**	Anthrone	**1.25E-06**	**8.06E-09**	**2.87E-08**	**7.74E-09**
		1.08E-09	*1.22E-10*	*7.84E-10*	*3.45E-08*		*2.89E-07*	*5.54E-09*	*1.43E-08*	*3.56E-09*
	BaP	**5.96E-08**	**5.37E-10**	**6.40E-09**	**ND**	Anthanthrene	**ND**	**5.50E-10**	**2.40E-09**	**1.39E-11**
		1.39E-09	*2.83E-10*	*5.58E-10*	*3.45E-08*		*3.45E-08*	*3.62E-10*	*6.31E-11*	*9.08E-12*
	Perylene	**1.70E-08**	**ND**	**2.34E-09**	**ND**	dibenzo(a,j)acridine	**ND**	**2.35E-09**	**6.64E-09**	**2.39E-10**
		2.98E-09	*3.45E-08*	*1.17E-09*	*3.45E-08*		*3.45E-08*	*1.94E-09*	*6.64E-09*	*2.39E-10*
	3-methylcholanthrene	**ND**	**3.98E-09**	**1.68E-09**	**ND**	Indeno[123-cd]pyrene	**2.53E-08**	**1.91E-09**	**6.72E-09**	**6.94E-11**
		3.45E-08	*2.44E-09*	*8.39E-10*	*3.45E-08*		*1.02E-09*	*7.60E-10*	*1.15E-09*	*2.33E-12*
	7-methylbenzo(a)pyrene	**ND**	**9.38E-10**	**ND**	**ND**	Dibenzo(ah+ac)anthracene	**N/A***	**ND**	**ND**	**ND**
		3.45E-08	*5.74E-10*	*3.45E-08*	*3.45E-08*			*3.45E-08*	*3.45E-08*	*3.45E-08*
	Indeno[123-cd]fluoranthene	**ND**	**9.11E-10**	**ND**	**ND**	Dibenzo(ac)anthracene	**1.09E-09**	**5.72E-10**	**4.79E-10**	**ND**
		3.45E-08	*6.67E-10*	*3.45E-08*	*3.45E-08*		*1.09E-09*	*4.53E-10*	*2.73E-10*	*3.45E-08*
	dibenzo(a,h)acridine	**ND**	**6.15E-10**	**ND**	**ND**					
		3.45E-08	*6.15E-10*	*3.45E-08*	*3.45E-08*					
Nitro-PAH	1-nitronaphthalene	**4.83E-08**	**1.42E-06**	**5.62E-08**	**2.30E-06**	2-nitrophenanthrene	**2.69E-08**	**6.75E-11**	**8.82E-10**	**1.53E-10**
		2.47E-08	*2.47E-08*	*2.58E-08*	*3.89E-07*		*3.87E-09*	*6.75E-11*	*3.54E-13*	*1.07E-10*
	1-methyl-5-nitronaphthalene	**3.77E-08**	**1.13E-07**	**9.18E-10**	**4.07E-07**	2-nitroanthracene	**ND**	**ND**	**ND**	**ND**
		1.84E-08	*8.40E-09*	*2.36E-10*	*2.85E-08*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	2-nitronaphthalene	**2.03E-07**	**4.58E-07**	**1.34E-08**	**1.43E-07**	2-nitrofluoranthene	**5.34E-09**	**7.18E-12**	**ND**	**ND**
		1.02E-07	*9.61E-09*	*5.18E-09*	*7.62E-09*		*1.12E-09*	*7.18E-12*	*4.83E-11*	*4.83E-11*
	2-nitrobiphenyl	**1.71E-08**	**1.87E-08**	**6.10E-10**	**1.93E-08**	3-nitrofluoranthene	**6.72E-10**	**5.06E-13**	**ND**	**ND**
		1.48E-09	*9.26E-10*	*3.66E-10*	*3.86E-09*		*4.56E-11*	*5.06E-13*	*4.83E-11*	*4.83E-11*
	2-methyl-4-nitronaphthalene	**1.64E-08**	**5.82E-09**	**9.75E-10**	**2.19E-08**	4-nitropyrene	**1.48E-08**	**2.53E-12**	**1.35E-10**	**ND**
		8.17E-09	*4.25E-10*	*2.79E-10*	*1.95E-09*		*4.22E-09*	*2.53E-12*	*1.33E-14*	*4.83E-11*
	1-methyl-4-nitronaphthalene	**ND**	**6.61E-09**	**4.83E-10**	**2.16E-08**	1-nitropyrene	**3.90E-08**	**1.71E-09**	**2.80E-09**	**1.98E-10**
		4.83E-11	*3.34E-10*	*3.73E-10*	*1.43E-09*		*1.20E-09*	*1.40E-10*	*8.96E-12*	*2.11E-11*
	1-methyl-6-nitronaphthalene	**4.09E-08**	**2.13E-10**	**7.03E-10**	**6.10E-10**	2-nitropyrene	**8.93E-09**	**ND**	**2.57E-11**	**ND**
		4.09E-08	*3.07E-11*	*3.63E-10*	*6.10E-10*		*4.68E-09*	*4.83E-11*	*2.57E-11*	*4.83E-11*
	3-nitrobiphenyl	**1.07E-08**	**9.55E-09**	**6.35E-10**	**6.57E-10**	2,7-dinitrofluorene	**ND**	**ND**	**ND**	**ND**
		4.34E-09	*4.63E-10*	*4.62E-10*	*1.27E-10*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	4-nitrobiphenyl	**2.47E-08**	**2.12E-07**	**4.02E-09**	**8.91E-08**	2,7-dinitrofluoren-9-one	**ND**	**ND**	**ND**	**ND**
		1.08E-08	*1.38E-08*	*2.38E-09*	*4.79E-09*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	1,3-dinitronaphthalene	**5.91E-09**	**5.28E-09**	**2.39E-09**	**7.44E-11**	7-nitrobenz(a)anthracen	**5.35E-09**	**2.20E-11**	**1.27E-10**	**ND**
		2.67E-10	*3.84E-10*	*1.01E-09*	*2.56E-11*		*8.55E-10*	*2.20E-11*	*1.16E-13*	*4.83E-11*
	1,5-dinitronaphthalene	**4.18E-10**	**1.68E-08**	**4.81E-09**	**3.29E-09**	6-nitrochrysene	**7.15E-10**	**ND**	**ND**	**ND**
		3.01E-10	*1.05E-09*	*2.71E-09*	*6.73E-10*		*1.18E-10*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	5-nitroacenaphthene	**1.42E-09**	**1.55E-10**	**1.69E-09**	**7.10E-11**	3-nitrobenzanthrone	**ND**	**ND**	**ND**	**ND**
		1.75E-10	*1.68E-11*	*1.41E-09*	*7.10E-11*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	2-nitrofluorene	**2.74E-09**	**1.90E-10**	**1.18E-09**	**9.79E-11**	1,3-dinitropyrene	**4.23E-10**	**ND**	**ND**	**ND**
		3.28E-10	*4.74E-11*	*7.77E-10*	*9.79E-11*		*4.23E-10*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	4-nitrophenanthrene	**4.34E-09**	**1.10E-08**	**5.04E-09**	**6.13E-11**	1,6-dinitropyrene	**1.35E-10**	**ND**	**ND**	**ND**
		2.26E-10	*1.02E-09*	*3.95E-09*	*3.21E-11*		*7.52E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	9-nitroanthracene	**2.12E-08**	**4.79E-10**	**2.63E-09**	**8.99E-11**	1,8-dinitropyrene	**3.05E-09**	**ND**	**ND**	**ND**
		1.39E-09	*3.65E-11*	*1.58E-09*	*3.99E-11*		*2.35E-10*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	9-nitrophenanthrene	**3.57E-08**	**1.30E-09**	**2.36E-08**	**6.25E-09**	6a+1e-nitrobenzopyrene	**ND**	**ND**	**ND**	**ND**
		3.78E-09	*7.71E-11*	*2.36E-08*	*4.63E-09*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	1,8-dinitronaphthalene	**6.59E-10**	**4.35E-09**	**2.98E-10**	**3.22E-10**	3-nitrobenzo[e]pyrene	**ND**	**ND**	**ND**	**ND**
		2.22E-10	*4.81E-10*	*2.23E-10*	*3.83E-11*		*4.83E-11*	*4.83E-11*	*4.83E-11*	*4.83E-11*
	3-nitrophenanthrene	**5.54E-08**	**6.27E-10**	**6.63E-09**	**9.30E-10**	Non-Detected species (ND) show the lab minimum detection limit in units of [g/hphr]				
		1.80E-08	*3.04E-11*	*2.99E-09*	*6.22E-11*					
						Not Applicable (N/A) species were not analyzed				

Table S.3. PEFs proposed by California EPA and IARC classifications for all measured compounds. Number of benzene rings for each compound is shown in parentheses.

Compound (Benzene Rings)	***PEF***	***IARC***
Naphthalene (2)	--	2B
Acenaphthene (2)	--	3
Fluorene (2)	--	3
Dibenzothiophene (2)	--	3
Phenanthrene (3)	--	3
Anthracene (3)	--	3
1-methylphenanthrene (3)	--	3
Fluoranthene (3)	--	3

Pyrene (4)	--	3
benzo(a)fluorene (3)	--	3
benzo(b)fluorene (3)	--	3
benzo(c)phenanthrene (4)	0.00	2B
Benzo(ghi)fluoranthene (4)	--	3
Cyclopenta(c,d)pyrene (4)	0.00	--
Benz(a)anthracene (4)	0.10	2B
Chrysene (4)	0.01	2B
Triphenylene (4)	--	3
3-methylchrysene (4)	--	3
5-methylchrysene (3)	1.00	2B
6-methylchrysene (3)	--	3
7,12-dimethylbenz(a)anthracene (4)	10.00	--
Benzo(b)fluoranthene (4)	0.10	2B
Benzo(k)fluoranthene (4)	0.10	2B
Benzo(j)fluoranthene (4)	0.10	2B
Benzo(a)fluoranthene (4)	--	3
BaP (5)	1.00	1
Perylene (5)	--	3
3-methylcholanthrene (4)	1.00	--
Indeno[123-cd]pyrene (5)	0.10	--
7H-dibenzo[c,g]carbazole (4)	1.00	--
Benzo(ghi)perylene (6)	--	3
Dibenzo(a,l)pyrene (6)	10.00	2A
Coronene (7)	--	3
Dibenzo(a,e)pyrene (6)	1.00	3
Dibenzo(a,i)pyrene (6)	10.00	2B
Dibenzo(a,h)pyrene (6)	10.00	2B
Anthraquinone (2)	--	2B
Picene (5)	--	3
Benzo(b)chrysene (5)	--	3
Anthanthrene (6)	--	3
1-nitronaphthalene (2)	--	3
2-nitronaphthalene (2)	--	3
4-nitrobiphenyl (2)	--	3
5-nitroacenaphthene (2)	--	2B
2-nitrofluorene (2)	0.01	2B
9-nitroanthracene (3)	--	3
3-nitrofluoranthene (3)	--	3
4-nitropyrene (4)	0.10	2B
1-nitropyrene (4)	0.10	2A
2-nitropyrene (4)	--	3
7-nitrobenz(a)anthracene (4)	--	3

6-nitrochrysene (4)	10.00	2A
3-nitrobenzanthrone (3)	--	2B
1,3-dinitropyrene (4)	--	2B
1,6-dinitropyrene (4)	10.00	2B
1,8-dinitropyrene (4)	1.00	2B

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Mitigation of PAH and Nitro-PAH Emissions from Nonroad Diesel Engines

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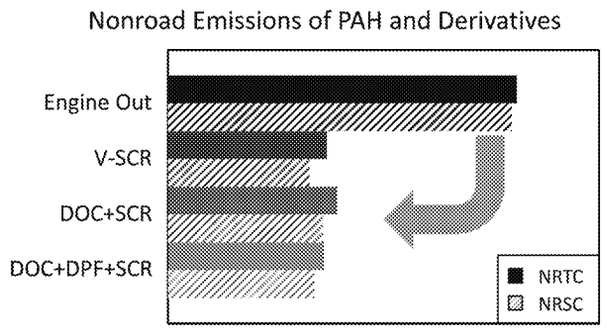
Supporting Information

ABSTRACT: More stringent emission requirements for nonroad diesel engines introduced with U.S. Tier 4 Final and Euro Stage IV and V regulations have spurred the development of exhaust aftertreatment technologies. In this study, several aftertreatment configurations consisting of diesel oxidation catalysts (DOC), diesel particulate filters (DPF), Cu zeolite-, and vanadium-based selective catalytic reduction (SCR) catalysts, and ammonia oxidation (AMOX) catalysts are evaluated using both Nonroad Transient (NRTC) and Steady (8-mode NRSC) Cycles in order to understand both component and system-level effects of diesel aftertreatment on emissions of polycyclic aromatic hydrocarbons (PAH) and their nitrated derivatives (nitro-PAH). Emissions are reported for four configurations including engine-out, DOC+CuZ-SCR+AMOX, V-SCR+AMOX, and DOC+DPF+CuZ-SCR +AMOX. Mechanisms responsible for the reduction, and, in some cases, the formation of PAH and nitro-PAH compounds are discussed in detail, and suggestions are provided to minimize the formation of nitro-PAH compounds through aftertreatment design optimizations. Potency equivalency factors (PEFs) developed by the California Environmental Protection Agency are then applied to determine the impact of aftertreatment on PAH-derived exhaust toxicity. Finally, a comprehensive set of exhaust emissions including criteria pollutants, NO_2, total hydrocarbons (THC), *n*-alkanes, branched alkanes, saturated cycloalkanes, aromatics, aldehydes, hopanes and steranes, and metals is provided, and the overall efficacy of the aftertreatment configurations is described. This detailed summary of emissions from a current nonroad diesel engine equipped with advanced aftertreatment can be used to more accurately model the impact of anthropogenic emissions on the atmosphere.



INTRODUCTION

Diesel exhaust is a complex mixture of gas- and particle-phase chemical compounds, which, in its untreated state, has been found to be both toxic to humans and detrimental to environmental systems. While there is no single source of nascent diesel exhaust's toxicity, polycyclic aromatic hydrocarbons (PAH) and their derivatives contribute significantly.[1,2]

PAHs and their derivatives are volatile and semivolatile hydrocarbons with two or more benzene rings and a boiling point of at least 200 °C. They occur naturally in hydrocarbon deposits and are also a byproduct of the combustion of hydrocarbon-based fuels. There is general agreement that many of these compounds are highly toxic atmospheric pollutants. Benzo(a)pyrene (BaP), listed by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen, is the most extensively studied of the thousands of PAH compounds in existence.[3] Several other PAH compounds are listed by the IARC and U.S. Environmental Protection Agency (EPA) as probable human carcinogens.[2] Nitro-PAHs are generally more toxic than their parent PAHs because of the resulting localized electron displacement.[4−6] Additionally, PAHs with more benzene rings tend to negatively affect human health and the environment more than lower molecular weight PAHs with only two benzene rings.[5] To calculate a cumulative toxicity from PAH concentrations in the environment, Collins et al. and the California EPA defined potency equivalency factors (PEFs) which can be applied to emissions of individual PAH and nitro-PAH compounds.[7] All 19 of the PAHs that have assigned PEFs contain at least four benzene rings, as do the majority of nitro-PAH compounds with PEFs.

The effect of diesel aftertreatment on PAH and nitro-PAH emissions has previously been studied. Heeb et al. investigated the formation and removal of nitro-PAHs in a diesel engine operated with a diesel particulate filter (DPF). The analysis showed an overall decrease in diesel exhaust toxicity, but selected PAHs were nitrated, forming primarily 2- and 3-ring nitro-PAHs.[8] Another study on PAH and nitro-PAH emissions by Carrara et al. utilized a Euro IV heavy duty engine and diesel oxidation catalyst (DOC)+DPF system.[9] Out of the 11 nitro-PAH compounds investigated by the authors, five had increased emissions after the DPF, with the low temperature B25 condition being significantly more prone to nitro-PAH formation than the high temperature C100 condition. Addi-

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tionally, the Advanced Collaborative Emissions Study (ACES) reported a reduction of unregulated emissions in their first phase using 2007 on-highway engines equipped with a DOC +DPF system. A reduction of 79% and 81% was reported from 2004 engine technology for PAH and nitro-PAH emissions, respectively.[10]

Previous work, cited above, has focused on the combined ability of a DOC+DPF system to reduce emissions because on-highway aftertreatment systems for EPA 2007 and 2010 required DPF technology to meet particulate matter (PM) regulations. Several studies have shown that DPFs reduce semivolatile and particle-phase organics and consume NO_2 via passive soot oxidation.[10,11] However, some nonroad aftertreatment architectures that meet emissions standards for criteria pollutants do not contain a DPF, raising questions about the efficacy of these systems for PAH and nitro-PAH emissions reduction.

In this study, a source dilution sampling system was implemented to characterize PAH and nitro-PAH emissions in the exhaust of a nonroad, Tier 4 Final diesel engine. Various aftertreatment systems, including DOC+copper zeolite selective catalytic reduction (CuZ-SCR) catalyst+ammoxia oxidation (AMOX) catalyst, vanadium-based SCR (V-SCR) catalyst +AMOX, and DOC+DPF+CuZ-SCR+AMOX, were evaluated. Experiments were performed with both the Nonroad Transient Cycle (NRTC) and the 8-mode Nonroad Steady Cycle (NRSC). Emission rates of more than 135 PAH and nitro-PAH compounds are reported, and the effect of aftertreatment components and system-level interactions on the formation and destruction of these compounds is discussed in detail. Potency equivalency factors (PEFs) defined by the California EPA are then applied to relevant brake-specific PAH and nitro-PAH emissions in order to gauge emissions toxicity and discern the impact of the various aftertreatment configurations. Finally, a comprehensive set of exhaust emissions including NO_2, NO_x, PM, total hydrocarbons (THC), CO, *n*-alkanes, branched alkanes, saturated cycloalkanes, aromatics, aldehydes, hopanes and steranes, and metals is provided, and the overall efficacy of the aftertreatment configurations is described.

FORMATION AND REDUCTION MECHANISMS OF PAH AND THEIR DERIVATIVES

PAH and nitro-PAH emissions cannot be explained by a single mechanism because of the possibility of both formation and destruction in diesel engine exhaust,[12] diesel aftertreatment systems,[8,9,13] and in the atmosphere.[6,14,15] In an engine, nitro-PAHs along with parent PAHs are formed de novo during combustion. During combustion's extreme conditions, low molecular weight hydrocarbon radicals form and participate in ring-forming reactions with small, reactive radicals like acetylene (C_2H_2) and propargyl (C_3H_3).[16] Aromatics continue to grow by combining with other radicals either present in fuel or formed by combustion. In comparison to the extensive research on in-cylinder PAH formation, significantly less information on the in-cylinder formation of PAH derivatives is available. Aromatic compounds and nitrogen components may participate in the growth of nitro-PAHs.[17,18]

Postcombustion, in the engine and aftertreatment system, nitro-PAHs can be formed de novo and through electrophilic substitution reactions. De novo formation is possible with a combination of high temperature, nitro-PAH precursors, and long residence times.[8] Thus, de novo formation may proceed more favorably in aftertreatment systems that contain a DPF which significantly increases the residence time of particulate matter. In addition, PAHs in particle- and liquid-phases may react with NO or NO_2 ions or acids (HNO_2, HNO_3), and gas-phase PAHs may react with electrophiles such as NO_2, NO_3, N_2O_5, or OH found in diesel exhaust to form nitro-PAHs through electrophilic substitution.[8] There are several reaction paths through which a nitro-PAH compound may be formed via the electrophilic substitution of a parent PAH, and these follow a few general mechanistic schemes. First, the PAH is activated when a charged species (NO_2, NO_3, or OH) disrupts the aromaticity of a benzene ring. A nitrogen−carbon bond is formed, creating a reactive intermediate. Then, an elimination step takes place so that the hydrogen on the substituted carbon is abstracted by a base, making the ring a conjugated system again. Another mechanism involves two substitution steps by electrophilic nitrogen radicals or ions. In this case, one of the substituents is removed by a base (NO_3^+, H_2O, or O_2) to produce the respective PAH derivative.[19,20]

Electrophilic substitution of aromatic compounds with hydrocarbon substituents, like PAHs, typically occurs at either the ortho or para positions, also known as the α- and γ-carbons. In general, the position that results in an intermediate with the most aromaticity or largest conjugated system is selectively nitrated.[19] For example, naphthalene can be nitrated in either the α- or β-position to produce 1-nitronaphthalene or 2-nitronaphthalene, respectively. Since the α-intermediate has two transition states with intact aromaticity and the β-intermediate has only one, the yield of 1-nitronaphthalene is higher than 2-nitronaphthalene.

Diesel aftertreatment systems also actively remove PAH and nitro-PAH compounds through oxidation. In addition to hydrocarbon oxidation by oxygen, oxidation by NO_2 is also possible.[21] Diehl et al. investigated the oxidation of polycyclic aromatic hydrocarbons over a Pt/Al_2O_3 catalyst, similar to the DOC substrate used in the present study.[22] The researchers measured T50 temperatures—the temperature at which 50% of a compound is oxidized—in air for naphthalene, flourene, acenaphthene, and acenaphthylene of 240, 220, 243, and 255 °C, respectively. Partial oxidation to oxygenated PAHs is possible at lower temperatures. In addition, multiple studies previously mentioned have shown that a DPF can efficiently remove PAHs by filtration mechanisms.[8−11]

EXPERIMENTAL SECTION

Engine and Aftertreatment. An 8.9 L engine rated for 380 HP (283 kW) at 2100 rpm was used for this study. The engine was turbocharged and charge air cooled and was equipped with electronically controlled high pressure common rail fuel injection and cooled exhaust gas recirculation. Additional engine details are located in Supporting Information (SI) Table S.1. This is an industrial nonroad U.S. Tier 4 Final/ Euro Stage IV engine rated for use with ultralow-sulfur diesel (ULSD). The engine was operated with BP #2 ULSD fuel with approximately 6 ppm of sulfur and Valvoline Premium Blue 15W-40 lubrication oil.

Three aftertreatment systems were evaluated in this study. The first consisted of a DOC designed to reduce CO, THC, and the soluble organic fraction of PM, as well as convert NO to NO_2 for optimal reduction of total NO_x, a CuZ-SCR catalyst for NO_x emission control, and an AMOX catalyst for NH_3 reduction. This configuration is referred to as "DOC+SCR" throughout this study. The second configuration consisted of a V-SCR catalyst followed by the same AMOX catalyst as used in

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the first configuration, referred to as "V-SCR." The final configuration consisted of the same catalysts as the first, with an additional catalyzed DPF retrofitted upstream of the CuZ-SCR, referred to as "DOC+DPF+SCR." All catalysts evaluated in this study are state-of-the-art and their sizes are typical of commercial components for this engine with a maximum SCR gas hourly space velocity in this study of approximately 80 000 h^{-1}. The engine was equipped with an open crankcase ventilation system.

Sampling Apparatus. Engine exhaust samples were collected with a source dilution sampling (SDS) system composed of a critical flow venturi-constant volume system (CFV-CVS) for primary dilution, a residence time chamber (RTC) used to simulate atmospheric aging of exhaust samples, isokinetic sampling probes, and multiple mass flow controlled sample trains for filter- and cartridge-based sample collection. Dilution air was humidity and temperature controlled, and high-efficiency particulate air (HEPA) and activated carbon filters removed background particles and organic compounds. SI Figure S.1 shows a schematic of the RTC portion of the SDS system, and a detailed discussion of the design, operating principles, quality assurance and quality control (QA/QC) procedures for the SDS system is provided elsewhere by Liu et al.[23]

The CVS system was operated at a nominal flow rate of 2250 standard cubic feet per minute (SCFM) (64.7 sm^3/min), which resulted in average primary dilution ratios ranging from 4.3 to 5.3, depending on the test cycle. Gas- and particle-phase criteria pollutants and THC were quantified, per Title 40, Part 1065 of the U.S. Code of Federal Regulations, using a Horiba MEXA 7200 DEGR gas analyzer bench and an AEI PM sampler. An MKS HS 2030 Fourier transform infrared spectrometer (FTIR) was incorporated for NH_3, N_2O, and NO_2 measurements.

The RTC was equipped with multiple sampling ports, each containing upstream $PM_{2.5}$ cyclone separators and collection media specific to the target compounds. Samples for elemental and organic carbon (EC/OC) and organic species were collected on prebaked quartz filters, ion and trace metals samples on acid-treated polytetrafluoroethylene (PTFE) filters, and soluble organic fraction samples using PTFE filters. Aldehyde and ketone emissions were measured with a sample train consisting of a PTFE prefilter for PM removal, a potassium iodide ozone scrubber (Waters Corp., WAT054420), and a 2,4-dinitrophenylhydrazine (DNPH) cartridge (Waters Corp., WAT047205). Finally, emissions of PAHs and nitro-PAHs were collected with a high-volume sampler. A 90 mm PTFE impregnated glass fiber (TIGF) filter was used to trap PM-phase emissions and was located upstream of an Amberlite XAD-4 polymeric adsorbent cartridge (Sigma-Aldrich Corp.) which trapped volatile and semivolatile species that were not PM-bound in the sampling apparatus.

Prior to each day of testing, the components of all filter holders in contact with sampling media were cleaned with nitric acid (metals sample train) or with acetone and hexane (all other sample trains). Dilution air samples were then taken, and this data was utilized to background correct emissions from all configurations. Handling, storage, and transportation blanks were analyzed for every batch of sample media, and the RTC was purged after each experiment to ensure that subsequent tests were not affected by residual exhaust in the sampling apparatus.

Test Cycles. Four configurations were tested during this study. In addition to the three aftertreatment configurations discussed above, engine-out measurements were conducted to attain a reference level of engine emissions. During experiments without aftertreatment, an electronic exhaust throttling valve was used to simulate the backpressure of the aftertreatment system in order to maintain consistency of performance of the internal combustion system across all exhaust aftertreatment configurations.

Tests were conducted utilizing both the transient and steady-state engine dynamometer test-cycles required by U.S. EPA Tier 4 Final standards for nonroad compression-ignition engines. The NRTC "provides a representation of a broad range of nonroad diesel equipment activity" and is a composite of various duty cycles based on seven different nonroad applications.[24] The ISO 8178 test cycle, in its 8-mode, C1 schedule, applies to nonroad vehicles and industrial equipment and simulates intermittent engine use at various steady-state operating conditions between idle and rated power. This cycle is referred to as the NRSC throughout this study. The NRTC was run four times in succession for each sample, beginning with a cold start. This resulted in 82 min of sample time and a cold start weighting factor of 25%. In contrast, cold start weighting factors of 5% (U.S. Tier 4 Final) and 10% (Euro Stage IV) are stipulated for criteria pollutant reporting. A 20 min hot soak was performed after the first cold cycle during which the engine was shut off and sampling was suspended. In addition, the engine was shutdown overnight to achieve an initial cold start system temperature between 20 and 25 °C. NRSC experiments had a duration of 40 min, and each experiment was preceded by a NRTC cycle to bring the engine and aftertreatment system to a repeatable starting temperature.

Analysis. PM mass emissions were determined from pre- and post-test weights of Teflon filters measured with a XP2U Mettler Toledo Ultramicrobalance with antistatic kit which weighed each filter with three repetitions under controlled temperature and humidity. Samples collected with the RTC were analyzed at the Wisconsin State Laboratory of Hygiene (WSLH) and Desert Research Institute (DRI). WSLH analyzed media for EC/OC with National Institute for Occupational Safety and Health (NIOSH) Method 5040. The analytical methods utilized by WSLH for the quantification of aldehydes, metals, and organic pollution tracers which include *n*-alkanes, branched alkanes, saturated cycloalkanes, aromatics, hopanes, and steranes have been previously detailed.[11]

Sampling media for PAH and nitro-PAH compounds was prepared and analyzed by DRI. Prior to sampling, the XAD prefilter was sonicated for 10 min twice in both dichloromethane (DCM) and methanol and was then dried in a vacuum oven at 50 °C for a minimum of 24 h. The XAD-4 resin was washed with liquinox soap and rinsed with hot water, deionized water, and methanol before being extracted with DCM and then acetone at 1500 pounds per square inch (psi) and 80 °C. The XAD-4 resin was then dried in a vacuum oven at 50 °C and finally loaded in a glass sampling cartridge. After sampling, the TIGF prefilter and XAD-4 resin were spiked with deuterated PAH and nitro-PAH standards and then extracted separately with DCM followed by acetone at 1500 psi and 80 °C. The full method is explained in detail by Zielinska et al.[16] The PAH and nitro-PAH compounds of interest were isolated with the use of a solid-phase extraction aminopropyl Sep-Pak cartridge (Waters). PAH compounds were either measured with a Varian 4000 gas chromatograph/mass spectrometer (GC/MS) or a Scion 456 GC coupled to a Scion triple quadrupole (TQ) MS for XAD-4 and prefilter extracts,

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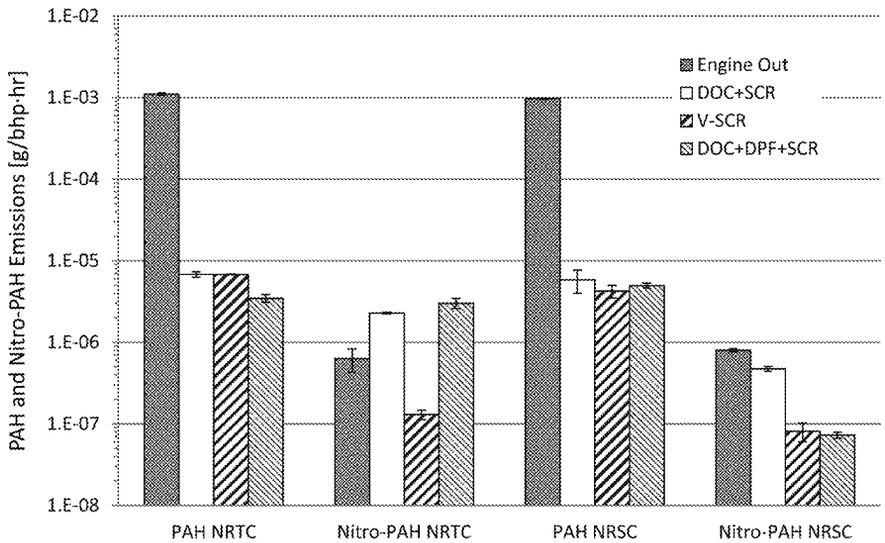

Figure 1. Total emissions of PAH and nitro-PAH compounds for all aftertreatment configurations.

respectively. Nitro-PAHs were analyzed by negative ion chemical ionization mass spectrometry (NICI-MS) with methane as the reagent gas.[25] A 6-level calibration was performed for all analytes, and a midlevel standard was run at least once every 10 samples. For all configurations, at least three replicate experiments were performed to determine measurement repeatability. All results reported are average background corrected values with their corresponding standard error.

RESULTS AND DISCUSSION

PAH and Nitro-PAH Emissions Overview. Emissions of more than 100 PAH and 30 nitro-PAH compounds were measured in order to understand the effect of various, relevant aftertreatment configurations. Oxygenated PAHs are primarily reported with the group of unsubstituted PAHs, but since some of these species are mutagenic,[26] their emissions are reported separately in the discussion of PEF adjusted emissions. SI Table S.2 summarizes the NRTC emissions from all aftertreatment configurations for all measured compounds. All PAH and nitro-PAH values reported in this article include particle- and gas-phase emissions, as discussed above. The standard error is provided, and the detection limit (DL) is given for all nondetect (ND) species. Because reported emissions are background corrected, it is possible to have an emitted value lower than the detection limit. When this occurred, the emitted value was still used for all subsequent calculations.

Naphthalene, 1-methylnapthalene, 2-methylnapthalene, and dimethylnapthalenes were the largest contributors to engine-out PAH emissions, whereas 1-nitronaphthalene, 2-nitronaphthalene, and 1-methyl-6-nitronaphthalene were the largest contributors to engine-out nitro-PAH emissions. The engine-out PAH emissions measured in this study are similar to previously published emissions from diesel engines.[11,27−30] Lea-Langton et al., in their study of PAH formation during diesel combustion, showed that PAH emission levels decreased monotonically as the temperature of combustion and the molecular weight of PAH compounds increased.[28] This trend was observed for engine-out measurements with 14% higher PAH emissions during the lower temperature NRTC and with 45 and 59% of total PAH emissions accounted for by two-ring naphthalene and its methylated derivatives in the NRSC and NRTC cycles, respectively. In contrast to results for PAH compounds, nitro-PAH emissions are orders of magnitude lower and appear to vary depending on the engine and operating conditions. For example, Khalek et al. did not report significant emissions of nitronaphthalene isomers from either 2000 or 2007 engine technologies.[10] However, similar to the present study, Heeb et al. measured higher emissions of 1-nitronaphthalene than other reported nitro-PAH compounds.[8] Engine and combustion parameters clearly have an effect on the speciation of engine-out nitro-PAHs. Additional work outside the scope of this study is needed to understand and model in cylinder PAH and nitro-PAH formation and destruction.

The various diesel aftertreatment configurations achieved large reductions in PAH compounds and the majority of nitro-PAH compounds shown in SI Table S.1, but an increase above engine out levels is noted for some of the nitro-PAH compounds. Total PAH and nitro-PAH emissions are shown in Figure 1. All aftertreatment configurations reduce PAH emissions by 2 orders of magnitude over both nonroad cycles in comparison to engine-out. A similar PAH reduction was reported by Liu et al. for DOC+DPF and SCR+AMOX architectures.[31] The authors showed that these aftertreatment systems reduce PAH emissions by greater than 85% in comparison to engine-out for an on-highway diesel engine operating under Federal Test Procedure (FTP) cycles. In the present study, PAH reductions of 99% were measured for similar aftertreatment configurations with current catalyst and filter technologies and a nonroad engine operating over nonroad drive cycles. In addition, the V-SCR configuration, which approximates Euro IV and V on-highway and U.S. and Euro nonroad architectures, also reduced PAH emissions by 99%. Total nitro-PAH emissions measured in this study are reduced by all aftertreatment architectures in the NRSC (396 °C average DOC temperature), but an increase in emissions is seen during the NRTC (330 °C average DOC temperature) for the DOC+SCR and DOC+DPF+SCR configurations. Similarly, Carrara et al. have observed higher nitro-PAH emissions from a DOC+DPF at B25 (300 °C) in comparison to C100 (440 °C).[9] Interestingly, the V-SCR aftertreatment reduced NRTC nitro-PAH emissions by 87%. All architectures reduced combined PAH and nitro-PAH emissions (not shown) by 2 orders of magnitude in comparison to engine-out emissions.

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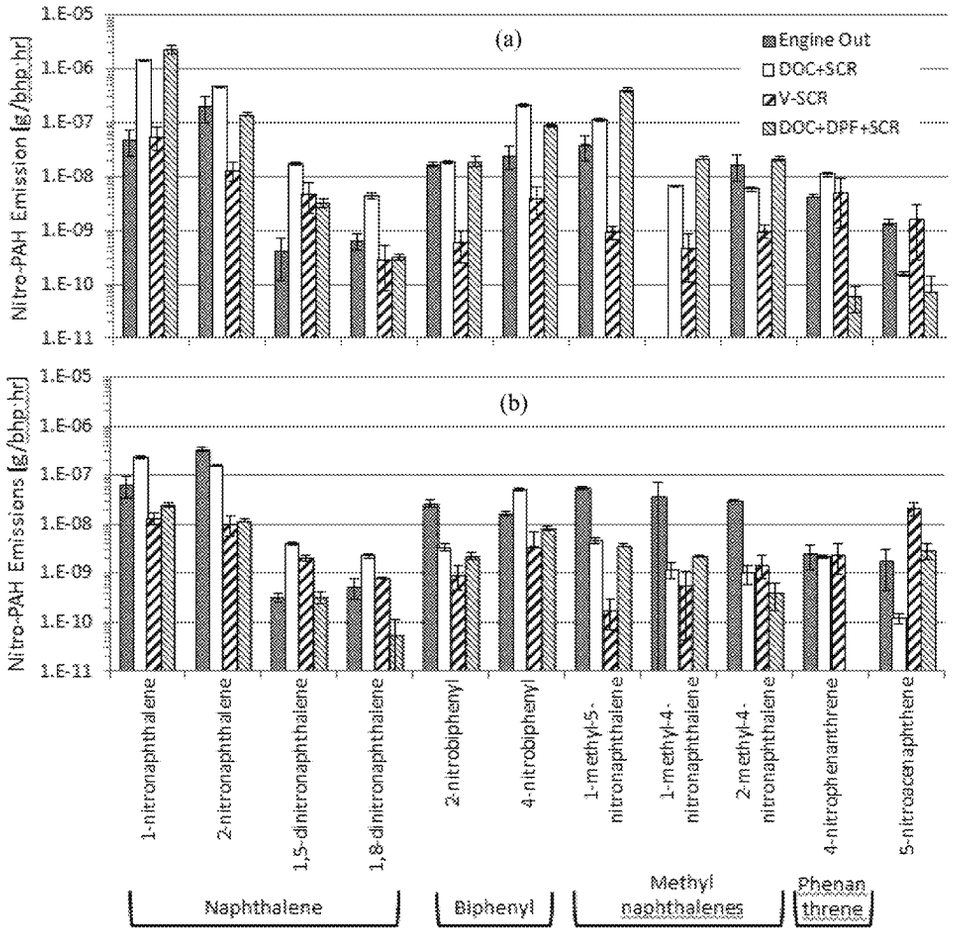

Figure 2. Emissions of nitro-PAH compounds which increased as a result of diesel aftertreatment during NRTC (a) and NRSC (b) testing.

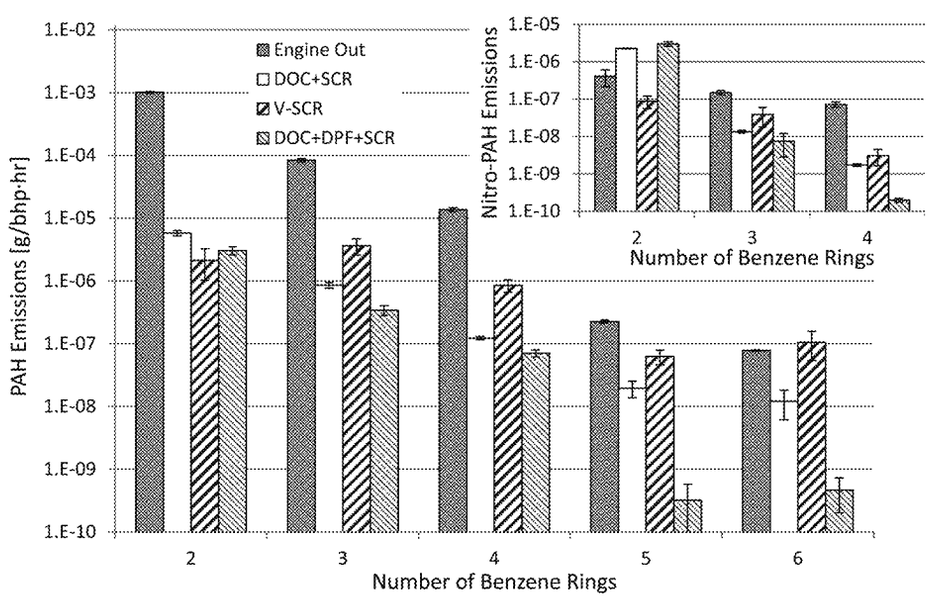

Figure 3. NRTC emissions of PAH and nitro-PAH compounds by number of benzene rings.

Formation of Nitro-PAH Compounds. The 11 nitro-PAH compounds with increased NRTC emissions are shown in Figure 2. These all have two benzene rings, with the exception of 4-nitrophenanthrene (3-ring), and all of these compounds are derivatives of five parent PAHs: acenaphthene, biphenyl, naphthalene, 1-methylnaphthalene, and phenanthrene. This increase in nitro-PAH emissions is likely due to electrophilic aromatic substitution reactions between parent PAH species and nitrogen containing cations such as NO_2^+. Engine-out emissions of all parent PAHs, shown in SI Figure S.2, are at least 2 orders of magnitude higher than their respective nitro-PAH emissions, indicating that these PAHs are available for

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nitration. Furthermore, emissions of these parent PAH compounds are reduced significantly with the addition of aftertreatment. As expected, formation of 1-nitronaphthalene (nitrated in the higher electron density α-position) is greater than 2-nitronaphthalene (nitrated in the β-position). Other nitro-PAH compounds with increased emissions were also nitrated to a greater extent at the structural location most favorable for such substitution reactions (e.g., nitrobiphenyl).

Several recent studies have also reported the selective nitration of some PAH compounds by aftertreatment systems.[8,9,29,32] Carrara et al., in their study of PAH emissions from a Euro IV engine, reported that a DPF increased nitro-PAH emissions of 2-nitronaphthalene, 1- and 6-nitrobenzo[a]-pyrene, and 1,6-dinitropyrene.[9] Hu et al., in their study of retrofit aftertreatment technologies, found that a DPF increased particle-phase emissions of 3- and 9-nitrophenanthrene.[29] Finally, Heeb et al. has reported that a DPF can increase nitro-PAH emissions of 1- and 2-nitronaphthalene, 3-nitro-phenanthrene, 9-nitroanthracene, and 1-nitropyrene.[32] The authors showed that DPFs with low oxidation activity—unable to oxidize CO to CO_2—were more likely to increase nitro-PAH emissions in comparison to DPFs with high oxidation activity. Similar to these previous studies, emissions of 1- and 2-nitronaphthalene were increased by both DOC+SCR and DOC +DPF+SCR aftertreatment in the present study. But, the increase occurred to the same degree in both configurations, indicating that the DPF has negligible impact on the formation of these nitro-PAH compounds under the conditions studied. In fact, the addition of a DPF has only a minor impact on nitro-PAH emissions in this study (Figure 1). While the DPF reduced some nitro-PAH compounds such as dinitronaph-thalenes, it also increased the concentration of others such as 1-methyl-nitronaphthalenes. The DPF is likely ineffective at reducing nitro-PAH compounds in this study because of the relatively low molecular weight and high vapor pressure of the predominant 2- and 3-ring nitro-PAHs. To illustrate this, NRTC emissions are presented as a function of benzene ring no. in Figure 3. While the benefit of a DPF is minimal for 2- to 4-ring PAH species, it is effective at reducing 4-ring nitro-PAH species and PAH compounds with more than 4-rings. In agreement with the previous work of Heeb et al.,[32] the DPF used in this study, which is catalyzed and has high oxidation activity (i.e., converts CO to CO_2), does not significantly increase the formation of nitro-PAH compounds.

Without a DPF, the DOC+SCR aftertreatment evaluated in this study increased nitro-PAH emissions in comparison to engine-out. However, it is unlikely that the CuZ-SCR component promotes the formation of nitro-PAHs. Both the V-SCR and CuZ-SCR catalysts significantly reduce exhaust NO_2 concentrations through the fast SCR reaction at temperatures above 200 °C when diesel exhaust fluid (DEF) dosing generally begins, minimizing the availability of NO_2 for PAH nitration. In addition, while the small pore zeolite of this CuZ-SCR permits molecules such as NO_x and NH_3 to diffuse into the zeolite framework, larger molecules such as PAHs are excluded, reducing their residence time in the post-DOC, high-NO_2 portion of the diesel aftertreatment system.[33] Further-more, Hu et al. evaluated the impact of V-SCR and CuZ-SCR catalysts placed behind a DOC+DPF.[29] The authors found that the addition of a CuZ-SCR to a DOC+DPF aftertreatment reduced nitro-PAH emissions, and that this combined after-treatment had the lowest nitro-PAH emissions measured.

The predominantly 2-ring nitro-PAH compounds with increased emissions are most likely formed as a result of the DOC catalyst. While DOC catalysts contribute to the removal of PAH and nitro-PAH species,[9] they also oxidize NO to NO_2. NO_2 is beneficial for both SCR NO_x conversion and DPF soot oxidation, so it plays a critical role in today's aftertreatment systems. However, high NO_2 concentrations are also known to increase the rate of nitro-PAH formation. Carrara et al. have studied the impact of NO_2 concentration on the formation rate of both 1-nitropyrene and 6-nitrobenzo(a)pyrene.[13] The authors could not observe 1-nitropyrene formation at a NO_2 concentration of 0.11 ppm, but a rate of 0.0011 $ng_{1\text{-nitropyrene}}/(mg_{soot}\cdot min)$ was observed at a NO_2 concentration of 4 ppm. A similar dependence on NO_2 concentration was reported for the formation rate of 6-nitrobenzo(a)pyrene. In the lower temperature NRTC cycle, it appears that high NO_2 concentrations, resulting from the DOC, increase the nitration rates of some predominantly gas-phase PAH compounds such as naphthalene and biphenyl. It is likely that the DOC is still participating in the catalytic oxidation of these same compounds as reported by Diehl,[22] but that the rate of decomposition is slower than the nitration rate in high-NO_2 conditions. In contrast to these results, a previous study by Liu et al. on a DOC+DPF aftertreatment system operated over the FTP cycle did not find increased nitro-PAH emissions.[31] However, while the DOC catalysts used in these two studies are similar, the engine-out NO_x levels differ significantly. The previous work of Liu et al. was conducted on a 2007 on-highway engine tuned for low NO_x emissions (<1.2 g NO_x/bhp·hr), whereas the engine out NO_x of this nonroad engine tuned for low PM exceeds 3 g NO_x/bhp·hr for both nonroad cycles. The higher NO_x levels of the nonroad engine substantially increase both engine-out and post-DOC NO_2 concentrations available for PAH nitration.

Total NRSC nitro-PAH emissions were reduced by all aftertreatment configurations as seen in Figure 1, indicating that the DOC is more effective at removal of nitro-PAH compounds at the higher temperatures of the NRSC cycle. Even so, emissions of some compounds are increased above engine-out levels. Emissions of 1-nitronaphthalene, 4-nitrobiphenyl, 1,5-dinitronaphthalene, and 1,8-dinitronaphthalene all increased as a result of the DOC+SCR aftertreatment. The lack of nitrated methylnaphthalenes during the NRSC cycle is likely due to the decomposition of 1-methylnaphthalene to naphthalene at the higher temperatures of this cycle.[34]

V-SCR. The V-SCR configuration is the only one to achieve a net reduction in NRTC nitro-PAH emissions. This configuration does not contain an upstream DOC catalyst, and, thus, the average NO_2 concentration is significantly lower than in the other two aftertreatment configurations. Engine-out NO_2 is rapidly reduced by the fast SCR reaction in the V-SCR catalyst. In addition to significantly lower NO_2 concentrations in the V-SCR configuration, it is also possible that the V-SCR catalyst participates in the reduction of PAH and nitro-PAH species. V-SCR catalysts are active for hydrocarbon conversion including aromatics such as benzene,[35] but the authors are not aware of a study that has evaluated PAH conversion and nitration over these catalysts, a significant gap in the literature since V-SCRs are used in the majority of the world for NO_x removal from diesel exhaust. In contrast to the DOC catalyst in the DOC+SCR configuration, the downstream AMOX catalyst (the only oxidation catalyst in the V-SCR configuration) likely contributes to nitro-PAH reduction since post-SCR NO_x

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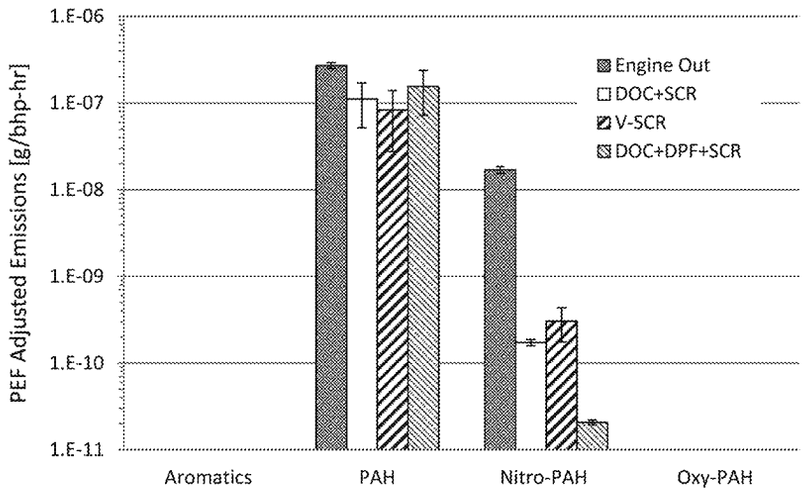

Figure 4. NRTC PEF adjusted emissions based on California EPA PEF assignments.[7]

concentrations are significantly lower than they are in the case of a pre-SCR DOC.

Even with an overall reduction in nitro-PAH emissions, the V-SCR configuration still promotes the formation of 5-nitroacenaphthene and 1,5-dinitronaphthalene as seen in Figure 3. In fact, this is the only configuration with higher emissions of 5-nitroacenaphthene; the other configurations reduced this compound by at least 85%. Although, it should be noted that this compound was only detected in one of the three V-SCR NRTC runs, so additional investigation into the formation of this Group 2B carcinogen is needed. Furthermore, juxtaposing the V-SCR configurations ability to reduce 2-ring nitro-PAH compounds (Figure 3), this configuration is less active for the reduction of PAH compounds with 3-rings or more. The lack of a DOC leads to lower 2-ring nitro-PAH emissions but increased high molecular weight PAH emissions.

Potency Equivalency Factor Emissions. All aftertreatment configurations reduce combined PAH and nitro-PAH emissions by 2 orders of magnitude, but since the toxicity of these compounds ranges from nontoxic to carcinogenic, it is also important to consider the impact of aftertreatment on emissions toxicity. To calculate PAH and nitro-PAH derived emissions toxicity, the potency equivalency factors (PEFs) originally proposed by the California Air Resources Board (CARB) in 1994 and later modified by Collins et al. (1998) and the California EPA (2005) were used.[7] The PEFs used in this study are shown in SI Table S.3, along with all IARC classifications for the compounds evaluated in this study. As is evident from the table, there is not complete agreement on the toxicity and carcinogenicity of these compounds, and this underscores the fact that toxicity assessments are based on the best available information and are subject to change as new information becomes available. Per all PEF classifications for PAH and nitro-PAH compounds, BaP is assigned a PEF of 1.0, and all other compounds are scored relative to BaP.

Figure 4 presents the NRTC PEF adjusted emissions of aromatics, PAH, nitro-PAH, and oxygenated-PAH for all aftertreatment configurations. Engine-out PEF adjusted emissions are 3 orders of magnitude lower than brake-specific PAH emissions (Figure 1). In comparison to engine-out, aftertreatment has only a minimal impact on PEF adjusted emissions of PAHs. This is because PEF adjusted emissions for engine-out, DOC+SCR, and DOC+DPF+SCR are all dominated by 7,12-dimethylbenz(a)anthracene (DMBA), an immunosuppressor used in laboratory studies to induce tumor formation. Even though this compound makes up less than 0.5% of total PAH emissions, 52% of NRTC PEF adjusted emissions from the DOC+SCR configuration are a result of DMBA. While the V-SCR reduced emissions of DMBA by more than 1 order of magnitude, V-SCR PEF adjusted emissions are dominated by dibenzo(a,e)pyrene, a PAH only found in V-SCR experiments.

Nitro-PAH PEF adjusted emissions are at least an order of magnitude lower than engine-out regardless of aftertreatment configuration. Thus, while emissions of some nitro-PAHs are increased due to aftertreatment, the overall PEF-based toxicity of nitro-PAH emissions is substantially reduced by all aftertreatment configurations. The DOC+SCR and V-SCR configurations reduced PEF adjusted emissions by nearly 2 orders of magnitude, and the addition of a DPF further reduced PEF adjusted emissions. The nitro-PAH compounds with higher emissions as a result of aftertreatment (shown in Figure 2) are primarily 2-ring nitronaphthalene and nitrobiphenyl congeners which do not have associated PEFs. On the other hand, engine-out nitro-PAH PEF adjusted emissions are dominated by 1-nitropyrene and 6-nitrochrysene with PEFs of 0.1 and 10, respectively. All aftertreatment configurations reduced 1-nitropyrene emissions by at least 1 order of magnitude, and 6-nitrochrysene emissions were reduced below the detection limit by all aftertreatment systems.

Optimizing Diesel Exhaust Aftertreatment. From both the current study and the body of literature already available on this subject, it is clear that certain conditions favor the formation of PAH and nitro-PAH compounds while others promote the destruction of those same compounds. A clear understanding of these parameters can enable the cautious design and integration of aftertreatment that minimizes these emissions. As with the majority of chemical processes, temperature plays a key role in the formation and destruction of PAH and nitro-PAH compounds. At higher temperatures, such as the NRSC cycle in this study, aftertreatment is successful at reducing nitro-PAH emissions. While exhaust gas temperature is ultimately determined by the engine operating condition, catalyst temperatures can be influenced with state-of-the-art aftertreatment packaging designed to minimize external surface area, insulation, and by positioning catalysts within close proximity of the turbine outlet. Minimizing high concentrations

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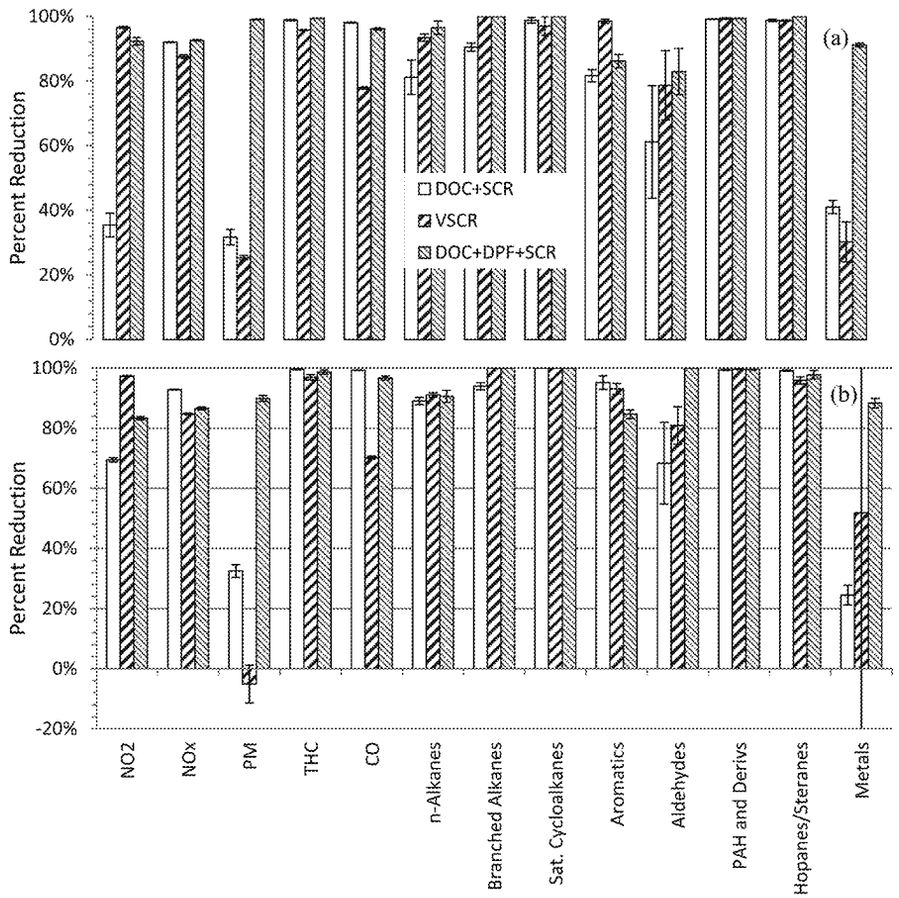

Figure 5. Percent reductions of NO_2, NO_x, PM, THC, CO, *n*-alkanes, branched alkanes, saturated cycloalkanes, aromatics, aldehydes, PAH and derivatives, hopanes and steranes, and metals for NRTC (a) and NRSC (b) cycles.

and the colocation of precursor molecules (i.e., PAH compounds and electrophiles such as NO_2) is another method to control the formation of nitro-PAHs. For example, while NO_2 is beneficial for certain catalytic processes (e.g., passive soot oxidation and NO_x conversion via the fast SCR reaction), aftertreatment systems and engine calibrations can be designed that minimize the requirement for NO_2. By eliminating the upstream DOC, the V-SCR configuration in this study successfully controls the NO_2 concentration, and, as a result, nitro-PAH emissions for this configuration are significantly lower than the other configurations. The combined oxidation activity of the V-SCR and AMOX catalysts in the V-SCR configuration is still adequate to reduce CO and THC emissions. Furthermore, advances in SCR technology continue to improve low temperature NO_x conversion of the standard SCR reaction, which does not depend on NO_2. Additional research in this area is needed to further minimize the NO_2 requirement of SCR catalysts. High capacity and low restriction DPFs can also help by extending the intervals between active DPF regenerations and reducing the need for NO_2-dependent passive soot oxidation. Finally, since the substitution reactions that increase nitro-PAH emissions occur at a finite rate, reducing exhaust residence time can decrease nitro-PAH formation. This is especially true if the NO_2 exhaust concentration is at engine-out levels or higher. A reduction in residence time can be achieved through technologies such as selective catalytic reduction on filter (SCRF) and through designs that are compact and/or close-couple aftertreatment components to the engine.

Comprehensive Emissions from a Nonroad Diesel Engine with Aftertreatment. The combined brake-specific and PEF adjusted PAH and nitro-PAH emissions reported above provide insight into the benefits and trade-offs of various nonroad aftertreatment architectures. These emissions, in addition to other relevant emissions such as criteria pollutants, THC, etc., must be considered in order to find the best available technology for each aftertreatment application. Percent reductions of NO_2, NO_x, PM, THC, CO, *n*-alkanes, branched alkanes, saturated cycloalkanes, aromatics, aldehydes, PAH and derivatives, hopanes and steranes, and metals by the three aftertreatment configurations are presented for both test cycles in Figure 5. Details on the individual species included in these categorized emissions have been previously published.[11,36] The DOC+SCR has the lowest NO_2 reduction, but this configuration still reduces engine-out NO_2 by 35% over the NRTC. Both the DOC+DPF+SCR and the V-SCR configuration reduce NO_2 by more than 90%; passive soot oxidation over the DPF contributes to this reduction. NO_x conversion is slightly lower for the V-SCR due to the lower activity of the V-SCR catalyst evaluated in this study in comparison to the CuZ-SCR. As expected, the DPF configuration reduces greater than 99% of PM mass and 92% of metal emissions, whereas the other configurations have lower reductions of PM mass and metals, a constituent of PM. On the other hand, the addition of a DPF increases fuel consumption and CO_2 emissions (not shown). It should be noted that sulfur is not included in metal emissions in this study, and the release of residual sulfur—present as a result of manufacturing—as

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sulfate may contribute to the negative PM reduction reported for the V-SCR configuration. In addition to the large reduction in total and PEF adjusted emissions of PAH and derivatives (Figures 1 and 4, respectively), other organic species including aromatics, aldehydes, hopanes, and steranes are reduced to a significant extent by all aftertreatment configurations. Similarly, THC emissions are also reduced by greater than 90% for all configurations. This is of particular interest for the V-SCR configuration which does not contain a DOC. As mentioned previously, the combined oxidation capability of the V-SCR and AMOX enable this configuration to reduce hydrocarbons, including aromatics and PAH and derivatives.

ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Author Contributions

The manuscript was written through contributions of all authors, and all authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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DOI: 10.1021/es505434r
Environ. Sci. Technol. 2015, 49, 3662−3671

ED_002029_00005616-00010

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 3/15/2015 5:42:55 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Re: Checking in -- Time for a call Monday?

Personal Matters / Ex. 6

Sent from my iPhone

> On Mar 15, 2015, at 10:41 AM, "Grundler, Christopher" <grundler.christopher@epa.gov> wrote:
>
>

Personal Matters / Ex. 6

>
> C--
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. EPA
> 202-564-1682 (DC)
> 734-214-4207 (Ann Arbor)
>
>> On Mar 12, 2015, at 8:28 PM, John C Wall <john.c.wall@cummins.com> wrote:
>>
>> Chris -- got time for a quick connect? I made a pass through DC for meetings on the Hill Tuesday, so I can tell you about that. And we shared some numbers with the Ann Arbor staff that might be worth a brief conversation. Also, I'm helping to organize a conference at Asilomar in August (that I understand you got wind of in a way I did not expect (:>)) and I'd like to talk to you about EPA presence there (maybe you?). I'm sure there are other things we can kick around, too.
>>
>> I am mysteriously very open on Monday. Got 20-30 min to catch up? Otherwise we can look for time during the week.
>>
>> Thanks,
>>
>> John
>>
>> Sent from my iPhone
>
> This email has been scanned for Malware.
> _____

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 3/13/2015 12:27:22 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Checking in -- Time for a call Monday?

Chris -- got time for a quick connect? I made a pass through DC for meetings on the Hill Tuesday, so I can tell you about that. And we shared some numbers with the Ann Arbor staff that might be worth a brief conversation. Also, I'm helping to organize a conference at Asilomar in August (that I understand you got wind of in a way I did not expect (:>)) and I'd like to talk to you about EPA presence there (maybe you?). I'm sure there are other things we can kick around, too.

I am mysteriously very open on Monday. Got 20-30 min to catch up? Otherwise we can look for time during the week.

Thanks,

John

Sent from my iPhone

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 3/5/2015 12:23:31 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Jackie M Yeager [jackie.m.yeager@cummins.com]; John C Wall [john.c.wall@cummins.com]
Subject: Motoring onward: part two of emissions regimes

Chris, Bill and Matt – Thought you would be interested in seeing this recent article from Today's Trucking on Phase 2.

http://www.todaystrucking.com/motoring-onward-part-two-of-emissions-regimes?page=1

TODAY'S TRUCKING

Motoring onward: part two of emissions regimes

By Rolf Lockwood, Posted: Mar 3, 2015 4:35 PM | Last Updated: Mar 3, 2015 4:35 PM

TORONTO-- Apples and oranges. That's how Brian Mormino describes the difference between the emissions regimes of the previous decade and the one that was launched last year and will enter its second phase in 2020. Executive director, worldwide environmental strategy and compliance at Cummins, he says all the hard work and heartache of dealing with engine emissions from 2002 on to 2010 has left us well equipped for the next steps.

We've already taken the first of those steps, starting a year ago, with Phase 1 of the fuel economy and greenhouse gas regulations as decreed by President Obama. Back in 2010, with so-called 'criteria' pollutants like nitrogen oxide (NOx) under control, he ordered the Environmental Protection Agency (EPA) and the National Highway Traffic Administration to move on. He told them to cut carbon dioxide (CO2) emissions, along with other gases in lesser amounts, while improving fuel economy in medium- and heavy-duty trucks.

The challenge was anything but small, the timeline short, but the 2014 targets were met, largely because so much had already been achieved. And the next target in 2017 will be met as well.

"I'd like to help people understand that the industry is in a great place from the standpoint of technology and the future," Mormino told me in a lengthy recent interview. "What I mean by that is that we now have diesel particulate filters, we have SCR systems, we're taking care of emissions in the exhaust. And we have learned and improved on those systems.

"And so when we look at meeting the first GHG and fuel-consumption standard in 2013, a year early, how did Cummins do that? We did it by improving the engine architecture that we already had in place. And what are we going to do for 2017? We're going to improve on the engine architecture that we already have in place. And I would even venture to say that when we look at 2021, we're going to improve on the engine architecture that we already have in place."

The New Regime

Phase 1 of the GHG and fuel-economy regime does not involve just engines as in the past, but trucks as well, with tires and aerodynamic devices tested and taken into account. The present 2014-19 rules say that heavy-duty tractors must achieve as much as a 20-percent reduction in CO2 emissions and fuel consumption by 2017, a little more by 2019. Engines, tested separately, had to improve three percent by 2014, and six percent by 2017. Mixers, refuse haulers, and other vocational machines must get to a 10-percent reduction in fuel consumption by 2017.

None of this change caused a stir last year, and initial targets were met with ordinary improvements of existing hardware and software. Things will get tougher on engines in 2017 but radically new hardware -- like waste-heat recovery -- won't be required.

When these rules were announced it seemed to many observers that, with so many variations in commercial vehicles, it would be near impossible to find a standard that applies to all. But not so, apparently, and for reasons similar to those cited by Mormino.

"It's complicated but we've been able to manage all the configurations in Phase 1," said Sean Waters, director of compliance and regulatory affairs at Daimler Trucks North America. "Mostly we're able to manage all the differences because we spent a lot of money developing fuel-efficient technologies years ago. All those decisions that have paid off for our business and paid off for our customers, have also paid off in the regulatory world and enabled us to deal with all the different configurations out there."

Phase 2 Tougher

Phase 2 of the fuel-efficiency/greenhouse gas regulations will soon be unveiled. A draft rulemaking proposal was due to be released this month by the EPA and NHTSA, but I'm hearing there's a delay. Regardless, the final rule is due some time in 2016, affecting trucks built in 2020 and beyond.

We don't know much about it, and even the people I've talked to lately who keep track of what's going on in Washington can only guess. All we really know is that Phase 2 will demand even tougher, more stringent CO2 and fuel-consumption reductions. Much tougher, it seems. But our firm knowledge stops there.

Will trailers be added to the mix? It's almost certain, it seems, and there are suggestions that it will happen in 2018. At least for dry vans and reefers.

One test or two?

Engines and vehicles are tested separately in Phase 1, but there are those who urge that just one test, with engines rolled into the whole truck like any other component, is the better approach for Phase 2. Both sides are pretty vehement.

As things stand now engines are tested on a dynamometer as they have been all along, and Cummins thinks it should stay that way. Among other reasons, Mormino says that this would preserve spec'ing flexibility for truck buyers and ensure repeatability in the testing process.

Trucks, on the other hand, are tested by way of computer modelling in Phase 1, with some inputs coming from on-track trials using standard SAE protocols and that data then fed into the modelling software. Daimler and Volvo (including Mack), the only fully integrated OEMs, are arguing that a single all-inclusive test would be simpler and more cost-effective.

Mormino says the implementation of Phase 1 was pretty much seamless, and he attributes that success largely to the continued use of familiar regulatory tools and testing methods that had been in place for decades.

For 30 years engine makers have tested NOx and particulates on the dyno, and it was easy to include CO2 as well.

"We just added CO2," Mormino says, "which means that we allowed all that diversity to continue in the marketplace because the engine is certified to operate in a wide range of vehicles and applications. So customers and end-users still have all the choice that is really, really important... in terms of all of their preferences and the types of work they have to do. The regulation didn't... limit their choices."

Perhaps a more compelling argument is the one he makes about the huge number of fuel-economy variables when a truck is put to use. Like driver skills, terrain, trailer type, highway or city, load, and countless others.

"That is a challenge for any type of regulation that tries to drive technology on vehicle aspects that are highly variable," Mormino says. "And the way that the regulation attempted to deal with that is that it separated out the most certain

aspect, the engine, and provided a much brighter focus on something you can repeatably and accurately measure and do so in a way where it can be enforced."

On the other side of this argument sits DTNA's Sean Waters, as well as the Volvo Group's Tony Greszler.

"Our goal has always been to provide our customers with the lowest total operating costs to increase their revenues, and the most effective way to do that has been to provide better fuel efficiency," says Waters. "Regulations have interfered with this goal in the past where criteria-pollutant emissions control technology had a great negative impact on fuel economy.

"It's critical that regulations to reduce fuel consumption do not in actuality result in negative impacts on real-world fuel efficiency gains, and this is where the current separate engine standard program has failed. Engine test cycles are based on historical operating data and cannot reflect changes in engine size, powertrains, or vehicle power demand and do not accurately represent the fuel used in the real-world, nor were they ever designed to do so," Waters suggests.

"DTNA believes the best way to ensure that the Phase 2 regulation provides a total-cost-of-operation benefit to customers is to give manufacturers the ability to focus on improving the entire vehicle as it operates on the road and in the application for which its customers want to use the vehicle. Any regulation that doesn't give manufacturers the flexibility to meet it in the manner that works best for our customers, results in vehicles that customers can't afford, or doesn't provide sufficient real-world payback and risks creating a pre-buy prior to the regulation becoming effective."

Waters goes further, saying that the tests for criteria pollutants -- NOx and PM -- are based on a test designed in 1990 or 1991 "when trucks had higher horsepower, more torque. It was just a different way of operating an engine. The test was never designed for CO2." Nor was it designed to measure fuel economy, he adds.

He figures the test was used for convenience in Phase 1 to get a rule done quickly.

At Volvo Group North America, Tony Greszler is vice president of government and industry relations, and he's the point man on Phase 2 rules.

"The bottom line here is that the engine test doesn't test the engine the way it runs in the truck," he says. "It's impossible for any engine test to do that. And it also doesn't account for the impact of the engine on the rest of the truck.

Waste-heat Recovery

"The technology of most concern is what we call waste-heat recovery," Greszler goes on.

It's a tool that Cummins expects to deploy in 2020 or so, though Brian Mormino says some customers may get field-test units in 2017 or 2018. In fact all engine makers are developing it, and a variation is even used in today's Formula One race cars where they add it to the standard V6 and call the package a hybrid. It recovers exhaust heat and turns it back into energy.

"It's essentially a second engine," says Greszler. "And it requires that you run the exhaust heat through a fluid, via a heat exchanger in the exhaust, and run it through an expansion machine to make power, and then condense that fluid again. Which means that you've got a lot more cooling demand. You've now got to cool most of the heat from the exhaust, because the process isn't very efficient, so most of that heat ends up in your condenser.

"And we end up having to add substantial weight, space, and cooling capacity into our trucks," he continues, "which means that we lose aerodynamic performance and we lose freight capacity because of weight. So we add efficiency to the engine but we take it away from the truck. That doesn't make sense.

"Why would you force us to do something like that? Give us the flexibility to look at the truck as a complete entity and make the best, most cost-effective decisions about how to improve the fuel efficiency in a way that meets the target," Greszler urges.

"I think it's also obvious that a system like that adds a lot of components, a lot of sensors, a lot of complexity, and potentially a lot of unreliability. Which customers don't want or need. And if you're not getting the full benefit from it

anyway, you're really kidding yourself when you measure the efficiency of the engine in a test cell where weight, space, and cooling demand are not accounted for at all."

Waste heat recovery is just an example, of course, and there might be any number of similar examples that could come up in the future.

"A particular customer could well benefit from efficiency improvements that have nothing to do with the engine and hit the overall targets that EPA will establish," Greszler continues. "Are we going to force him into engine efficiency solutions that don't necessarily match his operational requirements because EPA structured a rule that said X amount had to come from the engine? It just doesn't make sense to us."

Depending on the stringency of the coming rules, and whether or not we have a separate engine test, waste-heat recovery may or may not be needed.

"If we have a fairly stringent engine efficiency requirement measured in a test cell, then WHR may be the only available technology to meet that target," Greszler says. "If it's not applied to the engine but to the truck, we may find quite a few other options.

"We're all developing waste-heat recovery," he adds, "don't get me wrong. I'm not saying it's a technology that shouldn't be explored and exploited when and where it makes sense, but it ought not be forced into production on a time schedule that doesn't allow adequate reliability development and it shouldn't be forced into applications where it doesn't really deliver."

So, much remains to be seen on this topic, and given how much information couldn't be packed into this space, a Part Three seems to be in order. Stay tuned.

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 11/23/2015 9:50:52 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]; Stewart, Gwen [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3f8c5838943241caadb6005ffaddd7db-gstewart]
CC: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
Subject: RE: CMI Ann Arbor Visit on 10/29

Thanks Chris. We definitely understand that to be the case.

It has been about a year or more since we touched base with key leaders in DC on Phase 2, and Jen has recently assumed her new role as CTO. Thus, it seemed appropriate for us to at least submit the meeting requests to the Administrator and Assistant Administrator as we move to a final rule.

However, we would only do so after talking with you. Thus, Bill and I discussed the visit this afternoon and I followed up with the emails requesting the meetings. We would like your guidance and support on the right places in the Agency for Jen to engage during this trip on December 18th. Please advise, and let me know if you would like to discuss.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Monday, November 23, 2015 4:40 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>; Stewart, Gwen <Stewart.Gwen@epa.gov>
Cc: Charmley, William <charmley.william@epa.gov>
Subject: RE: CMI Ann Arbor Visit on 10/29

Brian—you should not expect that a meeting with the Administrator will happen

---

From: Brian C Mormino [mailto:brian.c.mormino@cummins.com]
Sent: Monday, November 23, 2015 4:26 PM
To: Stewart, Gwen
Cc: Grundler, Christopher; Charmley, William
Subject: RE: CMI Ann Arbor Visit on 10/29

Gwen, I am following up on the emails below. We are working to schedule a meeting between Cummins CTO Jen Rumsey and Chris on Friday, December 18th. Please let us know times that will work.

Bill, as I just mentioned to you, we will also take advantage of Jen's time in DC on December 18th to request meetings with Gina McCarthy and Janet McCabe. I will copy both of you on those meeting requests and appreciate your support.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Wednesday, November 18, 2015 5:41 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: Re: CMI Ann Arbor Visit on 10/29

Thanks Brian

I think I will be in DC that day. Will confirm with you tomorrow on avail times

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

On Nov 17, 2015, at 12:01 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Chris, I am following up on your note. We have looked at the schedule and Jen and I could get to DC on Friday, December 18th. Would you be available that day?

> **From:** Grundler, Christopher [mailto:grundler.christopher@epa.gov]
> **Sent:** Tuesday, October 20, 2015 9:01 PM
> **To:** Brian C Mormino <brian.c.mormino@cummins.com>
> **Subject:** Re: CMI Ann Arbor Visit on 10/29
>
> Great. Pls let me know if Jennifer travels to DC ever and we can arrange to coordinate our travel schedules as John and I have done
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. Environmental Protection Agency
> 202.564.1682 (Washington)
> 734.214.4207 (Ann Arbor)
> www.epa.gov/otaq
>
> On Oct 20, 2015, at 8:54 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:
>
>> Thanks Chris. Good to see you as well. We will catch up in the coming weeks and I will arrange for time for Jen Rumsey to connect with you soon.
>
> ---
>
> **From:** Grundler, Christopher [mailto:grundler.christopher@epa.gov]
> **Sent:** Monday, October 19, 2015 5:50 PM
> **To:** Brian C Mormino <brian.c.mormino@cummins.com>
> **Subject:** Re: CMI Ann Arbor Visit on 10/29
>
> Brian I'm sorry we did not have more time today to catch up. I hope all goes well for Adrienne.
>
> We should talk about a get-to-know-you session with John's successor
>
> Chris
>
> Christopher Grundler, Director

Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

On Oct 19, 2015, at 5:47 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Chris, Bill and Matt – As I mentioned to Chris today, I unfortunately will not be joining the Cummins team on the visit to Ann Arbor next week
>
> Ex. 6 Personal Privacy (PP)
>
> I will be involved in the preparation and will connect with them after. We look forward to continuing to work with you on Phase 2,
>
> Brian
>
> ---
> **Brian C. Mormino**
> *Executive Director -- Worldwide Environmental Strategy & Compliance*
> Cummins Inc.
> MC 60203, 500 Jackson Street
> Columbus, IN 47201
> 812-377-0512 (p)
> Ex. 6 Personal Privacy (PP)
> brian.c.mormino@cummins.com
>
> CONFIDENTIALITY NOTICE: This email, including any attachments, is for the exclusive and confidential use of the intended recipient(s). If you are not an intended recipient, please do not read, distribute or take action in reliance upon this message. If you have received this in error, please notify the sender immediately by return email and promptly delete this message and its attachments from your computer system.

Message

From: Brian C Mormino [brian.c.mormino@cummins.com]
Sent: 11/20/2015 12:56:59 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: RE: CMI Ann Arbor Visit on 10/29

Thanks Chris. Let me know what times will work and who I should follow-up with on any details.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Wednesday, November 18, 2015 5:41 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: Re: CMI Ann Arbor Visit on 10/29

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> **Sent:** Tuesday, October 20, 2015 9:01 PM
> **To:** Brian C Mormino <brian.c.mormino@cummins.com>
> **Subject:** Re: CMI Ann Arbor Visit on 10/29
>
> Great. Pls let me know if Jennifer travels to DC ever and we can arrange to coordinate our travel schedules as John and I have done
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> Christopher Grundler, Director
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> 202.564.1682 (Washington)
> 734.214.4207 (Ann Arbor)
> www.epa.gov/otaq
>
> On Oct 20, 2015, at 8:54 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:
>
>> Thanks Chris. Good to see you as well. We will catch up in the coming weeks and I will arrange for time for Jen Rumsey to connect with you soon.

From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
Sent: Monday, October 19, 2015 5:50 PM
To: Brian C Mormino <brian.c.mormino@cummins.com>
Subject: Re: CMI Ann Arbor Visit on 10/29

Brian I'm sorry we did not have more time today to catch up. I hope all goes well for

Ex. 6 Personal Privacy (PP)

We should talk about a get-to-know-you session with John's successor

Chris

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

On Oct 19, 2015, at 5:47 PM, Brian C Mormino <brian.c.mormino@cummins.com> wrote:

> Chris, Bill and Matt – As I mentioned to Chris today, I unfortunately will not be joining the Cummins team on the visit to Ann Arbor next week
>
> **Ex. 6 Personal Privacy (PP)**
>
> I will be involved in the preparation and will connect with them after.
> We look forward to continuing to work with you on Phase 2,
>
> Brian
>
> ---
> **Brian C. Mormino**
> *Executive Director -- Worldwide Environmental Strategy & Compliance*
> Cummins Inc.
> MC 60203, 500 Jackson Street
> Columbus, IN 47201
> 812-377-0512 (p)
> Ex. 6 Personal Privacy (PP)
> brian.c.mormino@cummins.com
>
> CONFIDENTIALITY NOTICE: This email, including any attachments, is for the exclusive and confidential use of the intended recipient(s). If you are not an intended recipient, please do not read, distribute or take action in reliance upon this message. If you have received this in error, please notify the sender immediately by return email and promptly delete this message and its attachments from your computer system.

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 7/30/2015 6:23:48 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Re: Follow up -- and do you have time to meet in DC Monday?

Chris -- Thanks for the quick response. I do think we are in better alignment than it may seem -- and glad you and Brian had the time to talk directly.

I'm still doing my last round of technical reviews in the UK and will be on the road until August 14. Let's find some time together at Asilomar.

I'm the meantime we will keep working it. If anything unusual comes out of the NGO meeting we will let you know.

All the best,

John

Sent from my iPhone

On Jul 29, 2015, at 10:31 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:

> Or we can find time in Chicago on August 6 if you plan to be at the public hearing
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. EPA
> 202-564-1682 (DC)
> 734-214-4207 (Ann Arbor)
>
> Begin forwarded message:
>
> > **From:** "Grundler, Christopher" <grundler.christopher@epa.gov>
> > **Date:** July 29, 2015 at 10:05:43 PM EDT
> > **To:** John C Wall <john.c.wall@cummins.com>
> > **Subject: Re: Follow up -- and do you have time to meet in DC Monday?**
> >
> > Hi John
> > I'd welcome the opportunity to clear the air. Clear air is my business after all.....
> >
> > Brian scored a lot of points with me by asking for some time with me last week. We had a frank exchange, as diplomats say. I told him exactly how I interpreted your last email with me, the one that said all our nprm will do is force some technologies on to trailers.
> >
> > Unfortunately i am in Traverse City Monday - Wednesday next week then to Chicago for the hearing. Clearing of the air is best done in person in my opinion so perhaps we can attempt to do so at Asilomar.

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

On Jul 29, 2015, at 4:39 PM, John C Wall <john.c.wall@cummins.com> wrote:

> Chris - Sorry we missed by phone last week. By the time I landed in Newark it was well after 5:00 and you were off.
>
> I understand from Brian that you all had very productive meetings on Tuesday and we are following up to continue to dive into the details with you on specific technologies and the reliability/durability issues. We will also work on trying to synthesize some engine maps incorporating the various technologies that your staff can run through GEM. (That will take a little work but we're on it.)
>
> Based on your reaction, I think you really misinterpreted my email and how communication played out among NGOs and Cummins following the NPRM. But we can hopefully clear the air on all that when we talk. To be clear, my only comments have been about our perception about engine stringency which won't surprise you -- nothing disparaging about EPA in any way and certainly nothing personal.
>
> Brian told you that we will be in a meeting among NGOs in Washington next Monday, August 3, to review engine technologies as we have with you (which will not be as detailed with them as with you). Any chance you'll be in DC Monday afternoon? I'd be happy and eager to come to your office afterward (3:30 onward) to debrief on that and talk about how best to work cooperatively going forward.
>
> Otherwise I'll pick up the trail with you for a telephone call. It's definitely time for us to connect and plan how to go forward together.
>
> Thanks,
>
> John
>
> Sent from my iPhone

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 6/30/2015 2:53:03 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Re: Call follow up

No I didn't.

Want to talk tomorrow?

Sent from my iPhone

> On Jun 29, 2015, at 9:13 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:
>
> John-
> Wow. That's quite an indictment of Bill Charmley and his team's 2+ years of effort--that all we are doing is forcing some trailer technology. We obviously have either a major technical disagreement, a failure to communicate, or both. In any event, I look forward to Cummins' comments, and hopefully before the summer is out we can get the technical teams to meet in Ann Arbor to go over them. As we have said, this is a true proposal, and likely to change one way or another based on public comments.
>
> But you missed the point of my note.
>
> Chris
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. EPA
> 202-564-1682 (DC)
> 734-214-4207 (Ann Arbor)
>
>> On Jun 29, 2015, at 6:02 PM, John C Wall <john.c.wall@cummins.com> wrote:
>>
>> Chris -- Sorry for the slow response. My "official" retirement announcement went out internally today and I've been more than a little distracted.
>>
>> Bill called on the Friday and I talked with him at some length. I think he know we were very surprised and also very disappointed by the lax engine standard -- I was pretty clear. So was Brian.
>>
>> I haven't had a calling campaign, but I've received a few calls from others about our perspective and I've been direct about it as I was with Bill. And you might imagine this was a topic of conversation when I was at ARB last week. I don't think the engine standards are doing anything near what you think they are -- same for the vehicle stringency level. For example, the last step of Heavy Duty Tractor engine standards in 2027, from 443 g/bhp-hr to 441 g/bhp-hr, which was supposed to be added for stringency, is within current measurement error!
>>
>> I'm not sure how big a deal this is in the grand scheme of things. Cummins will develop leading technologies and compete with or without standards. But unless a rule is "technology forcing", there doesn't need to be a rule at all. This one may force some technology on trailers, but not on engines.
>>
>> How are you fixed for time tomorrow? Except for 10-11, I can talk any time.
>>
>> Thanks,
>>
>> John
>>
>> _____
>>
>> Dr. John C. Wall, NAE
>> Vice President - Chief Technical Officer
>> Cummins Inc.
>> Mailcode 60912
>> 500 Jackson Street
>> Columbus, IN 47201
>> tel: 1-812-377-7344
>> fax: 1-812-377-2731
>> e-mail: john.c.wall@cummins.com
>>
>> -----Original Message-----
>> From: Grundler, Christopher [mailto:grundler.christopher@epa.gov]
>> Sent: Monday, June 29, 2015 1:38 PM

>> To: John C Wall
>> Subject: RE: Call follow up
>>
>> John--
>> If you are unhappy or disappointed with something EPA has done, I expect you to call me directly. I am disappointed that you have not, and instead chosen to call just about everyone else first
>>
>> Chris
>>
>> -----Original Message-----
>> From: John C Wall [mailto:john.c.wall@cummins.com]
>> Sent: Friday, June 19, 2015 9:01 AM
>> To: Grundler, Christopher
>> Subject: Call follow up
>>
>> Chris -- Got the call from Janet just now -- really good exchange with Tom. Thanks for the heads up!
>>
>> Can you confirm her email address? She asked for a photo of the rainbow engine in the Pride Parade (:>).
>>
>> Thanks!
>>
>> John
>>
>> Sent from my iPhone

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 10/21/2015 2:09:35 AM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Re: Just a quick resend ... Fwd: Where are you? It's time we talked again

Hang in there! Whatever the apparent disconnect, I think we are heading to the same place -- just juggling the nerdy technical details. (Welcome to MY world (:>)) . Talk tomorrow -- and whenever we need to ... -J

Sent from my iPhone

On Oct 20, 2015, at 9:51 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:

> Sorry. Day got away from me.
>
> I don't know how In the world I found myself managing a HD rule, 3 years of RFS standards, and an aircraft CO2 endangerment finding/international standard all at the same time.....poor planning? now mix in an international defeat device scandal.....and life is full. Will try to connect tomorrow. Am seeing a disconnect between what I heard from you at Asilomar about what to expect and what my guys are hearing/received from your guys.
>
> Christopher Grundler, Director
> Office of Transportation and Air Quality
> U.S. Environmental Protection Agency
> 202.564.1682 (Washington)
> 734.214.4207 (Ann Arbor)
> www.epa.gov/otaq
>
> On Oct 20, 2015, at 9:45 PM, John C Wall <john.c.wall@cummins.com> wrote:
>
>> In case this didn't connect. ... Want to be responsive and feeling the same way. This NPRM is getting WAY more political than my past experience between EPA and "industry". Maybe I missed it over the years as a dumb engineer .... but Geeeeezzzzz!!!
>>
>> Sent from my iPhone
>>
>> Begin forwarded message:
>>
>>> **From:** John C Wall <john.c.wall@cummins.com>
>>> **Date:** October 20, 2015 at 8:31:11 AM EDT
>>> **To:** "Grundler, Christopher" <grundler.christopher@epa.gov>
>>> **Subject: RE: Where are you? It's time we talked again**
>>>
>>> I've been thinking the same thing, but didn't want to bug you too much given the VW mess. I tried to send you a supportive text to what I thought was your cell number, but it turned out I had put your land line in as "mobile". Anyway, I was thinking about you (and reading everything I could find!).

I'm in Columbus this week and next (except in Ann Arbor Oct 29 -- will you be there then?)

I'm free now until 10, free again after about 4:00; free tomorrow except 11-1, and super flexible Thursday and Friday thanks to pulling the plug on a last China trip that was scheduled for this week.

What works for you?

Dr. John C. Wall, NAE
Vice President, Vice Chair - Cummins Executive Team
Cummins Inc.
Mailcode 60912
500 Jackson Street
Columbus, IN 47201
tel: 1-812-377-7344
fax: 1-812-377-2731
e-mail: john.c.wall@cummins.com

-----Original Message-----
From: Grundler, Christopher
[mailto:grundler.christopher@epa.gov]
Sent: Monday, October 19, 2015 7:19 PM
To: John C Wall <john.c.wall@cummins.com>
Subject: Where are you? It's time we talked again

Christopher Grundler, Director
Office of Transportation and Air Quality U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

Message

From: John C Wall [john.c.wall@cummins.com]
Sent: 10/20/2015 12:43:48 PM
To: Grundler, Christopher [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d3be58c2cc8545d88cf74f3896d4460f-Grundler, Christopher]
Subject: Personal contact information

While I'm thinking about it, once my Cummins ID winks out at the end of the month, you can contact me at

Personal Email / Ex. 6

Cell: Personal Phone / Ex. 6

I'll be happy to continue to kibbitz on anything environmental given the opportunity (:D)

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 7/28/2016 12:20:22 PM
To: brian.c.mormino@cummins.com
Subject: Pls call me

Important
202-564-1682

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202/564-1682 (Washington DC)
734/214-4207 (Ann Arbor MI)

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 10/22/2015 3:05:01 AM
To: John C Wall [john.c.wall@cummins.com]
Subject: Re: Let's do talk if you can

Sorry. Again.
VW is 24/7
Will try again tomorrow. Urgency was lessened after Bill and Brian solved mystery of lit review.....

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. Environmental Protection Agency
202.564.1682 (Washington)
734.214.4207 (Ann Arbor)
www.epa.gov/otaq

> On Oct 21, 2015, at 10:57 PM, John C Wall <john.c.wall@cummins.com> wrote:
>
> Chris -- I think Bill and Brian sorted out the "where's the data report?" issue (Charlton submitted it independently into the docket), but I can give you a little technicolor on how that played out with EDF and I'd value your perspective and guidance on a few other things. I also want to hear if there are any other points you are concerned that we address next Thursday in Ann Arbor.
>
> I'm totally flex Thirs-Fri. And I don't think it's a long call, given all else that's going on. Let me know if you can work a time.
>
> I'm running out of (Cummins) time!! (:>)
>
> Thanks,
>
> John
>
> Sent from my iPhone

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 8/17/2015 2:30:58 AM
To: John C Wall [john.c.wall@cummins.com]
Subject: Re: Asilomar presentation / discussion

You are dating yourself (and yours truly)

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

On Aug 16, 2015, at 7:18 PM, John C Wall <john.c.wall@cummins.com> wrote:

> Anyone who can channel Alfred E. Newman is a friend of mine (:D)
>
> Sent from my iPhone
>
> On Aug 15, 2015, at 8:02 PM, Grundler, Christopher <grundler.christopher@epa.gov> wrote:
>
> > What? Me worry?!
> >
> > Re: comparing our proposal to SuperTruck, Bill will be trying to reach you this weekend to compare notes because Karl will be making the same comparison in his presentation on Wednesday. It would be good if we are doing the math the same way.
> >
> > Chris
> >
> > Christopher Grundler, Director
> > Office of Transportation and Air Quality
> > U.S. EPA
> > 202-564-1682 (DC)
> > 734-214-4207 (Ann Arbor)
> >
> > On Aug 14, 2015, at 1:16 PM, John C Wall <john.c.wall@cummins.com> wrote:
> >
> > > Chris -- Just to try to allay any residual anxiety before we talk next week (:>) ... I have no intention of getting into anything controversial about the Phase 2 rule! I have the guys working on a chart that puts SuperTruck, Phase 2 (comparable at the vehicle level), "50 in 30" and "80 in 50" in the same context then to talk about "what else besides tailpipe FTP regulations" where we have worked with customer to create significant fuel savings in operation and which should be equally relevant for NOx and likely more effective than simply reducing FTP NOx another 90%.
> > >
> > > I'll be happy to review it all with you next week.
> > >
> > > See you in CA!

-John

Sent from my iPhone

Begin forwarded message:

From: Daniel Sperling <dsperling@ucdavis.edu>
Date: August 14, 2015 at 11:24:16 AM EDT
To: John C Wall <john.c.wall@cummins.com>
Cc: "Chris Grundler (grundler.christopher@epa.gov)" <grundler.christopher@epa.gov>, "Bob Larson (EPA) (larson.robert@epa.gov)" <larson.robert@epa.gov>
Subject: RE: Asilomar presentation / discussion

John
You and Chris will each give a 10 minutes talk. then I'll bring both of you on stage and we'll have a chat with me asking the two of you some follow up questions. Then we'll open to audience. (I'm cc'ing Chris Grunder and Bob Larson of EPA so we're all on the same page)

In your 10 minute presentation, you should not get into any weeds. We are looking to you as a big thinker that makes sense of everything. This is intended to be the session that synthesizes everything, gives a "state of the world", and some insights going forward. The details were presented in earlier sessions (or not). Chris Grundler will focus on fuels and light duty vehicles but with a broad brush and thoughts on how cars and fuels fit into larger energy/enviro challenges (including behavior and politics). I'm thinking you will talk about the future of freight, as it relates to modes, trucks, fuels, land use, pollution, GHGs, also linking to behavior and policy and politics.
The types of questions you might address are:

- <!--[if !supportLists]--><!--[endif]-->Is PM solved and is NOx only a calif issue? what roles will they play in future?
- <!--[if !supportLists]--><!--[endif]-->Prospects for CO2/fuel reductions--per truck and for all of freight (including your views on Phase 2 and supertruck)
- <!--[if !supportLists]--><!--[endif]-->role of trucks versus other modes and what that means for energy/CO2
- <!--[if !supportLists]--><!--[endif]-->opportunities to improve freight efficiency as way of both reducing costs and improving environment

- <!--[if !supportLists]--><!--[endif]-->thoughts about future of freight overall, and what it means for energy and environment
- <!--[if !supportLists]--><!--[endif]-->Global (beyond US) insights (speed of improvements elsewhere and what it means for global CO2, etc)

Perhaps you might organize your comments by generating 3-5 big findings/insights and elaborating a bit on each of them?

Dan

-----Original Message-----
From: John C Wall [mailto:john.c.wall@cummins.com]
Sent: Friday, August 14, 2015 7:43 AM
To: Daniel Sperling
Subject: Asilomar presentation / discussion

Dan -- I'm getting my head into the game for next week and could use some coaching! What are your expectations for my speaking session with Chris? Should I prepare a PowerPoint presentation covering my views on some of the subject matter? How long? Any particular content you want me to cover (e.g. Something like I did for the Haagen-Smit seminar looking back at NOx and PM and forward to CO2)? I was also thinking I could look "beyond the tailpipe" to work we've done with customers to improve fleet fuel economy and to compare the Phase 2 standards to SuperTruck. So I have a lot of ideas swirling around but not having been to Asilomar before, and being conscious that ours is the final session, I want to be sure I'm on the beam and doing a good job for you!

Thanks,

John

Sent from my iPhone

Appointment

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 8/17/2016 11:38:57 AM
To: Alt Susan [susan.alt@volvo.com]

Subject: Declined: GHG Phase 2 discussion with Chris Grundler at EPA
Location: Call in 877-748-8068 PIN 425701129 or Skype Meeting

Start: 8/17/2016 4:00:00 PM
End: 8/17/2016 5:00:00 PM

Recurrence: (none)

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 6/19/2015 1:07:34 PM
To: John C Wall [john.c.wall@cummins.com]
Subject: Re: Call follow up

Great!

McCabe.janet@epa.gov

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

> On Jun 19, 2015, at 9:01 AM, John C Wall <john.c.wall@cummins.com> wrote:
>
> Chris -- Got the call from Janet just now -- really good exchange with Tom. Thanks for the heads up!
>
> Can you confirm her email address? She asked for a photo of the rainbow engine in the Pride Parade (:>).
>
> Thanks!
>
> John
>
> Sent from my iPhone

Message

From: Grundler, Christopher [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=D3BE58C2CC8545D88CF74F3896D4460F-GRUNDLER, CHRISTOPHER]
Sent: 4/9/2015 5:44:26 PM
To: John C Wall [john.c.wall@cummins.com]
CC: Jerry Z Liu [jerry.z.liu@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Jennifer Rumsey [jennifer.rumsey@cummins.com]; Rich S Wagner [rich.s.wagner@cummins.com]; Carol Henry
Ex. 6 Personal Privacy (PP)
Subject: Re: Follow up on Tier-4F DPF DOC emissions

Thank you John! I will read this with interest and share with my team

Christopher Grundler, Director
Office of Transportation and Air Quality
U.S. EPA
202-564-1682 (DC)
734-214-4207 (Ann Arbor)

> On Apr 7, 2015, at 10:46 PM, John C Wall <john.c.wall@cummins.com> wrote:
>
> Chris – This is a follow up to our discussion about health effects, Tier-4F DOC and DPF emissions. Sorry for the delay, but I wanted to be sure our paper had been officially published before I sent it along.
>
> This is probably way more information than you're looking for, but I do want to reinforce that we take all this very seriously. We embarked on a comprehensive study of PAH and nitro-PAH emissions from Tier-4F engines so WE would know the story, and we have made the data public. We have published similar studies comparing on-highway engine emissions with various aftertreatment configurations in the past.
>
> Emissions testing was done over the Non-Road Steady Cycle (NRSC) and Non-Road Transient Cycle (NRTC).
>
> The PowerPoint presentation is probably more digestible. It is focused on the DOC+SCR system through slide 16, but begins some comparisons with DPF systems at slide 17. The "money slide" is no. 20 in the PowerPoint. As you will see, n-PAH toxicity as measured by potency-equivalency factors (PEF) is down two orders of magnitude from the engine-out levels with the DOC system and another order of magnitude with the DPF. You will also see that the DOC system actually increased two-ring n-PAH emissions slightly (slide 10). Some nitration mechanisms are postulated in the PowerPoint and paper. Occasionally we see similar nitration as a sampling artifact, and we see similar effects with a DPF and even with SCR. Nonetheless, thanks to reduction in higher ring n-PAH species, total n-PAH PEF is reduced significantly with both the DOC and the DPF systems as noted above.
>
> The PEF for PAH doesn't drop much with any system since it is dominated by 7,12 dimethylbenz(a)anthracene (DMBA), and immunosuppressant, which none of the systems with the exception of vanadia SCR reduce to any degree. (DMBA makes up less than 0.5% of the total PAH but accounts for more than 50% of the PEF!).
>
> You'll see in Figs 9-11 of the PowerPoint and Fig. 5 of the paper that with the exception of the noted increase in 2-ring n-PAH, the DOC based system produces significant reductions in all the hydrocarbon species we care about the most from a health effects standpoint, and is quite comparable to the DPF in most cases.
>
> Figures 1 in the paper are also a good comparison across the various systems studied. Figure 1 shows that the DOC and DPF based systems are equivalent in reducing PAH and n-PAH mass emissions with the exception of n-PAH on the steady state cycle. Both aftertreatment configurations reduced combined PAH + n-PAH by two orders of magnitude.
>
> I thought this might be useful perspective for you as you raise the subject at HEI. It turns out that the DOC+SCR based systems are generally comparable to DOC+DPF+SCR systems from a health-effects standpoint, and both are way better than engine-out.
>
> You'll see that key members of your staff have been engaged and briefed (also CARB staff, including Alberto Ayala, who also publishes in this area). They know our expert, Jerry Liu, very well.
>
> If you'd like to discuss any of this in greater detail, we'd be more than happy to set up a call.
>
> All the best,
>
> John
>
>
> _____

>
> Dr. John C. Wall, NAE
> Vice President - Chief Technical Officer
> Cummins Inc.
> Mailcode 60912
> 500 Jackson Street
> Columbus, IN 47201
> tel: 1-812-377-7344
> fax: 1-812-377-2731
> e-mail: john.c.wall@cummins.com
>
> <Cummins Liu Tier IV-F DOC DPF PAH Presentation 10-14-2014.pdf>
> <Cummins -- Liu et al EST PAH 2015.pdf>
> <Cummins -- Liu et al EST PAH 2015 Supplemental Info.pdf>

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 12/12/2016 5:42:19 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: HD Phase 2 discussion with Tim Blubaugh, EMA
Location: Matt will call Tim Personal Matters / Ex. 6 from Matt's Office, N123

Start: 12/14/2016 7:00:00 PM
End: 12/14/2016 8:00:00 PM
Show Time As: Tentative

Hi Tim,

Please feel free to counter this meeting scheduler with another date/time, if this date/time does not work well for you, thanks.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Friday, December 09, 2016 4:38 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Subject: GHG Phase 2

Hi Matt,

I wanted to find a time when we could talk in a little more detail about the GHG Phase 2 topics we last discussed on November 28th. Could we find a time next week? My best days are Wednesday and Thursday, but I could find a time on Tuesday or Friday if either of those days work better for you. Please let me know what might work.

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax

tblubaugh@emamail.org

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Appointment

From: EMA [ema@emamail.org]
Sent: 10/24/2016 8:37:09 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Erin Luke (Erin.Luke@PACCAR.com) [Erin.Luke@PACCAR.com]; steven.wolverton@paccar.com; Dawn Friest [DFriest@emamail.org]; Timothy A. French [TFrench@clpchicago.com]; Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Jed R. Mandel [JMandel@clpchicago.com]

Subject: EMA - October 26, 2016, Meeting – Heavier Tractors Proposal
Attachments: 2016 09 16 ECCC GHG Phase 2 - EMA Proposals.pdf; Heavier Tractors & Transition Adjustments - EMA Proposals 15Sep16.pdf; EMA Heavier Tractors Proposal - Baseline & Stringency Details 15Sep16.pdf
Location: EPA Offices; 2000 Traverwood Drive; Ann Arbor, Michigan

Start: 10/26/2016 5:00:00 PM
End: 10/26/2016 6:00:00 PM
Show Time As: Tentative

Recurrence: (none)

TO: Matt Spears, EPA
Chuck Moulis, EPA
Dan Kieffer, PACCAR
Erin Luke, PACCAR
Steven Wolverton, PACCAR
Dawn E. Friest, EMA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: October 24, 2016

RE: **October 26, 2016, Meeting – Heavier Tractors Proposal**

The purpose of this meeting is to discuss EMA's proposal for two new heavier tractor categories for Environment and Climate Change Canada's GHG Phase 2 rule. Dan Kieffer will attend the meeting in person to walk through the slides that we sent to EPA last week. For reference, attached are the relevant documents.

DATE: Wednesday, October 26, 2016
TIME: 1:00 p.m. (Eastern Time)
Location: EPA Offices
2000 Traverwood Drive
Ann Arbor, Michigan
Following is the call-in formation for those joining by teleconference:

DIAL IN #: Personal Phone / Ex. 6
CONFERENCE ID: Personal Phone / Ex. 6

CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Appointment

From: EMA [ema@emamail.org]
Sent: 10/19/2016 7:51:02 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: EMA - October 27, 2016, Conference Call – GHG Phase 2
Attachments: 2016 10 27 CVEC GHG Conference Call – GHG Phase 2.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 10/27/2016 3:00:00 PM
End: 10/27/2016 4:30:00 PM
Show Time As: Tentative

Recurrence: (none)

TO:	CVEC GHG Subcommittee Matt Spears, EPA Chuck Moulis, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	October 19, 2016
RE:	**October 27, 2016, Conference Call – GHG Phase 2**

Please join this conference call of EPA and EMA to discuss several aspects of the GHG Phase 2 final rule. Specifically, during the call, we will walk through the (i) interim glider provisions, (ii) available IRAF calculation options, and (iii) Phase 1 vocational engine credit carryover restrictions.

Following is the call-in information:

DATE: Thursday, October 27, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFERENCE ID: Personal Phone / Ex. 6
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Tel: (312) 929-1970 I Fax: (312) 929-1975
www.truckandenginemanufacturers.org

TO: CVEC GHG Subcommittee
Matt Spears, EPA
Chuck Moulis, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: October 19, 2016

RE: **October 27, 2016, Conference Call – GHG Phase 2**

Please join this conference call of EPA and EMA to discuss several aspects of the GHG Phase 2 final rule. Specifically, during the call, we will walk through the (i) interim glider provisions, (ii) available IRAF calculation options, and (iii) Phase 1 vocational engine credit carryover restrictions.

Following is the call-in information:

DATE:	Thursday, October 27, 2016
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/14/2016 2:04:59 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: HD Phase 2 items with EMA
Location: Matt's Office, Telecon: Matt will call Tim's office: (312) 929-1972

Start: 10/19/2016 6:00:00 PM
End: 10/19/2016 7:00:00 PM
Show Time As: Tentative

Tim will provide the list of items verbally during the call or perhaps via email.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 5/5/2016 9:11:40 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; James Tamm (james.tamm@dot.gov) [james.tamm@dot.gov]; Mitchell, George [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d0fbd740a76d4abab36090575cae0c6f-Mitchell, G]
CC: Matthew Psota [matthew.psota@cummins.com]

Subject: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6
Location: AA-Room-Office-N170-ConfRoom/AA-OTAQ-OFFICE

Start: 5/10/2016 4:30:00 PM
End: 5/10/2016 5:00:00 PM
Show Time As: Tentative

Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/16/2016 7:04:39 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: Phase 2 Items, Matt will call Tim
Location: Matt's office

Start: 4/18/2016 9:00:00 PM
End: 4/18/2016 10:00:00 PM
Show Time As: Busy

Does this time work?

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/6/2016 2:37:12 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Miller Marc [marc.miller@volvo.com]; Berry Steve [steve.berry@volvo.com]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Steele, Lauren [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=a3f01d4fca2b46d49ef723223af29267-Steele, Lauren P.]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Sherwood, Todd [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f6a5d8decf654ce99b5de0923ccff361-Sherwood, Todd]
CC: Todd Sherwood Ex. 6 Personal Privacy (PP) Anderson Rick (ey) [rickey.anderson@volvo.com]

Subject: Canceled: Meeting with Volvo at EPA (after EMA meeting)
Location: AA-Room-Office-C34-ConfRoom/AA-OTAQ-OFFICE

Start: 4/25/2016 8:00:00 PM
End: 4/25/2016 10:00:00 PM
Show Time As: Free

Importance: High

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 2/4/2016 4:39:58 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [tblubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: Touch Base, please counter later in the day if you're not avail
Location: Matt will call Tim

Start: 2/4/2016 9:00:00 PM
End: 2/4/2016 10:00:00 PM
Show Time As: Tentative

Appointment

From: EMA [ema@emamail.org]
Sent: 10/27/2015 3:39:30 PM
To: EMA [ema@emamail.org]; Timothy A. French [tfrench@clpchicago.com]; shirish.a.shimpi@cummins.com; Bill Martin Ex. 6 Personal Privacy (PP) dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Erin Luke (Erin.Luke@PACCAR.com) [Erin.Luke@PACCAR.com]; Cortney Guzlas (Cortney.Guzlas@Navistar.com) [Cortney.Guzlas@Navistar.com]; Thomas Kramer (tom.kramer@navistar.com) [tom.kramer@navistar.com]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Donald Keski-Hynnila (donald.keski-hynnila@daimler.com) [donald.keski-hynnila@daimler.com]; Rey Agama (agama_rey@cat.com) [agama_rey@cat.com]; George Lin (Lin_George@cat.com) [Lin_George@cat.com]; Steve Berry (steve.berry@volvo.com) [steve.berry@volvo.com]; mark.malowicki@paccar.com; Jed R. Mandel [jmandel@clpchicago.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: EMA - October 28, 2015, Conference Call to Discuss Fuel Map Variability Research Project
Location: Dial-In# Personal Phone / Ex. 6 Chair: Timothy A. French

Start: 10/28/2015 4:00:00 PM
End: 10/28/2015 7:00:00 PM
Show Time As: Tentative

Recurrence: (none)

When: Wednesday, October 28, 2015 11:00 AM-2:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In# Personal Phone / Ex. 6 Chair: Timothy A. French
Note: The GMT offset above does not reflect daylight saving time adjustments.
~~*~*~*~*~*~*~*~*

TO:

Shirish Shimpi
Bill Martin
Dan Kieffer
Mark Malowicki
Erin Luke
Cortney Guzlas
Thomas Kramer
Chuck Moulis
James Sanchez
Chris Laroo
Don Keski-Hynnila
Rey Agama
George Lin
Steve Berry

CC:

Matt Spears
Houshun Zhang
Chris Sharp
Jed R. Mandel
Timothy A. Blubaugh

FROM: Timothy A. French

DATE: October 27, 2015

RE: **October 28, 2015, Conference Call to Discuss Fuel Map Variability Research Project**

We will be meeting with Matt Spears, Houshun Zhang and Chris Sharp in Chicago tomorrow – Wednesday, October 28th – at 11:00 a.m. (Chicago time) to discuss the development of a more detailed test plan that SwRI could implement to assess the test-to-test and lab-to-lab variability associated with the generation and use of steady-state and cycle-average fuel maps for confirmatory and SEA testing under the Phase 2 GHG program. You are encouraged to join and participate in this meeting through a call-in option, the details for which are as follows:

DATE: Wednesday, October 28, 2015

TIME: 11:00 a.m. – 2:00 p.m. (Chicago time)

Ex. 6 Personal Privacy (PP)

CHAIR: Timothy A. French

If you have any questions, please feel free to contact me.

Timothy A. French
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1954 direct ? (312) 572-6688 fax
tfrench@emamail.org

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Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/6/2015 9:41:34 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: HD Phase 2 EMA Issues Discussion
Location: Telecon, Matt and Chuck will call Tim

Start: 10/8/2015 2:00:00 PM
End: 10/8/2015 4:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Appointment

From: EMA [ema@emamail.org]
Sent: 5/4/2015 2:27:59 PM
To: EMA [ema@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [tblubaugh@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]

Subject: FW: May 5, 2015, Conference Call with EMA
Attachments: 2015 05 05 CVEC GHG Conference Call Notice.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 5/5/2015 7:00:00 PM
End: 5/5/2015 9:00:00 PM
Show Time As: Busy

-----Original Appointment-----
From: EMA [mailto:ema@emamail.org]
Sent: Friday, May 01, 2015 3:54 PM
To: EMA; Timothy A. Blubaugh; Spears, Matthew
Subject: May 5, 2015, Conference Call with EMA
When: Tuesday, May 05, 2015 2:00 PM-4:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In#: Personal Matters / Ex. 6 Conference ID Personal Matters / Ex. 6 Chair: Tim Blubaugh

When: Tuesday, May 05, 2015 2:00 PM-4:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Note: The GMT offset above does not reflect daylight saving time adjustments.

+~+~+~+~+~+~+~+~+~+

TO: CVEC GHG Subcommittee
Matt Spears, EPA
Timothy A. Blubaugh

FROM:
DATE: May 1, 2015
RE: **May 5, 2015, Conference Call with EPA**

Please join this conference call of EMA's CVEC GHG Subcommittee and EPA. The purpose of the call is to continue discussing preliminary issues regarding the forthcoming GHG Phase II rule. We plan to pick up where we left off during our meeting in Ann Arbor on Friday, April 24th.

Following is the call-in information:

DATE: Tuesday, May 5, 2015
TIME: 2:00 p.m. (Chicago time)

DIAL IN #: Personal Phone / Ex. 6
CONFERENCE ID:
CHAIR: Timothy A. Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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2015 05 05 CVEC GHG Conference...

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Chicago, Illinois 60606
Tel: (312) 929-1970 I Fax: (312) 929-1975
www.truckandenginemanufacturers.org

TO: CVEC GHG Subcommittee
Matt Spears, EPA

FROM: Timothy A. Blubaugh

DATE: May 1, 2015

RE: **May 5, 2015, Conference Call with EPA**

Please join this conference call of EMA's CVEC GHG Subcommittee and EPA. The purpose of the call is to continue discussing preliminary issues regarding the forthcoming GHG Phase II rule. We plan to pick up where we left off during our meeting in Ann Arbor on Friday, April 24th.

Following is the call-in information:

DATE:	Tuesday, May 5, 2015
TIME:	2:00 p.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Timothy A. Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

81853_1.DOCX

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/14/2015 2:47:34 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [tblubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: Telecon: HD Phase 2 items with Tim Blubaugh, Matt & Chuck
Location: Telecon: Personal Phone / Ex. 6

Start: 4/14/2015 7:00:00 PM
End: 4/14/2015 8:00:00 PM
Show Time As: Tentative

Hi Tim,

Are you available at this date/time? If not, please counter this meeting notice.

During this telecon let's step through our current responses to the 11 items we previously discussed, and let's also discuss the agendas for next Friday's meetings (April 24).

Thanks,

Matt

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 4/1/2016 11:57:20 AM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]
CC: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Silverman, Steven [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=2cabad28b2394fbda8c047cdc4ef3fdc-SSILVE02]
Subject: FW: Gliders at MATS
Attachments: IMG_2534.JPG

Hi Bill
Good to see you Tuesday; two productive meetings.
Interesting graphic at Mid-America Truck Show, attached, from a glider assembler. Also, a brief summary from MATS below.
Steve

From: Nash Jay
Sent: Monday, March 30, 2015 4:33 PM
To: Alt Susan
Cc: Fasnacht Robert; Brandis Keith; Berry Steve; Anderson Rick (ey)
Subject: Gliders at MATS

Susan,
As promised, here's the info regarding the three booths dedicated to gliders that I found at MATS:

- Fitzgerald claims 5,000 vehicles/year (just opened a new facility to keep up with demand!)
  - They install Detroit Series 60, Caterpillar, & Cummins engines
  - The gliders they use are Freightliner Coronado & Columbia, Kenworth T660 & T800, & Peterbilt 386 & 389
- Harrison Truck Centers claims 1,200 vehicles/year
  - They were displaying a diesel / CNG blended engine at the show, but the huge majority of their current builds are diesel
  - They install Detroit Series 60, Caterpillar, & Cummins engines
  - They only install on Freightliner gliders – for now
- Daimler Gliders
  - This booth was set up to highlight the ease of ordering a Freightliner or Western Star glider
    - Including, a "loose parts box", which contains exhaust parts, rear suspension components, etc. to additionally ease in the retrofit of the remanufactured driveline

I also have some pictures & brochures if you're interested. Just let me know how else I can help!

Jay Nash
Product Research & Industry Trends Manager
Volvo Group Trucks Technology

Global Product Planning
7900 National Service Rd.
Greensboro, NC, 27409, USA
Ex. 6 Personal Privacy (PP)
Jay.Nash@volvo.com

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 3/24/2016 10:30:51 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: RE: Phase 2 Baseline Values

Thanks, Chuck.

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Thursday, March 24, 2016 5:15 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Subject: Phase 2 Baseline Values

Attached is a docket memo summarizing baseline GEM inputs for the various vehicle categories. I'm also attaching the baseline axle maps for Class 8 tractors and vocational vehicles. For other axles, use the GEM defaults as the baselines.

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 2/22/2016 10:30:45 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: RE: Revised Agendas + CdA Calculations

Thanks, Chuck. See you tomorrow,

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Monday, February 22, 2016 3:22 PM
To: Timothy A. Blubaugh
Subject: RE: Revised Agendas + CdA Calculations

FYI – Here are a couple of reg-related memos we are adding to the docket.

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Monday, February 22, 2016 12:39 PM
To: Spears, Matthew <spears.matthew@epa.gov>; Moulis, Charles <moulis.charles@epa.gov>
Subject: Revised Agendas + CdA Calculations

Matt, Chuck,

Attached are slightly revised draft agendas for our meetings this week. The only new items are on the agenda for tomorrow: vocational vehicle technology packages and penetration rates, and engine fuel mapping SEA for child ratings. Let me know if we need to talk about those topics, or anything else. I should be reachable at my desk this afternoon.

Also attached is a preview of our recommendations for reducing the variability in CdA calculations.

See you tomorrow,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 2/22/2016 9:22:30 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Automatic reply: Revised Agendas + CdA Calculations

Out of the office until Thursday, February 25. If urgent, contact Angie at: (312) 929-1973.

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 2/22/2016 5:38:41 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Revised Agendas + CdA Calculations
Attachments: 2016 02 08 AS CdA Calculation Recommendations DRAFT.pdf; 2016 02 23 Draft Meeting Agenda GHG Phase 2.pdf; 2016 02 24 Draft Meeting Agenda GHG Phase 2.pdf

Matt, Chuck,

Attached are slightly revised draft agendas for our meetings this week. The only new items are on the agenda for tomorrow: vocational vehicle technology packages and penetration rates, and engine fuel mapping SEA for child ratings. Let me know if we need to talk about those topics, or anything else. I should be reachable at my desk this afternoon.

Also attached is a preview of our recommendations for reducing the variability in CdA calculations.

See you tomorrow,

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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DRAFT – February 10, 2016

C_dA Calculation Variability

Recommendations

EMA recommendations the following to reduce the variability associated with calculating C_dA values from coastdown test data.

1. Use the largest possible amount of vehicle speed data, including the first point less than 72 mph and the last point greater than 58 mph, and the first point less than 27 mph and the last point greater than 13 mph. Additionally, use only matched pairs of data sets, including a complete high speed range and a complete low speed range.

2. Filter the following data elements with a Hampel (moving median) filter using a three second range and three standard deviations:

   a. Air speed
   b. Yaw angle
   c. Vehicle speed
   d. Track side wind data

3. Calibrate the yaw angle and air speed run-by-run with linear regression of filtered on-board data against filtered track side wind data, using data from the high speed range.

4. Utilize the following method for discarding outliers when evaluating C_dA as a function of yaw angle:

   a. Measure data from multiples runs (which constitute one test).
   b. Discard known outliers or errors (*e.g.*, driver hit the brake during a run).
   c. Find the mean angle, Θ, of all remaining runs.
   d. Draw vertical lines at $\Theta \pm X°$ (where X is to be determined), and discard all points outside the lines as not characteristic of the test's Θ.
   e. Find the average drag area and standard deviation, C_dA and σ, of the remaining runs' drag areas.
   f. Draw horizontal lines at $C_dA \pm 2\sigma$. Discard all points outside the lines.
   g. Take all remaining runs, average the angles to get a new mean angle Θ', and average the drag areas to get a new mean drag area C_dA'.
   h. If there are at least 24 runs remaining after all of the runs are discarded, then Θ' and C_dA' are valid for that test.

90957_3

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GHG Phase 2 Meeting
February 23, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Notice of Data Availability

- A. Data included
- B. Strategies addressed
- C. Timing

II. Vocational Vehicle Program

- A. Segmentation
  1. Weight class categories
  2. Duty cycles
  3. Equalization
- B. Custom chassis categories
- C. Technology packages and penetration rates
  1. Hybrid technologies
  2. Other vocational technologies
- D. Powertrain testing
- E. Credit life and transfer

III. Engine Fuel Mapping

- A. Cycle average approach
- B. SEA for child ratings
- C. SwRI test plan

IV. Miscellaneous Issues

- A. N_2O standard
- B. Road Grade Profile D
- C. In-use tractor testing
- D. NO_X measurement during engine testing
- E. Powertrain modifications in use
- F. Powertrain SEAs

V. Rulemaking Timeline

VI. Other Issues

91093_3

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GHG Phase 2 Meeting
February 24, 2016
U.S. EPA
2000 Traverwood Drive
Ann Arbor, Michigan

DRAFT AGENDA

I. Aerodynamic Issues

- A. Baseline and bins
  1. High roof sleeper cab tractors
  2. Day cab tractors
- B. CdA Calculation Variability
  1. Draft recommendations
  2. ±X° yaw angle for discarding outliers
- C. Coastdown data frequency
- D. Yaw curve asymmetry
- E. Tire rolling resistance as a function of speed
  1. EMA testing
  2. Scalar shift vs. multiplicative
- F. CdA SEA strawman

II. GEM Inputs

- A. TPMS
- B. AES
- C. Speed limiter

III. Miscellaneous Issues

- A. MY17 default engine map
- B. 6x2 penetrations

IV. Other Issues

V. Next Steps

91094_3

Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/9/2016 4:43:14 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Brian C Mormino [brian.c.mormino@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Manik Narula [manik.narula@cummins.com]

Subject: Cummins/EPA call on Phase 2 cycle average map
Attachments: Joining Skype for Business Meetings (External).pdf
Location: US toll-free Personal Phone / Ex. 6 or Gary's office at CTC

Start: 2/17/2016 6:00:00 PM
End: 2/17/2016 7:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Follow up to our cycle average map discussion on 1/29
Agenda:

1. Review of issues - Cummins
2. Testing update - Cummins, EPA
3. Generic vehicle definition - Cummins

Teleconference call-in number:

US toll-free Personal Phone / Ex. 6
Access code

Skype information:
Link for non-Cummins attendees (see additional instructions in the attachment):
Join Skype Meeting (Web Guest)
Link for Cummins attendees:

Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Help
Audio for this Skype for Business meeting is not available. When prompted, please select "Don't Join Audio". Use a phone to call the conference number provided in this invitation.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 2/4/2016 4:40:00 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: Touch Base, please counter later in the day if you're not avail
Location: Matt will call Tim

Start: 2/4/2016 9:00:00 PM
End: 2/4/2016 10:00:00 PM
Show Time As: Tentative

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 2/2/2016 7:51:07 PM
To: Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]
CC: Brian C Mormino [brian.c.mormino@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Manik Narula [manik.narula@cummins.com]
Subject: Cummins slides from 1/29/16 - Confidential Business Information
Attachments: message.html

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To view your message
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Sign in using the following email address: **moulis.charles@epa.gov**

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 12/17/2015 1:11:16 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Miller Marc [marc.miller@volvo.com]
Subject: Vocational program

Matt, Chuck,

Good meeting yesterday. I was wondering if the material concerning vocational program alternatives can be made available sooner rather than later. Recognizing you may be concerned about what gets misinterpreted in the record, maybe you could replace "stop-start" and "auto-shutdown" in the examples with "Tech A" and "Tech B". If you're uncomfortable with it, ok, but I thought it worth asking to improve our understanding of the proposal more quickly; I've forgotten when you said you expect to make the materials available.

Thanks for giving this some thought. Have a great holiday.
Steve

Message

From: Timothy A. Blubaugh [tblubaugh@emamail.org]
Sent: 12/11/2015 7:06:03 PM
To: Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
CC: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: RE: Draft Agendas

Thanks, Angela. Have a nice weekend.

Tim

PS: We'll supply the lunch orders and attendee lists on Monday.

From: Cullen, Angela [mailto:cullen.angela@epa.gov]
Sent: Friday, December 11, 2015 1:05 PM
To: Timothy A. Blubaugh; Spears, Matthew
Cc: Moulis, Charles
Subject: RE: Draft Agendas

Thanks, Tim.

We should be ok covering the items on Tuesday and Wednesday.

Angela

From: Timothy A. Blubaugh [mailto:tblubaugh@emamail.org]
Sent: Friday, December 11, 2015 1:54 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Cc: Cullen, Angela <cullen.angela@epa.gov>; Moulis, Charles <moulis.charles@epa.gov>
Subject: Draft Agendas

Hi Matt,

Attached are slightly revised draft agendas for our meetings next week. Please let me know if you have any questions or concerns. If you need to reach me, I will be in the office most of the day Monday and otherwise available on my mobile phone: Personal Phone / Ex. 6 I look forward to seeing you next week in Ann Arbor.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1972 direct • (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Matthew Psota [matthew.psota@cummins.com]
Sent: 12/21/2016 7:09:04 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Schaefer, Ron [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=e4cf03e763744da1a7baa1f2951ab544-Schaefer, Ron]
Subject: RE: GHG Phase 2 Question - Non-Road Engine Exemption in Hybrids

Chuck –

Thanks for the clarification, they are very helpful!

Regards,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Cell 812.341.6361

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Wednesday, December 21, 2016 10:54 AM
To: Matthew Psota <matthew.psota@cummins.com>
Cc: Schaefer, Ron <schaefer.ron@epa.gov>
Subject: RE: GHG Phase 2 Question - Non-Road Engine Exemption in Hybrids

Matt,

Answers to your questions about engines for hybrid vehicles are shown below.

Chuck

From: Matthew Psota [mailto:matthew.psota@cummins.com]
Sent: Tuesday, December 20, 2016 9:16 AM
To: Moulis, Charles <moulis.charles@epa.gov>
Cc: Schaefer, Ron <schaefer.ron@epa.gov>
Subject: RE: GHG Phase 2 Question - Non-Road Engine Exemption in Hybrids

Hello Chuck –

I am getting pressure internally on the questions below as the non-road option is available in the next model year (e.g., are the N_2O units of 0.1 g/kW-hr correct?). Any help you can provide would be greatly appreciated.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com

Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Matthew Psota
Sent: Friday, November 11, 2016 5:40 PM
To: 'moulis.charles@epa.gov' <moulis.charles@epa.gov>
Cc: 'Schaefer, Ron' <schaefer.ron@epa.gov>
Subject: GHG Phase 2 Question - Non-Road Engine Exemption in Hybrids

Hello Chuck –

I was hoping you may help me with some questions regarding sections of the GHG Phase 2 rule that provide exemptions to allow non-road (e.g., 40 CFR 1039 certified) engines in hybrid vehicles. Specifically, 1037.605 allows vehicle manufactures to produce up to 1000 vehicles with a non-road certified engine – hybrid powertrain combination; however, 1037.605(a) states:

§ 1037.605 Installing engines certified to alternate standards for specialty vehicles.
(a) General provisions. …You may not install an engine certified to these alternate standards if there is an engine certified to the full set of requirements of 40 CFR part 86 that has the appropriate physical and performance characteristics to power the vehicle. …

If Cummins were to certify an engine to the full requirements of 40 CFR 86 (e.g., a 4.5L MHD engine) to be used with hybrid powertrains, would that prevent other manufacturers from using the non-road exemption for hybrid vehicles or vice versa? In other words, would this provision force a manufacturer to either use the other manufacturer's engine or create a product that meets 40 CFR 86? Is that the intent of the above section?

→Yes, the language of 1037.605(a) would disallow the use of engines meeting the alternate standard for any vehicle installations in which your full highway-certified engines would have the appropriate physical and performance characteristics to power the vehicle. Although this is a somewhat subjective criterion, we have found this approach to serve as a workable benchmark for other provisions.

As a follow-up, what if a manufacturer is currently using the non-road exemption for a 4.5L engine with hybrids and another manufacturer comes along and certifies an engine to the full requirements of 40 CFR 86? Would the non-road exemption go away immediately?

→These vehicles are subject to annual certification under 40 CFR part 1037, and the provisions of §1037.605 apply on an annual basis. As a result, if a full highway-certified engine becomes available that appears to be a suitable substitute for the existing hybrid installation (using engines meeting the alternate standards), we would coordinate that with the vehicle manufacturer. The expectation would be that the vehicle manufacturer would need to discontinue the installation of engines meeting the alternate standards for the next model year (or if we determine that would be impractical, the second model year after the full highway-certified engine becomes available).

Finally, 40 CFR 86.007-11(g) sets the emissions requirements for these exempted non-road engines with hybrids as follows:

§ 86.007–11 Emission standards and supplemental requirements for 2007 and later model year diesel heavy-duty engines and vehicles.
(g) Model year 2018 and later engines at or above 56 kW that will be installed in specialty vehicles as allowed by 40 CFR 1037.605 may meet alternate emission standards as follows:
(1) The engines must be of a configuration that is identical to one that is certified under 40 CFR part 1039, and meet the following additional

standards using the same duty cycles that apply under 40 CFR part 1039:
(i) The engines must be certified with a Family Emission Limit for PM of 0.020 g/kW-hr.
(ii) Diesel-fueled engines using selective catalytic reduction must meet an emission standard of **0.1 g/kW-hr for N_2O.** (emphasis added)

Are the units for the N2O standard of 0.1 g/kW-hr correct? If you convert these units to g/hp-hr, you would have a more stringent N2O standard than is required for engines certified to 40 CFR 1036 (e.g., 0.1 g/hp-hr (part 1036) vs 0.075 g/hp-hr (86.007-11(g)(1)(ii)). Should these units be g/hp-hr instead?

→The comparison of standards needs to account for rounding. The goal is to set a g/kW-hr standard for N2O that equates to the 0.10 g/hp-hr standard in §1036.108. Remember that with rounding this two-decimal place standard allows measured emissions as high as 0.1049 g/hp-hr. However, because the 0.1 g/kW-hr standard includes only one decimal place, it allows measured emissions as high as 0.149 g/kW-hr before rounding. This value converts to 0.1111 g/hp-hr. That figure is slightly higher than 0.1049, so the 0.1 g/kW-hr standard is actually about 5% less stringent than the 0.10 g/hp-hr standard.

Again, I understand you may be busy, but any assistance you can provide would be greatly appreciated.

Thanks in advance,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Matthew Psota
Sent: Monday, October 17, 2016 5:31 PM
To: 'moulis.charles@epa.gov' <moulis.charles@epa.gov>
Subject: GHG Phase 2 Question

Hello Chuck –

Hope you have had some time to breath since the release of the GHG Phase 2 Final Rule. Cummins has been going through the rule and from time to time have some clarification questions for EPA. Not sure of the best means to get questions answered as they pop up, but was wondering if email or a quick phone call is best method for EPA to provide clarification. Any direction you can provide on this manner is greatly appreciated.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 12/12/2016 5:42:18 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: HD Phase 2 discussion with Tim Blubaugh, EMA
Location: Matt will call Tim Ex. 6 Personal Privacy (PP) from Matt's Office, N123

Start: 12/14/2016 7:00:00 PM
End: 12/14/2016 8:00:00 PM
Show Time As: Tentative

Hi Tim,

Please feel free to counter this meeting scheduler with another date/time, if this date/time does not work well for you, thanks.

Regards,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Friday, December 09, 2016 4:38 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Subject: GHG Phase 2

Hi Matt,

I wanted to find a time when we could talk in a little more detail about the GHG Phase 2 topics we last discussed on November 28th. Could we find a time next week? My best days are Wednesday and Thursday, but I could find a time on Tuesday or Friday if either of those days work better for you. Please let me know what might work.

Thanks!

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax

tblubaugh@emamail.org

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 12/7/2016 12:30:08 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Miller Marc [marc.miller@volvo.com]
Subject: engine credits

Matt, Chuck,

I want to work on engine credit options discussed (FTP credits based on "new" 2017 baseline, Optional program with softened 2024-2026 FTP target, …), but as we've discussed there are various ways to perform credit accounting when you start to distinguish FTP credits from RMC credits. Recall my spreadsheet, which gives an example of one methodology. Another methodology is to treat them as completely separate averaging sets, and the FTP credits just disappear after 2020 – unless, of course, the balance is negative, in which case you now get to offset that negative balance with available RMC credits…?

Again, this can be taken as a completely separate discussion from vocational RMC credits of FTP credits on the basis of the new baseline.

Before going further to evaluate various regulatory schemes according to, perhaps, three separate accounting techniques, I thought I'd ask if you had studied this issue further, and have any guidance for me, or perhaps have rules certain techniques out.

Give me a call to discuss if you prefer. **Ex. 6 Personal Privacy (PP)** thereafter.

Thanks
Steve

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Appointment

From: EMA [ema@emamail.org]
Sent: 10/24/2016 8:36:56 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Erin Luke (Erin.Luke@PACCAR.com) [Erin.Luke@PACCAR.com]; steven.wolverton@paccar.com; Dawn Friest [DFriest@emamail.org]; Timothy A. French [TFrench@clpchicago.com]; Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Jed R. Mandel [JMandel@clpchicago.com]

Subject: EMA - October 26, 2016, Meeting – Heavier Tractors Proposal
Attachments: 2016 09 16 ECCC GHG Phase 2 - EMA Proposals.pdf; Heavier Tractors & Transition Adjustments - EMA Proposals 15Sep16.pdf; EMA Heavier Tractors Proposal - Baseline & Stringency Details 15Sep16.pdf
Location: EPA Offices; 2000 Traverwood Drive; Ann Arbor, Michigan

Start: 10/26/2016 5:00:00 PM
End: 10/26/2016 6:00:00 PM
Show Time As: Tentative

Recurrence: (none)

TO: Matt Spears, EPA
Chuck Moulis, EPA
Dan Kieffer, PACCAR
Erin Luke, PACCAR
Steven Wolverton, PACCAR
Dawn E. Friest, EMA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: October 24, 2016

RE: **October 26, 2016, Meeting – Heavier Tractors Proposal**

The purpose of this meeting is to discuss EMA's proposal for two new heavier tractor categories for Environment and Climate Change Canada's GHG Phase 2 rule. Dan Kieffer will attend the meeting in person to walk through the slides that we sent to EPA last week. For reference, attached are the relevant documents.

DATE: Wednesday, October 26, 2016
TIME: 1:00 p.m. (Eastern Time)
Location: EPA Offices
2000 Traverwood Drive
Ann Arbor, Michigan

Following is the call-in formation for those joining by teleconference:

DIAL IN #: Personal Phone / Ex. 6
CONFEREN

CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 10/24/2016 7:30:48 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: RE: Heavier Tractor Proposals

Thanks, Chuck!

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Monday, October 24, 2016 2:29 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>; Spears, Matthew <spears.matthew@epa.gov>
Cc: dan.kieffer@paccar.com
Subject: RE: Heavier Tractor Proposals

Tim,

1:00 EDT on Wednesday will work for us.

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Friday, October 21, 2016 1:45 PM
To: Spears, Matthew <spears.matthew@epa.gov>; Moulis, Charles <moulis.charles@epa.gov>
Cc: dan.kieffer@paccar.com
Subject: RE: Heavier Tractor Proposals

Matt, Chuck,

Can we confirm a brief meeting in AA at 1:00 Wednesday afternoon during which Dan can walk you through our proposal? Please let me know so I can send a meeting notice.

Thanks!

Tim

From: Timothy A. Blubaugh
Sent: Thursday, October 20, 2016 2:42 PM
To: 'Spears, Matthew' <spears.matthew@epa.gov>; 'Moulis, Charles' <moulis.charles@epa.gov>
Cc: Dan Kieffer <Dan.Kieffer@PACCAR.com>
Subject: Heavier Tractor Proposals

Matt, Chuck,

Following our discussion Wednesday, attached are some materials on the proposals we made to ECCC to create two new tractor categories in their GHG Phase 2 rule to address the heavier tractors in Canada. The first document is an overview of the three proposals we made to ECCC. The second is a high-level explanation of our proposed new tractor categories

(and it includes our transition adjustment proposal). The last document has details on the baselines and stringencies for the new tractor categories.

Could we walk you through the heavier tractor proposal on Wednesday, October 26th, at 1:00 p.m. EDT? Dan Kieffer and Erin Luke will be in Ann Arbor at that time, and we could link the other PACCAR people and me in via teleconference. If that timing works, I will send a meeting notice with call-in information. Please let me know.

Tim

Message

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/27/2015 7:14:24 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]
CC: Iffland, JoNell [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=269c8731e7c6417482f8a8ddccfc4887-Iffland, JoNell]; MacAllister, Julia [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=8d72e3dbea2843018007b53de3670d90-MacAllister, Julia]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Re: Zingerman's for Friday?

Hi Tim,

That works, and I have complete confidence in JoNell's skills of persuasion!

Matthew Spears
Center Director, Heavy-Duty Diesel Standards
U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

> On Oct 27, 2015, at 14:43, Timothy A. Blubaugh <tblubaugh@emamail.org> wrote:
>
> Hi Matt,
>
> I just saw your e-mail after I asked JoNell to use her clout to get Zingerman's to give us a dispensation to place the order by 8:30 Friday morning. The problem is that we never know exactly who is going to show up for these meetings. If that is possible, we can ensure that we have an accurate order (and I'll make sure that we discuss lunch before starting the meeting).
>
> Tim
>
> -----Original Message-----
> From: Spears, Matthew [mailto:spears.matthew@epa.gov]
> Sent: Tuesday, October 27, 2015 1:06 PM
> To: Iffland, JoNell; Timothy A. Blubaugh; MacAllister, Julia; Moulis, Charles
> Subject: Zingerman's for Friday?
>
> Hi Tim,
>
> Would you or someone else at EMA be able to coordinate EMA's Zingerman's lunch order for Friday with JoNell and Julia at EPA? I think Zingerman's prefer orders at least a day in advance. (We got lucky last time because it was a slow day at Zingerman's.) We'll then include any EPA orders & reimburse EMA. Cool?
>
> Matthew Spears
> Center Director, Heavy-Duty Diesel Standards
> U.S. Environmental Protection Agency
> 2000 Traverwood Dr.
> Ann Arbor, MI 48105
> spears.matthew@epa.gov
> w. 734-214-4921
Ex. 6 Personal Privacy (PP)

Appointment

From: EMA [ema@emamail.org]
Sent: 10/19/2016 7:50:54 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: EMA - October 27, 2016, Conference Call – GHG Phase 2
Attachments: 2016 10 27 CVEC GHG Conference Call – GHG Phase 2.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 10/27/2016 3:00:00 PM
End: 10/27/2016 4:30:00 PM
Show Time As: Tentative

Recurrence: (none)

TO: CVEC GHG Subcommittee
Matt Spears, EPA
Chuck Moulis, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: October 19, 2016

RE: **October 27, 2016, Conference Call – GHG Phase 2**

Please join this conference call of EPA and EMA to discuss several aspects of the GHG Phase 2 final rule. Specifically, during the call, we will walk through the (i) interim glider provisions, (ii) available IRAF calculation options, and (iii) Phase 1 vocational engine credit carryover restrictions.

Following is the call-in information:

DATE: Thursday, October 27, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFEREN
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/17/2016 6:18:18 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: HD Phase 2 items with EMA
Location: Matt's Office, Telecon: Matt will call Tim's office: Ex. 6 Personal Privacy (PP)

Start: 10/19/2016 6:00:00 PM
End: 10/19/2016 7:00:00 PM
Show Time As: Tentative

Tim will provide the list of items verbally during the call or perhaps via email.

Appointment

From: EMA [ema@emamail.org]
Sent: 10/27/2015 3:39:23 PM
To: Timothy A. French [tfrench@clpchicago.com]; shirish.a.shimpi@cummins.com; Bill Martin Ex. 6 Personal Privacy (PP) dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Erin Luke (Erin.Luke@PACCAR.com) [Erin.Luke@PACCAR.com]; Cortney Guzlas (Cortney.Guzlas@Navistar.com) [Cortney.Guzlas@Navistar.com]; Thomas Kramer (tom.kramer@navistar.com) [tom.kramer@navistar.com]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Donald Keski-Hynnila (donald.keski-hynnila@daimler.com) [donald.keski-hynnila@daimler.com]; Rey Agama (agama_rey@cat.com) [agama_rey@cat.com]; George Lin (Lin_George@cat.com) [Lin_George@cat.com]; Steve Berry (steve.berry@volvo.com) [steve.berry@volvo.com]; mark.malowicki@paccar.com; Jed R. Mandel [jmandel@clpchicago.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: EMA - October 28, 2015, Conference Call to Discuss Fuel Map Variability Research Project
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Timothy A. French

Start: 10/28/2015 4:00:00 PM
End: 10/28/2015 7:00:00 PM
Show Time As: Tentative

Recurrence: (none)

When: Wednesday, October 28, 2015 11:00 AM-2:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Personal Phone / Ex. 6 Chair: Timothy A. French
Note: The GMT offset above does not reflect daylight saving time adjustments.
~~*~*~*~*~*~*~*~*

TO:

Shirish Shimpi
Bill Martin
Dan Kieffer
Mark Malowicki
Erin Luke
Cortney Guzlas
Thomas Kramer
Chuck Moulis
James Sanchez
Chris Laroo
Don Keski-Hynnila
Rey Agama
George Lin
Steve Berry

CC:
Matt Spears
Houshun Zhang
Chris Sharp
Jed R. Mandel
Timothy A. Blubaugh

FROM: Timothy A. French

DATE: October 27, 2015

RE: **October 28, 2015, Conference Call to Discuss Fuel Map Variability Research Project**

We will be meeting with Matt Spears, Houshun Zhang and Chris Sharp in Chicago tomorrow – Wednesday, October 28th – at 11:00 a.m. (Chicago time) to discuss the development of a more detailed test plan that SwRI could implement to assess the test-to-test and lab-to-lab variability associated with the generation and use of steady-state and cycle-average fuel maps for confirmatory and SEA testing under the Phase 2 GHG program. You are encouraged to join and participate in this meeting through a call-in option, the details for which are as follows:

DATE: Wednesday, October 28, 2015

TIME: 11:00 a.m. – 2:00 p.m. (Chicago time)

Ex. 6 Personal Privacy (PP)

CHAIR: Timothy A. French

If you have any questions, please feel free to contact me.

Timothy A. French
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1954 direct ? (312) 572-6688 fax
tfrench@emamail.org

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/1/2016 2:50:28 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Automatic reply: Glider clarification

Business travel to Europe Monday 8/29 through Friday 9/2. Back in office. Tuesday 9/6, following the Labor Day Holiday.
Checking e-mails periodically.

Message

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/19/2015 5:25:02 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: EMA HD Phase 2 Items grouped by EPA staff
Attachments: EMA HD Phase 2 Items grouped by EPA staff.docx

Hi Tim,

Here are the EMA HD Phase 2 items we expect to discuss this Wednesday. We've grouped them according to how far along we might be on a path toward resolution, but we're happy if EMA further organizes them and/or further edits the items. Once EMA has made revisions, would you email a version back to us? Thanks,

Matthew Spears
Center Director, Heavy-Duty Diesel Standards
U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

EMA HD Phase 2 Items grouped by EPA staff

Items where EPA staff can share ideas on how EPA staff plan to propose a way forward for further discussion within EPA	● Model year mismatch ● Engine fuel mapping ● Phase 1 wind average drag calculations ●In-use tractor testing ●IRAFs ●Nonroad exemption ●Gliders ●Engine families ●Tire pressure monitoring systems ● Measuring NOx during fuel mapping ● Measuring transmission efficiencies
Items likely to be resolved with a clarifying discussion	<u>Phase 1 Items</u> ● Delegated assembly ● LNG evaporative emissions <u>Phase 2 Items</u> ● Delegated assembly ● Powertrain modifications ● Powertrain test procedure ● Engine manufacturer responsible for another's powertrain test ● Tire input to GEM: revolutions per mile instead of SLR ● Rolling resistance calculations ● New families for off-cycle technologies ● 4x2 tractors to be Class 8 if they have a Class 8 powertrain ● Heavy-haul tractor definition ● LNG venting and labeling requirements ● Alternative-fuel engine classifications to criteria pollutants ● Credit averaging ● Adjustable parameters
Items for further EPA-EMA technical discussion/clarification (EPA has questions)	<u>Technologies, market adoption rates, costs and/or how to credit them</u> ● Vocational (and tractor) Stop/Start and idle technologies ● Vocational hybrids ● 6x2 and 6x4 with enhanced disconnect (2 clutch) ● APU requirements ● Automatic engine shutdown (AES) systems ● Reprogrammable systems <u>Tractor program structure</u> ● Special purpose tractor category <u>Vocational vehicles: program structure</u> ● Subcategorization ● Normalization/equalization <u>Stringencies</u> ● N2O standards: engine only issue

Items for further EPA-EMA technical work	Tractors: aerodynamic items (detailed discussion for October 30th) ● Baselines, bins and stringency ● Compliance margin: statistical approaches ● Adjustment factors ● Standard trailer: 2027 tail? ● Coast-down test procedure refinements ● CFD test speed and surrogate yaw angle ● Constant speed testing: approach for Final Rule and follow-up Vocational vehicles: program structure ● Duty cycle weighting factors GEM ● GEM errors ● Other GEM items Fuel Mapping ● EMA SwRI test plan to evaluate GEM engine fuel mapping
Needs input from EPA's Compliance Division and OECA	● Electronic labels ● ABT report deadlines Confidential Business Information ● Engine fuel maps ● GEM inputs

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 10/6/2015 9:41:32 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: HD Phase 2 EMA Issues Discussion
Location: Telecon, Matt and Chuck will call Tim

Start: 10/8/2015 2:00:00 PM
End: 10/8/2015 4:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Message

From: Robert Jorgensen [rjorgensen@emamail.org]
Sent: 9/9/2015 2:25:08 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Available for a Quick Call?

Hi Chuck,
Hope all is well.
Would like to talk about some of the technical amendments and requests for comments in the NPRM. Please call when you get a chance.
Thanks,
Bob

Office: 312 929 1976
Ex. 6 Personal Privacy (PP)

Robert A. Jorgensen

Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1976 direct • (312) 929-1955 fax
mailto:rjorgensen@emamail.org

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Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 9/3/2015 9:27:38 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Alec Zacaroli (alec.zacaroli@haynesboone.com) [alec.zacaroli@haynesboone.com]
Subject: FW: Gliders OK until Jan 2022 ?
Attachments: 150715-EPA-420f15904.pdf

Thank you, Chuck. Alec Zacaroli (Volvo counsel) and I have taken a closer look and agree with your interpretation. We do have a question, based on "1037.635 Glider Kits", your third bullet, which we would expect to say:

- Gliders produced by small businesses under the 300 cap don't have to meet the criteria standards and would *not* have to meet the GHG *vehicle or engine* standards starting 2022. (Or does EPA intend to require all gliders to meet GHG standards in 2022, including those under the 300 cap? If so, the language of 1037.635 does not appear to support this.)

You start the first bullet with "Most"; is this simply a reference to the one glider manufacturer EPA knows of that is not a small business, as mentioned in the preamble?

FYI, the attached July 2015 **EPA Q&A** document reads:

> **What are the exemptions for small businesses that manufacture gliders for model years 2018 and beyond?**
> The HD Phase 1 regulations currently include an exemption for small businesses from all of the HD Phase 1 requirements of 40 CFR part 1037. This exemption, which was included in the Phase 1 rulemaking as an interim provision, also covers glider manufacturers. We are proposing to end this blanket exemption on January 1, 2018.

According to the EPA proposal, that should be January 2022, no?

Thanks again for addressing my questions.
Steve

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Thursday, September 03, 2015 8:41 AM
To: Berry Steve; Charmley, William
Subject: RE: Gliders OK until Jan 2022 ?

Steve,

The key point is the distinction between the "the greenhouse gas standards of §§ 1037.105 and 1037.106" and the other standards and requirements. The one-year delay applies only for the GHG requirements. The rule does not provide relief from the other standards and requirements -- except for the 300 glider allowance. So beginning January 1, 2018:

- Most gliders must meet the 2018 criteria and GHG standards
- Gliders produced by small businesses in excess of the 300 cap must meet the criteria standards, but don't have to meet the GHG standards until 2022.
- Gliders produced by small businesses under the 300 cap don't have to meet the criteria standards but would have to meet the GHG standards starting 2022

Gliders produced prior to 2018 could use older engines, but would need to meet the GHG standards unless they were produced by a small business.

I hope this helps clarify what we proposed.

Chuck

From: Berry Steve [mailto:steve.berry@volvo.com]
Sent: Wednesday, September 02, 2015 8:53 PM
To: Moulis, Charles; Charmley, William
Subject: RE: Gliders OK until Jan 2022 ?

Hello Bill and Chuck

Regarding EPA and NHTSA's proposal wrt glider vehicles, we read in the Preamble (p. 839 of the pre-issue):
EPA is proposing that this requirement for gliders to meet engine and vehicle standards applicable to other new vehicles and engines take effect on January 1, **2018.**

Yet, upon further review, and considering proposed 1037.150 (c)
(c) Provisions for small manufacturers. .... Qualifying manufacturers are not subject to the greenhouse gas standards of §§ 1037.105 and 1037.106 for vehicles built before January 1, **2022,**

...and 1037.150(j),
(j) Limited prohibition related to early model year engines. The provisions of this paragraph (j) apply only for vehicles that have a date of manufacture before January 1, **2018.** See § 1037.635 for related provisions that apply in later model years. The prohibition in § 1037.601 against introducing into U.S. commerce a vehicle containing an engine not certified to the standards applicable for the calendar year of installation does not apply for vehicles using model year 2014 or 2015 spark-ignition engines, or any model year 2013 or earlier engines.

Our interpretation is that:

1) SMALL BUSINESSES have until Jan 1, 2022 to comply with vehicle and engine GHG standards, and SMALL BUSINESS glider vehicle manufacturers also have until Jan 1, 2022 to comply, but at that time they are entitled to an annual exemption for 300 units or 2010-2014 annual volume peak, whichever is less.
2) Glider vehicle manufacturers that are NOT small businesses are already subject to the GHG *vehicle* standards today (the NPRM mentions that you know of only one such manufacturer), yet, according to (j), the vehicles they build before Jan 1, 2018 need not have engines whose model year is corresponding to the vehicle year of manufacture. After Jan 1, 2018, this non-small business glider vehicle manufacturer must comply with all vehicle GHG standards, and all engine GHG & criteria standards (that is, the engine's model year must correspond to the vehicle year of manufacture), *without* any exemptions.

As 1037.105 (j) is written, there is no qualifier as to what kind of manufacturer we're talking about. Even Volvo could build vehicles with 2013 or earlier diesel engines up to Jan 1, 2018. As well, I find the provision somewhat circular, essentially: *Your vehicle's engine model year must match the vehicle year of manufacture (1037.601) unless the engine model year doesn't match the vehicle year of manufacture (1037.150(j)).*

My question is: Can you tell us, please, if you agree with our interpretation with respect to #1 and #2 above, and if it was what the Agencies had intended? (I'm confused about the mismatch on the preamble dates and the reg language dates.)

Thanks
Steve B

Steve Berry
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Ex. 6 Personal Privacy (PP)
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Frequently Asked Questions

Frequently Asked Questions about Heavy-Duty "Glider Vehicles" and "Glider Kits"

Brief answers to common questions about potential changes to how EPA and NHTSA regulate glider vehicles.

What are heavy-duty "glider vehicles" and "glider kits"?

The term "glider kit" is used in the heavy-duty vehicle industry to describe a chassis and cab assembly that is generally produced by a vehicle manufacturer without a new engine, transmission, or rear axle. A third party then typically installs a used engine, transmission, and/or rear axle to complete assembly of the vehicle. The terms "glider vehicle" or "glider" are typically used for the completed vehicles.

Historically, gliders have been used as a means to salvage valuable components, such as used engines, transmissions, and axles, from vehicles that were badly damaged in collisions. Gliders have been most popular for salvaging the components of the largest and most expensive class of heavy-duty vehicles (i.e. "Class 8"). More recently the agencies have observed a sharp increase in glider sales, which suggests that gliders are being used more and more as a loophole to avoid purchasing engines that meet 2010 EPA emission standards, and potentially to avoid NHTSA safety regulations.

As discussed below, because of different regulatory frameworks for safety and emissions, NHTSA and EPA have subtle but important differences in their regulatory definitions of glider kits. NHTSA defines a "glider kit" as motor vehicle equipment that primarily includes the chassis and cab, but generally does not include the engine or rear axles. NHTSA is considering new regulations that would focus only on the completed glider vehicles. EPA defines "glider kits" to include both the complete and incomplete vehicles and applies its regulations to both. (See 40 CFR 1037.801 of EPA's proposed regulatory text.)

Are emissions from gliders a significant problem?

Most gliders manufactured today use remanufactured model year 2001 or older engines. Typically these engines have NOx and particulate matter (PM) emissions

EPA-420-F-15-904
July 2015

20 to 40 times higher than today's clean diesel engines. Since 2010 when EPA's current NOx and PM standards for heavy duty engines took effect, glider sales have increased nearly **10-fold** as compared to the 2004-2006 time frame.[1] EPA believes this increase reflects an attempt to avoid using engines that comply with EPA's 2010 standards, and is an attempt to circumvent the Clean Air Act's purpose to protect human health and the environment.

This increase in glider kit sales is a growing environmental concern. To give a sense of scale, annual glider sales now represent roughly **2%** of the Class 8 vehicles manufactured annually, and yet may account for as much as **one-half** of total NOx and PM emissions from all new Class 8 vehicles. Put another way, at current production rates, the contribution of NOx and PM emissions from gliders alone would nearly **double** the emissions of these pollutants from the entire Class 8 fleet.

The figure below illustrates in a relative sense how the NOx and PM emissions from gliders have increased and how they compare to the rest of Class 8 sales. This figure is based on estimated current and historic glider production rates. The first bar represents the NOx and PM emissions that would result from 500 "pre-emission" gliders, which was a typical annual sales volume before model year 2007. It shows that 500 gliders emitting 40 times the NOx and PM would have the same total NOx and PM emissions as 20,000 fully compliant vehicles. The second bar represents the NOx and PM emissions from 5,000 model year 2014 "pre-emission" gliders. This second bar shows that just 5,000 of these gliders could emit as much NOx and PM as 200,000 fully compliant 2014 Class 8 tractors. For comparison, the third bar shows the NOx and PM emissions of 250,000 fully compliant model year 2014 Class 8 vehicles, which represents the typical annual production of fully compliant new Class 8 vehicles.

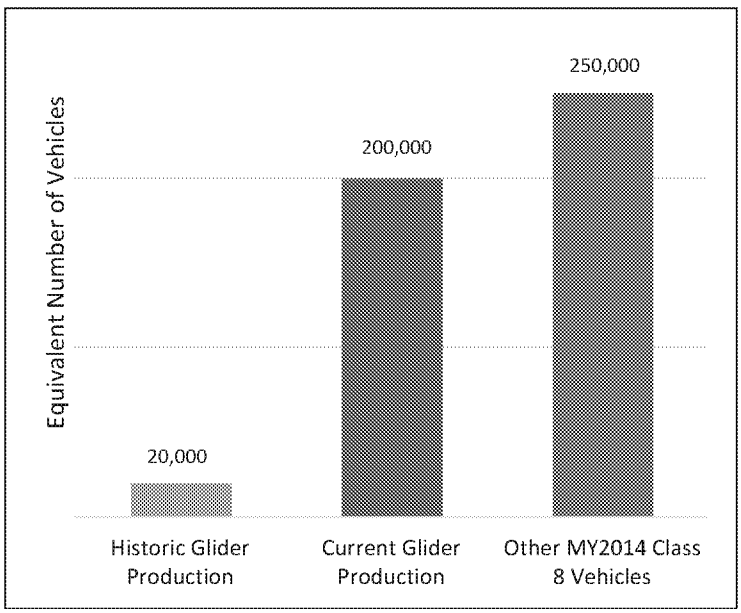

Figure 1 Growing Environmental Significance of Gliders

[1] Based on the following report that has been placed into the public docket for this rulemaking: "Industry Characterization of Heavy Duty Glider Kits", MacKay & Company, September 30, 2013.

Does EPA consider glider kits to be new motor vehicles?
Yes. The Clean Air Act definition of "new motor vehicle" is not based on the condition of the parts assembled to create the vehicle but rather encompasses the entire vehicle. Thus, newly created gliders are "new motor vehicles" under the Clean Air Act, even if they incorporate some previously used components. Under this framework, glider kits are regulated by EPA the same as other incomplete new heavy-duty vehicles.

Some glider manufacturers and customers may attempt to circumvent this definition by retaining the Vehicle Identification Number (VIN) of the donor vehicle from which the used engine was obtained. However, this technicality does not mean that the new glider is actually the old vehicle.

When does NHTSA consider glider vehicles to be new motor vehicles?
NHTSA also determines whether or not a motor vehicle is "new" based on criteria other than its retention of a pre-existing VIN. NHTSA considers all completed glider vehicles to be new unless they have a transmission, engine, and drive axle that are not new, and at least two of those components are from the same "donor vehicle." While NHTSA considers completed gliders to be motor vehicles, it does not consider glider kits (as it defines the term) to be motor vehicles. Rather, it considers glider kits to be "motor vehicle equipment."

Are EPA and NHTSA proposing to ban gliders?
No, neither EPA nor NHTSA are proposing to ban gliders. EPA is clarifying which existing standards apply already to gliders, and is proposing new emissions requirements for certain gliders. NHTSA is considering setting similar standards for complete glider vehicles, but not for glider kits.

What is EPA proposing for gliders in this rulemaking?
In general, EPA is proposing three things:

a. Clarifications to the existing HD Phase 1 EPA requirements for gliders.
b. New requirements for most gliders to have engines installed that meet the same requirements as new emissions-compliant engines.
c. Exceptions to the proposed new requirements for small businesses.

Each of these general areas is discussed further in related questions below.

a. **What are the *existing* EPA requirements for gliders, and how are these being clarified?**
EPA is clarifying that gliders, because they are *"new vehicles"* under the Clean Air Act, are subject to EPA's current HD Phase 1 GHG emission standards for new *vehicles* in 40 CFR part 1037, with some exemptions for small businesses. This means that glider vehicles not produced by small businesses are already required to comply with the HD Phase 1 vehicle standards.

The current regulations (which are being revised) have not prohibited the use of older model engines, such as those that have been rebuilt or remanufactured for additional use. However, these engines have always had to comply with emissions standards applicable to their own model year of manufacture. In other words, EPA's regulations have allowed older engines to be installed into new glider kits, as long as they remained in their originally certified configuration.

b. **What *new* EPA requirements are being proposed in the HD Phase 2 Notice of Proposed Rulemaking?**
EPA is proposing new requirements beginning January 1, 2018 that would generally require engines installed in new gliders to meet the same requirements as new emissions-compliant engines – both for GHGs and for other harmful pollutants such as NOx and PM. For example, if a glider was produced in 2020, it could use any engine that met the standards for model year 2020 engines. This could be an earlier model year engine that was originally subject to the same requirements, such as a model year 2018 engine.

Beginning in model year 2021, Phase 2 standards for heavy duty vehicles would also apply to gliders.

c. **What are the exemptions for small businesses that manufacture gliders for model years 2018 and beyond?**
The HD Phase 1 regulations currently include an exemption for small businesses from all of the HD Phase 1 requirements of 40 CFR part 1037. This exemption, which was included in the Phase 1 rulemaking as an interim provision, also covers glider manufacturers. We are proposing to end this blanket exemption on January 1, 2018.

In place of the blanket exemption, EPA is proposing limited grandfathering of exising small businesses that currently install the used engines and other used parts into gliders. Under these special provisions, existing small businesses would be allowed to continue their production up to 300 assembled gliders per year under the same type of exemption that covered them in HD Phase 1. Any additional gliders an existing small business would produce (beyond their existing production rates or beyond 300 per year, as applicable) would need to meet the new proposed requirements for both engines and vehicles. These grandfathering provisions for existing small businesses should allow this industry to produce enough gliders to address legitimate purposes (e.g., salvaging engines and other parts from damaged vehicles). However, manufacturers that have significantly ramped up glider production in recent years to avoid EPA's 2010 NOx and PM engine standards and other requirements, may need to alter their business practices.

How did EPA develop this small business exemption?
Prior to issuing the proposal, EPA convened a formal panel with the Small Business Administration (SBA) and the Office of Management and Budget (OMB) to consider ways to minimize impacts on small businesses. As a central part of this process, EPA invited potentially affected small businesses to serve as Small Entity Representatives (SERs) that would help the panel to identify and address adverse impacts on small businesses. One of the SERs was a small

manufacturer that assembled gliders. This manufacturer helped the panel to understand how this rule would impact small businesses that assemble gliders. Based in large part on this input, the panel recommended the exemption being proposed. The official Panel Report has been placed into the public docket for this rulemaking.

What are the existing NHTSA requirements for gliders, and is NHTSA considering adopting new provisions?

NHTSA does not currently consider glider kits or completed glider vehicles to be covered under NHTSA's HD Phase 1 standards. For completed glider vehicles, NHTSA is considering adopting requirements similar to EPA's proposed regulations. NHTSA would also consider special provisions for small business manufacturers consistent with the initial regulatory flexibility analysis that accompanies the rulemaking. NHTSA is not considering standards for glider kits (as NHTSA defines them).

Are EPA and NHTSA considering other options, and how can I provide new information to the agencies?

EPA is requesting comment on all of these proposed changes, and we may revise these provisions to offer more or less flexibility in the Final Rule. NHTSA is requesting comment on its consideration of similarly regulating completed glider vehicles, but not glider kits. Both agencies encourage commenters to provide data that would allow us to improve our proposal. See the notice for instructions on providing comments at:

www.epa.gov/otaq/climate/regs-heavy-duty.htm

or

www.nhtsa.gov/fuel-economy

Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 5/20/2016 11:29:20 AM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Gary C Salemme [gary.c.salemme@cummins.com]; Matthew Psota [matthew.psota@cummins.com]
Subject: RE: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

Business Confidential Information Submitted Subject to the Protections in 40 CFR PART 2

Matt and team,

Here are responses to the questions you asked during our call.

- Today we do not provide Cummins Emission Solutions (CES) aftertreatment customers with dosing or thermal management strategies used on Cummins products. For dosing, CES specifies items such as valid temperature and NOx ranges which the aftertreatment design can accommodate. This is accomplished via our interface agreement.
- The new SCR catalyst has some features that overall make it better performing. It is a different catalyst formulation that has more active catalyst material. The fundamental structure also holds less water at low temps which improves the performance and durability. So overall we would say it is better performing at low temperatures.
- The Navistar N9, N10, and N13 engines use CES aftertreatment.

Please let us know if you have any additional questions.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Wednesday, May 11, 2016 5:05 PM
To: 'Spears, Matthew' <spears.matthew@epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; 'Zhang, Houshun' <Zhang.Houshun@epa.gov>; 'Sanchez, James' <sanchez.james@epa.gov>; 'James Tamm (james.tamm@dot.gov)' <james.tamm@dot.gov>; 'Mitchell, George' <Mitchell.George@epa.gov>; Matthew Psota <matthew.psota@cummins.com>
Subject: RE: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

All – here is an updated version of the slide we sent yesterday. The only change is that we added a row in the table for intake throttle on the ISX families. We also shared the same slide with Alex Santos of ARB.

<< File: 2016-05-10 Cummins Vocational CO2 Certs rev2.pdf >>
Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Jackie M Yeager
Sent: Tuesday, May 10, 2016 11:39 AM
To: 'Spears, Matthew' <spears.matthew@epa.gov>; Gary C Salemme <gary.c.salemme@cummins.com>; Zhang, Houshun <Zhang.Houshun@epa.gov>; Sanchez, James <sanchez.james@epa.gov>; James Tamm (james.tamm@dot.gov) <james.tamm@dot.gov>; Mitchell, George <Mitchell.George@epa.gov>; Matthew Psota <matthew.psota@cummins.com>
Subject: RE: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

Matt S. and all,

Attached is some information about our vocational cert values that we would like to review on today's call. Talk to you soon.
Regards, << File: 2016-05-10 Cummins Vocational CO2 Certs.pdf >>
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

-----Original Appointment-----
From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Thursday, May 5, 2016 4:07 PM
To: Jackie M Yeager; Gary C Salemme; Zhang, Houshun; Sanchez, James; James Tamm (james.tamm@dot.gov); Mitchell, George
Subject: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6
When: Tuesday, May 10, 2016 12:30 PM-1:00 PM (UTC-05:00) Eastern Time (US & Canada).
Where: AA-Room-Office-N170-ConfRoom/AA-OTAQ-OFFICE

Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/27/2016 8:43:16 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: RE: Draft Vocational Screening Tool

Thanks, Chuck.

Tim

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Wednesday, April 27, 2016 3:08 PM
To: Timothy A. Blubaugh <TBlubaugh@emamail.org>
Cc: Spears, Matthew <spears.matthew@epa.gov>
Subject: Draft Vocational Screening Tool

Tim,

Attached is the screening tool we discussed at our Monday meeting. Feel free to share it with your members.

Chuck

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/27/2016 2:15:25 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Benchmarking Spreadsheet

Hi Matt, Hi Chuck,

Please let me know when you think you will be able to send us the benchmarking spreadsheet we discussed Monday. If we should chat before circulating it, call me. I should be available today until noon your time.

Tim

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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Message

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/26/2016 7:44:53 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]
CC: Manik Narula [manik.narula@cummins.com]
Subject: Cummins cycle average slides from yesterday
Attachments: Cummins Cycle Avg Map Update and ISX Results 4-25-16.pdf

Matt and Team,

Thanks for taking the time yesterday to meet and review our latest cycle average map results. I attached the slides I shared. Please let me know when you have had a chance to complete your internal discussions and when we are ready to have a review with Bill Charmley.

Houshun – here are answers to your questions about the material:

1) What is the axle ratio spread on page 9 of the ISX results (page 13 of PDF)? For Map points: 2.66 , 3.45, 4.26, for Test Points: 3.14, 4.08, 5.04
2) What is the formula we used for calculating the axle ratios for our 55 mph maps? Axle Ratio = [Engine Speed (rpm) * 60] / [Vehicle Speed(mph) * tire size (rev/mile) * Top Gear Ratio]

I still need to investigate EPA's question about our ISX 2016 FTP engine certs.

James – congratulations on the new baby!

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

Message

From: Timothy A. Blubaugh [TBlubaugh@emamail.org]
Sent: 4/22/2016 2:56:04 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: Automatic reply: GEM Corrections

Out of the office until Tuesday, April 26. If urgent, contact Angie at: Ex. 6 Personal Privacy (PP)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/21/2016 2:26:56 PM
To: Miller Marc [marc.miller@volvo.com]; Berry Steve [steve.berry@volvo.com]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Steele, Lauren [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=a3f01d4fca2b46d49ef723223af29267-Steele, Lauren P.]; Cullen, Angela [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff1b7c0675434915bade463ad4619509-Cullen, Angela]; Sherwood, Todd [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f6a5d8decf654ce99b5de0923ccff361-Sherwood, Todd]
CC: Todd Sherwood [Ex. 6 Personal Privacy (PP)] nderson Rick (ey) [rickey.anderson@volvo.com]

Subject: Canceled: Meeting with Volvo at EPA (after EMA meeting)
Location: AA-Room-Office-C34-ConfRoom/AA-OTAQ-OFFICE

Start: 4/25/2016 8:00:00 PM
End: 4/25/2016 10:00:00 PM
Show Time As: Free

Importance: High

Message

From: Berry Steve [steve.berry@volvo.com]
Sent: 8/27/2015 4:20:55 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]
Subject: Non-road engines acceptable for hybrid HD Hwy vehicles

Hello Chuck

Can you tell me, does EPA restrict the proposal below, allowing up to 1000 non-road engines to be used in hybrid applications, to either *series* or *parallel* hybrids?

Steve

XIV. Other Proposed Regulatory Provisions

A. Proposed Amendments Related to Heavy-Duty Highway Engines and Vehicles

(1) Alternate Emission Standards for Specialty Heavy-Duty Vehicles

Industry innovation in some cases leads to some configurations that make it particularly challenging to meet regulatory requirements. We are aware that plug-in hybrid-electric heavyduty vehicles are an example of this. An engine for such a vehicle would be expected to have a much lower power rating and duty cycle of engine speeds and loads than a conventional heavyduty engine. The costs of regulatory compliance and the mismatch to the specified duty cycle can make it cost-prohibitive for engine manufacturers to certify such an engine under the heavyduty highway engine program. EPA's nonroad emission standards have reached a point that involves near parity with the level of emission control represented by the emission standards for heavy-duty highway engines.

To address concerns about certifying heavy-duty engines to highway standards for use in hybrid vehicles, we are therefore proposing to allow manufacturers of heavy-duty highway vehicles the option to install limited numbers of engines certified to alternate standards. Qualifying engines would be considered motor vehicle engines, but they would be certified to standards that are equivalent to those adopted for comparable nonroad engines. Vehicles with hybrid powertrains would be a focus of this allowance. EPA believes the same principles apply for amphibious vehicles and for vehicles with maximum speed at or below 45 miles per hour and we are therefore proposing to apply the same provisions to these additional vehicles.

Under this approach, compression-ignition engines could be certified to alternate standards that are equivalent to the emission standards under 40 CFR part 1039, and spark ignition engines could be certified to alternate standards that are equivalent to the Blue Sky emission standards under 40 CFR part 1048. Engines meeting these alternate emission standards would generally be expected to use the same technologies to control emissions as engines certified to the applicable emission standards for heavy-duty highway engines. EPA would disallow this approach for compression-ignition engines below 56 kW since the nonroad standards for those engines are substantially less stringent than the standards that apply for heavy-duty highway engines. Also, since the nonroad duty cycles would generally better represent the in-use operating characteristics of these vehicles, we would expect the nonroad test procedures to be at least as effective in achieving effective in-use emission control. The regulations at 40 CFR part 1048 include a simplified form of diagnostic controls, and we

are proposing in these rules to include simplified diagnostic controls for 40 CFR part 1039. These engine-based diagnostic controls would substitute for the diagnostic requirements that would otherwise apply under 40 CFR 86.010-18.

It may also be appropriate to allow manufacturers of such heavy-duty vehicles to use an engine from a smaller vehicle that is already covered by chassis-based certification under 40 CFR part 86, subpart S. Many of the heavy-duty vehicles described under this section would be adequately powered by lower-displacement automotive engines, and the level of emission control would clearly be expected to match or exceed that of engines certified to the heavy-duty standards that would otherwise apply. However, engines used in chassis-certified vehicles involve some degree of calibration that relates engine operation to vehicle parameters. Adapting these engines to heavy-duty vehicles would therefore require some recalibration, which could involve changing the effectiveness of emission controls. It is also unclear how the heavy-duty vehicle would be designed for onboard diagnostic controls. EPA requests comment on the technical and regulatory issues surrounding the use of engines from chassis-certified vehicles in certain heavy-duty vehicles.

These alternate standards relate only to the engine certification-based emission standards and certification requirements. All vehicle-based requirements for evaporative and greenhouse gas emissions would continue to apply as specified in the regulation. This allowance is intended to lower the barrier to introducing innovative technology for motor vehicles. It is not intended to provide a full alternative compliance path to avoid certifying to the emission standards and control requirements for highway engines and vehicles. To accomplish this, EPA is proposing to allow a manufacturer to produce no more than 1,000 hybrid vehicles in a single model year under this program, and no more than 200 amphibious vehicles or speed-limited vehicles.

California ARB is in the process of developing similar provisions for a reduced compliance burden for a limited number of highway vehicles toward the goal of incentivizing hybrid vehicles and other advanced technology. EPA expects to be involved in that policy development and would be interested in aligning programs as much as possible. It may be necessary or appropriate for the final rule to include a reference to any new policy that has been adopted by California ARB in the meantime.

EPA requests comment on all aspects of this program to create alternate motor-vehicle emission standards that allow certified nonroad engines to be used in the identified types of heavy-duty highway vehicles.

This section as proposed does not appear in the current CFR:

§ 1037.605 Installing engines certified to alternate standards for specialty vehicles.
(a) General provisions. This section allows vehicle manufacturers to introduce into U.S. commerce certain new motor vehicles if the engines are certified to alternate emission standards that are equivalent to standards that apply for nonroad engines under 40 CFR part 1039 or 1048. See 40 CFR 86.007-11(g) and 40 CFR 86.008-10(g). The provisions of this section apply for the following types of vehicles:
(1) Vehicles with a hybrid powertrain in which the engine provides energy for the Rechargeable Energy Storage System.
(2) Amphibious vehicles.
(3) Vehicles with maximum speed at or below 45 miles per hour. If your vehicle is speedlimited to meet this specification by reducing maximum speed below what is otherwise possible, this speed limitation must be programmed into the engine or vehicle's electronic control module in a way that is tamper-proof. If your vehicles are not inherently limited to a maximum speed at or below 45 miles per hour, they may qualify under this paragraph (a)(3) only if we approve your design to limit maximum speed as being tamper-proof in advance.
* * *
(c) Production limits. You may produce up to 1,000 hybrid vehicles, up to 200 amphibious vehicles, and up to 200 speed-limited vehicles under this section in a given model year. This includes vehicles produced by affiliated companies. If you exceed this limit, the exemption is void for the number of vehicles that exceed the

limit for the model year. For the purpose of this paragraph (c), we will include all vehicles labeled or otherwise identified as exempt under this section.

(d) Vehicle standards. Hybrid vehicles using the provisions of this section remain subject to all other requirements of this part 1037. For example, you must use GEM in conjunction with powertrain testing to demonstrate compliance with emission standards under subpart B of this part. Vehicles qualifying under paragraph (a)(2) or (a)(3) of this section are exempt from the requirements of this part, except as specified in this section; these vehicles must include a label as specified in § 1037.135(a) with the information from § 1037.135(c)(1) and (2) and the following statement: "THIS [amphibious vehicle or speed-limited vehicle] IS EXEMPT FROM GREENHOUSE GAS STANDARDS UNDER 40 CFR 1037.605."

Steve Berry
Volvo Group Trucks Product Planning
2300 K St NW
South Building, Suite 401
Washington, DC 20007
Office: 202-536-1567
Ex. 6 Personal Privacy (PP)
steve.berry@volvo.com

Message

From: Matthew Psota [matthew.psota@cummins.com]
Sent: 8/10/2015 4:47:59 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
Subject: RE: GHG Phase 2 Follow-Up

Great. Thanks!

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Monday, August 10, 2015 9:43 AM
To: Matthew Psota <matthew.psota@cummins.com>
Subject: RE: GHG Phase 2 Follow-Up

OK. Call me at 4:00.

From: Matthew Psota [mailto:matthew.psota@cummins.com]
Sent: Monday, August 10, 2015 9:42 AM
To: Moulis, Charles
Subject: RE: GHG Phase 2 Follow-Up

Chuck –

Thanks for the reply. I left you a voicemail. I can talk 4 pm, if that works for you. I can call your desk if that's the best way to connect.

Please let me know.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Moulis, Charles [mailto:moulis.charles@epa.gov]
Sent: Monday, August 10, 2015 9:34 AM
To: Matthew Psota <matthew.psota@cummins.com>
Subject: RE: GHG Phase 2 Follow-Up

I am free now (until 10:00) or after 4:00.

From: Matthew Psota [mailto:matthew.psota@cummins.com]
Sent: Friday, August 07, 2015 5:18 PM
To: Moulis, Charles
Subject: RE: GHG Phase 2 Follow-Up

Hi Chuck –

Believe you were traveling last week, so wanted to check-in again to see if there are good times for EPA and Cummins to meet to discuss questions we have over the Phase 2 proposal.

Please let me know.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Matthew Psota
Sent: Wednesday, August 05, 2015 1:06 PM
To: 'Moulis.charles@Epa.gov' <Moulis.charles@Epa.gov>
Subject: RE: GHG Phase 2 Follow-Up

Hi Chuck –

Just wanted to check-in on possibly meeting to discussion questions we have with Phase 2. Please let me know.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Matthew Psota
Sent: Friday, July 31, 2015 1:22 PM
To: 'Moulis.charles@Epa.gov'
Subject: GHG Phase 2 Follow-Up

Chuck –

Wanted to see if there are some times EPA may have available to discuss questions we have regarding the GHG Phase 2 proposal. This request was originally discussed during Cummins-EPA meeting on 7/28. Realize your schedule next week may be difficult, so if there are various dates and times that work for you, I can try to accommodate.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/14/2015 2:47:32 PM
To: Timothy A. Blubaugh [tblubaugh@emamail.org]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]

Subject: Telecon: HD Phase 2 items with Tim Blubaugh, Matt & Chuck
Location: Telecon: Ex. 6 Personal Privacy (PP)

Start: 4/14/2015 7:00:00 PM
End: 4/14/2015 8:00:00 PM
Show Time As: Tentative

Hi Tim,

Are you available at this date/time? If not, please counter this meeting notice.

During this telecon let's step through our current responses to the 11 items we previously discussed, and let's also discuss the agendas for next Friday's meetings (April 24).

Thanks,

Matt

Message

From: Matthew Psota [matthew.psota@cummins.com]
Sent: 11/11/2016 10:39:59 PM
To: Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Schaefer, Ron [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=e4cf03e763744da1a7baa1f2951ab544-Schaefer, Ron]
Subject: GHG Phase 2 Question - Non-Road Engine Exemption in Hybrids

Hello Chuck –

I was hoping you may help me with some questions regarding sections of the GHG Phase 2 rule that provide exemptions to allow non-road (e.g., 40 CFR 1039 certified) engines in hybrid vehicles. Specifically, 1037.605 allows vehicle manufactures to produce up to 1000 vehicles with a non-road certified engine – hybrid powertrain combination; however, 1037.605(a) states:

§ 1037.605 Installing engines certified to alternate standards for specialty vehicles.
(a) General provisions. …You may not install an engine certified to these alternate standards if there is an engine certified to the full set of requirements of 40 CFR part 86 that has the appropriate physical and performance characteristics to power the vehicle. …

If Cummins were to certify an engine to the full requirements of 40 CFR 86 (e.g., a 4.5L MHD engine) to be used with hybrid powertrains, would that prevent other manufacturers from using the non-road exemption for hybrid vehicles or vice versa? In other words, would this provision force a manufacturer to either use the other manufacturer's engine or create a product that meets 40 CFR 86? Is that the intent of the above section?

As a follow-up, what if a manufacturer is currently using the non-road exemption for a 4.5L engine with hybrids and another manufacturer comes along and certifies an engine to the full requirements of 40 CFR 86? Would the non-road exemption go away immediately?

Finally, 40 CFR 86.007-11(g) sets the emissions requirements for these exempted non-road engines with hybrids as follows:

§ 86.007–11 Emission standards and supplemental requirements for 2007 and later model year diesel heavy-duty engines and vehicles.
(g) Model year 2018 and later engines at or above 56 kW that will be installed in specialty vehicles as allowed by 40 CFR 1037.605 may meet alternate emission standards as follows:
(1) The engines must be of a configuration that is identical to one that is certified under 40 CFR part 1039, and meet the following additional
standards using the same duty cycles that apply under 40 CFR part 1039:
(i) The engines must be certified with a Family Emission Limit for PM of 0.020 g/kW-hr.
(ii) Diesel-fueled engines using selective catalytic reduction must meet an emission standard of **0.1 g/kW-hr for N_2O.** (emphasis added)

Are the units for the N20 standard of 0.1 g/kW-hr correct? If you convert these units to g/hp-hr, you would have a more stringent N2O standard than is required for engines certified to 40 CFR 1036 (e.g., 0.1 g/hp-hr (part 1036) vs 0.075 g/hp-hr (86.007-11(g)(1)(ii)). Should these units be g/hp-hr instead?

Again, I understand you may be busy, but any assistance you can provide would be greatly appreciated.

Thanks in advance,
Matt
Matt Psota

On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

From: Matthew Psota
Sent: Monday, October 17, 2016 5:31 PM
To: 'moulis.charles@epa.gov' <moulis.charles@epa.gov>
Subject: GHG Phase 2 Question

Hello Chuck –

Hope you have had some time to breath since the release of the GHG Phase 2 Final Rule. Cummins has been going through the rule and from time to time have some clarification questions for EPA. Not sure of the best means to get questions answered as they pop up, but was wondering if email or a quick phone call is best method for EPA to provide clarification. Any direction you can provide on this manner is greatly appreciated.

Thanks,
Matt

Matt Psota
On-Highway Regulatory Affairs & Certification, US & Canada
Product Certification & Compliance
Cummins Inc

Email matthew.psota@cummins.com
Direct 812.377.7899
Ex. 6 Personal Privacy (PP)

Appointment

From: EMA [ema@emamail.org]
Sent: 11/18/2016 4:53:48 PM
To: EMA [ema@emamail.org]; Bill Martin - SGS - Transportation Division (William.Martin@sgs.com) [William.Martin@sgs.com]; Cassie Justice (cpogoda@ford.com) [cpogoda@ford.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Costi Nedelcu (costi.nedelcu@paccar.com) [costi.nedelcu@paccar.com]; David Gardner - Navistar, Inc. (david.gardner@navistar.com) [david.gardner@navistar.com]; David R. Smith (david.r.smith@volvo.com) [david.r.smith@volvo.com]; Donald Keski-Hynnila (donald.keski-hynnila@daimler.com) [donald.keski-hynnila@daimler.com]; Inderpal Singh (inderpal.singh@daimler.com) [inderpal.singh@daimler.com]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Jon Dolsen (jon.dolsen@daimler.com) [jon.dolsen@daimler.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matthew Smith (matt.smith@navistar.com) [matt.smith@navistar.com]; PIECH David (CNH Industrial) [david.piech@cnhind.com]; Radha Purushothaman (Purushothaman_Radha@cat.com) [Purushothaman_Radha@cat.com]; Ryan T. Parcell [Parcell_Ryan_T@cat.com]; shirish.a.shimpi@cummins.com; Tanfeng (Sam) Cao (tanfeng.cao@cummins.com) [tanfeng.cao@cummins.com]; Timothy A. French [TFrench@clpchicago.com]; Jed R. Mandel [JMandel@clpchicago.com]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]

Subject: EMA - Phase 2 Fuel-Mapping Variability Steering Committee - December 5, 2016, Conference Call Notice
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim French

Start: 12/5/2016 7:00:00 PM
End: 12/5/2016 8:00:00 PM
Show Time As: Busy

Recurrence: (none)

TO: Phase 2 Fuel-Mapping Variability Steering Committee

CC: Jed Mandel
William Martin
Chris Sharp

FROM: Timothy A. French

DATE: November 18, 2016

RE: **December 5, 2016, Conference Call**

We will convene a teleconference meeting on Monday, December 5, 2016, at 1:00 p.m. (Chicago time). The purpose of the call is to review the remaining open issues (including engine availability) relating to the design and implementation of the proposed fuel-mapping variability study.

Following is the call-in information:

DATE: Monday, December 5, 2016
TIME: 1:00 p.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFEREN
CHAIR: Tim French

If you have any questions, please do not hesitate to contact me.

Timothy A. French
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1954 direct ? (312) 572-6688 fax
tfrench@emamail.org

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Confidentiality Notice: This communication is confidential and may contain privileged information. If you have received it in error, please notify the sender by reply e-mail and immediately delete it and any attachments without copying or further transmitting the same.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 8/10/2016 3:55:19 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Matthew Psota [matthew.psota@cummins.com]

Subject: Discuss 2010+ NOx compliant engine availability for glider tractors
Location: EPA Telecon: Personal Phone / Ex. 6

Start: 8/11/2016 5:00:00 PM
End: 8/11/2016 5:30:00 PM
Show Time As: Busy

Hi Jackie and Matt,

Jackie, thank you for the reply.

If this date/time does not work for you, please feel free to counter.

The topic will be the potential availability of 2010+ NOx compliant engines for glider tractors.

Please see details below, thanks.

Regards,

Matt

Hi Matt,

We would be happy to talk to you this week. I will pull in Matt Psota who leads our US/Canada cert team to support the discussion. Would any of these times work for you:

Thursday 1-2 (Eastern)
Friday 12-1 or any time after 2

Please let us know if these will work for you.

Regards,
Jackie Yeager
GHG/Fuel Efficiency Policy Director
Environmental Strategy and Compliance
Cummins Inc.
Phone 812-377-8774
jackie.m.yeager@cummins.com

From: Spears, Matthew [mailto:spears.matthew@epa.gov]
Sent: Tuesday, August 9, 2016 4:04 PM
To: Jackie M Yeager <jackie.m.yeager@cummins.com>
Subject: Time this week to chat about 2010+ NOx compliant engines' availability for gliders in 2017?

Hi Jackie,

I hope you are doing well.

First I would like to thank you and the Cummins team who put together the IRAF CBI information. That information improved our confidence in not making any further changes to our HD Final Rule engine standards.

Second, on the topic of gliders, we're hoping to be able to communicate to others that in 2017, glider assemblers will have access to 2010+ NOx compliant engines that can be installed into gliders. We believe that these compliant engines could be either newly manufactured engines or in-use engines that are rebuilt or remanufactured to 2010+ NOx standards. Personally, I would expect that any in-use engines would likely be MY2010 or newer engines, but I suppose that even earlier engines could be retrofit to comply with 2010 NOx standards.

Based on the following spec.-ing guides at the end of this email, it would seem that new chassis that happen to be sold both as new vehicles and as gliders would be able to have installed in them a range of 2010+ NOx compliant engines.

We were wondering whether or not Cummins would share our view that 2010+ NOx compliant engines would be available for glider manufacturers in 2017.

Would you have any time this week to discuss this further? Thanks.

Regards,

Matt

Freightliner Cascadia with DD13, DD15, DD16, and Cummins ISX15
https://www.freightlinertrucks.com/Trucks/Models/Cascadia/Specs/

Kenworth T680 with Cummins ISX12, ISX15, and PACCAR MX-13
http://t680configurator.kenworthtruckco.com/

Peterbilt 587 with Cummins ISX 15 and PACCAR MX-13
http://www.peterbilt.com/resources/Truck%20Spec%20Sheets/587_Spec_Sheet.pdf

Matthew Spears
Center Director, Heavy-Duty Diesel Standards U.S. Environmental Protection Agency
2000 Traverwood Dr.
Ann Arbor, MI 48105
spears.matthew@epa.gov
w. 734-214-4921
Ex. 6 Personal Privacy (PP)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 8/1/2016 9:11:54 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: HD Phase 2
Location: Matt will call Tim's office

Start: 8/2/2016 3:00:00 PM
End: 8/2/2016 4:00:00 PM
Show Time As: Busy

Appointment

From: EMA [ema@emamail.org]
Sent: 7/29/2016 5:50:48 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Gururaja, Prashanth [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f401be9a5eb04b80bd24d487d7fab3ed-Gururaja, Prashanth]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: August 1, 2016, Conference Call – GHG Phase 2 Standard Trailer
Attachments: 2016 08 01 AS Conference Call – GHG Phase 2 Standard Trailer.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 8/1/2016 3:00:00 PM
End: 8/1/2016 4:00:00 PM
Show Time As: Busy

Recurrence: (none)

TO:	Aerodynamics Subcommittee Matt Spears, EPA Prashanth Gururaja, EPA
CC:	CVEC GHG Subcommittee Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	July 29, 2016
RE:	**August 1, 2016, Conference Call – GHG Phase 2 Standard Trailer**

Please join this conference call of EPA and EMA's Aerodynamics Subcommittee. The purpose of the call is to discuss the side skirt specifications for standard trailers in the GHG Phase 2 rule.

Following is the call-in information:

DATE: Monday, August 1, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFEREN
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Chicago, Illinois 60606
Tel: (312) 929-1970 I Fax: (312) 929-1975
www.truckandenginemanufacturers.org

TO: Aerodynamics Subcommittee
Matt Spears, EPA
Prashanth Gururaja, EPA

CC: CVEC GHG Subcommittee
Timothy A. French

FROM: Timothy A. Blubaugh

DATE: July 29, 2016

RE: **August 1, 2016, Conference Call – GHG Phase 2 Standard Trailer**

Please join this conference call of EPA and EMA's Aerodynamics Subcommittee. The purpose of the call is to discuss the side skirt specifications for standard trailers in the GHG Phase 2 rule.

Following is the call-in information:

DATE:	Monday, August 1, 2016
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Appointment

From: EMA [ema@emamail.org]
Sent: 7/28/2016 5:41:28 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: July 29, 2016, Conference Call with EPA – GHG Phase 2
Attachments: 2016 07 29 CVEC GHG - Conference Call with EPA – GHG Phase 2.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 7/29/2016 3:00:00 PM
End: 7/29/2016 4:30:00 PM
Show Time As: Busy

Recurrence: (none)

TO: CVEC GHG Subcommittee
Matt Spears, EPA

FROM: Timothy A. Blubaugh

DATE: July 28, 2016

RE: **July 29, 2016, Conference Call with EPA – GHG Phase 2**

Please join this conference call of EPA and EMA to discuss issues related to the GHG Phase 2 rule. Following is the call-in information:

DATE: Friday, July 29, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFERE
CHAIR: Tim Blubaugh

If you have any questions, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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www.truckandenginemanufacturers.org

TO: CVEC GHG Subcommittee
Matt Spears, EPA

FROM: Timothy A. Blubaugh

DATE: July 28, 2016

RE: **July 29, 2016, Conference Call with EPA – GHG Phase 2**

Please join this conference call of EPA and EMA to discuss issues related to the GHG Phase 2 rule.

Following is the call-in information:

DATE:	Friday, July 29, 2016
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions, please do not hesitate to contact me.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 7/28/2016 4:36:57 PM
To: Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: HD Phase 2 Discussion
Location: Matt Spears will call Tim Blubaugh's office

Start: 7/29/2016 1:30:00 PM
End: 7/29/2016 2:30:00 PM
Show Time As: Busy

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 7/20/2016 1:26:47 PM
To: Timothy A. French [tfrench@clpchicago.com]; Timothy A. Blubaugh [tblubaugh@emamail.org]

Subject: Discuss HD Phase 2, feel free to counter
Location: Matt Will call Tim Blubaugh

Start: 7/20/2016 3:00:00 PM
End: 7/20/2016 3:30:00 PM
Show Time As: Busy

Recurrence: (none)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 7/18/2016 2:01:07 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; rjorgensen@emamail.org

Subject: Discuss HD Phase 2 APU standards: Bob, Matt & Chris
Location: Bob will call Matt's office: Ex. 6 Personal Privacy (PP)

Start: 7/18/2016 3:30:00 PM
End: 7/18/2016 4:00:00 PM
Show Time As: Busy

Appointment

From: EMA [ema@emamail.org]
Sent: 7/13/2016 2:41:23 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: July 14, 2016, Conference Call with EPA – GHG Phase 2
Attachments: 2016 07 14 CVEC Conference Call with EPA – GHG Phase 2.pdf
Location: Dial-In#: (231) 929-6700; Conference ID: 8799006#; Chair: Tim Blubaugh

Start: 7/14/2016 4:00:00 PM
End: 7/14/2016 5:30:00 PM
Show Time As: Busy

Recurrence: (none)

TO:	CVEC GHG Subcommittee Matt Spears, EPA
CC:	Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	July 13, 2016
RE:	**July 14, 2016, Conference Call with EPA – GHG Phase 2**

Please join this conference call of EPA and EMA on the detailed GHG Phase 2 topics we discussed yesterday.

Following is the call-in information:
DATE: Thursday, July 14, 2016
TIME: 11:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFERE
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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Chicago, Illinois 60606
Tel: (312) 929-1970 I Fax: (312) 929-1975
www.truckandenginemanufacturers.org

TO: CVEC GHG Subcommittee
Matt Spears, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: July 13, 2016

RE: **July 14, 2016, Conference Call with EPA – GHG Phase 2**

Please join this conference call of EPA and EMA on the detailed GHG Phase 2 topics we discussed yesterday.

Following is the call-in information:

DATE:	Thursday, July 14, 2016
TIME:	11:00 a.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

93777_1

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 7/12/2016 8:22:51 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Timothy A. French [TFrench@clpchicago.com]

Subject: HD Phase 2 Discussion
Location: Matt wil call Tim Blubaugh's office (feel free to counter start time, I have no further meetings this afternoon)

Start: 7/12/2016 8:30:00 PM
End: 7/12/2016 9:30:00 PM
Show Time As: Busy

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 7/8/2016 1:38:58 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Timothy A. French [TFrench@clpchicago.com]

Subject: Discuss HD Phase 2 Vocational (feel free to counter if this time does not work for you)
Location: Matt will call Tim Blubaugh's office Ex. 6 Personal Privacy (PP)

Start: 7/8/2016 4:00:00 PM
End: 7/8/2016 4:30:00 PM
Show Time As: Busy

From: Timothy A. Blubaugh [mailto:TBlubaugh@emamail.org]
Sent: Thursday, July 07, 2016 5:05 PM
To: Spears, Matthew <spears.matthew@epa.gov>
Subject: Call with Tim(s)

Hi Matt,

Following yesterday's (odd) conference call, is there a time tomorrow when we could chat? Let me know what could work for you.

Thanks!

Tim

Appointment

From: EMA [ema@emamail.org]
Sent: 7/6/2016 1:54:31 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: July 6, 2016, Conference Call with EPA – HHD Manual Transmissions
Attachments: 2016 07 06 CVEC GHG Conference Call Conference Call with EPA – HHD Manual Transmissions.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 7/6/2016 6:00:00 PM
End: 7/6/2016 7:00:00 PM
Show Time As: Busy

Importance: High

Recurrence: (none)

TO: CVEC GHG Subcommittee
Matt Spears, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: July 6, 2016

RE: **July 6, 2016, Conference Call with EPA – HHD Manual Transmissions**

Please join this conference call with Matt Spears to discuss potential solutions to the issues with manual transmissions in the heavy-heavy duty vocational vehicle subcategories in the GHG Phase 2 rule. During the call, we will share the ideas we discussed during our conference call on Friday, July 1st.

Following is the call-in information:

DATE: Wednesday, July 6, 2016
TIME: 1:00 p.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFERE
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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www.truckandenginemanufacturers.org

TO: CVEC GHG Subcommittee
Matt Spears, EPA

CC: Timothy A. French

FROM: Timothy A. Blubaugh

DATE: June 29, 2016

RE: **July 6, 2016, Conference Call with EPA – HHD Manual Transmissions**

Please join this conference call with Matt Spears to discuss potential solutions to the issues with manual transmissions in the heavy-heavy duty vocational vehicle subcategories in the GHG Phase 2 rule. During the call, we will share the ideas we discussed during our conference call on Friday, July 1st.

Following is the call-in information:

DATE:	Wednesday, July 6, 2016
TIME:	1:00 p.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 6/28/2016 9:16:38 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: Phase 2 discussion
Location: Tim Blubaugh will call Matt

Start: 6/29/2016 7:00:00 PM
End: 6/29/2016 8:00:00 PM
Show Time As: Busy

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 6/21/2016 6:55:12 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: Discuss HD Phase 2
Location: Matt will call Tim

Start: 6/22/2016 1:30:00 PM
End: 6/22/2016 2:00:00 PM
Show Time As: Busy

Appointment

From: EMA [ema@emamail.org]
Sent: 6/20/2016 3:39:40 PM
To: EMA [ema@emamail.org]; (Schrodt.Thomas@epamail.epa.gov) [Schrodt.Thomas@epamail.epa.gov]; Aiko Matsunaga [amatsuna@arb.ca.gov]; Alberto Ayala (aayala@arb.ca.gov) [aayala@arb.ca.gov]; ANTHONY.BECK@sgs.com; Atul Shah (ashah@sensors-inc.com) [ashah@sensors-inc.com]; Barbara Marshik Ph. D. (Barbara_Marshik@MKSinst.com) [Barbara_Marshik@MKSinst.com]; Benjamin C. Shade - AVL Test Systems, Inc. (benjamin.shade@avl.com) [benjamin.shade@avl.com]; Berghof, Frank AVL/AT [Frank.Berghof@avl.com] [Frank.Berghof@avl.com]; Bertrand Lanher (blanher@sensors-inc.com) [blanher@sensors-inc.com]; Bill Martin (bmartin@cybermetrix.com) [bmartin@cybermetrix.com]; Bill Silvis (bill.silvis@avl.com) [bill.silvis@avl.com]; Bishnu, Dipak (dbishnu@arb.ca.gov) [dbishnu@arb.ca.gov]; Giannelli, Bob [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=7fb7b092ff064a509252056dcaaad9c0-Giannelli, Bob]; bradley.bane@ge.com; Brian Dueber (bdueber@mtlcorp.com) [bdueber@mtlcorp.com]; Brian Mace (brian.mace@horiba.com) [brian.mace@horiba.com]; Olson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c2db1c615e4c4055936aa784be9ae9aa-Olson, Brian]; Carl D. Ensfield (censfield@sensors-inc.com) [censfield@sensors-inc.com]; Ryan, Carl [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=afdc6098538644f99d9f606cc6e9debe-Ryan, Carl]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Chris Sharp (chris.sharp@swri.org) [chris.sharp@swri.org]; Dan Carder (daniel.carder@mail.wvu.edu) [daniel.carder@mail.wvu.edu]; Dan Sales (dsales@gasanalyzers.com) [dsales@gasanalyzers.com]; David Dikken (ddikken@mtlcorp.com) [ddikken@mtlcorp.com]; david.horstman@intertek.com; dmacdonald@acscm.com; Don Chernich [dchernic@arb.ca.gov]; Doug Sobotka (dougexcel@iowatelecom.net) [dougexcel@iowatelecom.net]; Hamady, Fakhri [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=3bb2f045b5f84ae88ecd1c1a405b59f3-Hamady, Fakhri]; Dustin Osborne (dustin.osborne@swri.org) [dustin.osborne@swri.org]; Dylan Mann [dmann@peaker.com]; Frank Berghof (Frank.Berghof@avlna.com) [Frank.Berghof@avlna.com]; Gil LaDuke (ghladuke@gw.dec.state.ny.us) [ghladuke@gw.dec.state.ny.us]; 'Glenn, Doug (GE Infra, Transportation)' [doug.glenn@ge.com]; Glinsky, Gerard (Aurora) [Gerard.Glinsky@sgs.com]; Granville Hayworth [GHayworth@Tenneco.com] [GHayworth@Tenneco.com]; Gurdas Singh Sandhu (gssandhu@ncsu.edu) [gssandhu@ncsu.edu]; Harlan Quan [hquan@arb.ca.gov]; htle@arb.ca.gov; IKhalek@swri.edu; jlourenc@arb.ca.gov [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=cf76217df2dd4056ae49eb48ed1d1796-jlourenc@arb.ca.gov]; Jackson, Cleophas [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=49ebd5e3637242ca84cfb4d53005a6d6-Jackson, Cleophas]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gumbs, Jason [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=267a3ad40b884a68b27d7c82c0dafc92-JGUMBS]; Jeff R. Wasil (jeff.wasil@brp.com) [jeff.wasil@brp.com]; jlowry@arb.ca.gov; Joe Sweeney (jsweeney@acscm.com) [jsweeney@acscm.com]; John Harrod (jdharrod@netzero.com) [jdharrod@netzero.com]; McDonald, Joseph [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=804802ec142f4c3898846a26d7bcdbe5-McDonald, Joseph]; Joseph McManus [joe.mcmanus@ricardo.com]; Joshua Israel [joshua.israel@mail.wvu.edu]; Keith Vertin (Keith.vertin@sgs.com) [Keith.vertin@sgs.com]; 'Kelly, Brian E (GE Infra, Transportation)' [Brian.Kelly1@ge.com]; Kent Johnson (kjohnson@cert.ucr.edu) [kjohnson@cert.ucr.edu]; KUMAR, Anuj [anuj.kumar@airliquide.com] [anuj.kumar@airliquide.com]; Laroo, Chris [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=6f4e3f827d6648ae8f3a5de78a5f4e16-Laroo, Chris]; Loren Mathews (lmathews@gasanalyzers.com) [lmathews@gasanalyzers.com]; Maldonado, Hector (hmaldona@arb.ca.gov) [hmaldona@arb.ca.gov]; Mang Zhang (mzhang@arb.ca.gov) [mzhang@arb.ca.gov]; Peralta, Maria [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff2ce4ee0cfe41ccb456f3654027afab-Peralta, Maria]; Mark Fuentes (mfuentes@arb.ca.gov) [mfuentes@arb.ca.gov]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Matt Swanson - CAI, Inc. (mswanson@gasanalyzers.com) [mswanson@gasanalyzers.com]; Matt Thiel (mthiel@acscm.com) [mthiel@acscm.com]; Mayotte, Steve [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c0af20a6cf7e4368b2a30f9027bf70ad-Mayotte, Steve]; mcarter@arb.ca.gov; Michael L. Traver (michael.traver@aramcoservices.com) [michael.traver@aramcoservices.com]; Mike Akard

(mike.akard@horiba.com) [mike.akard@horiba.com]; Mike May [mike.may@ricardo.com]; mjsmith@swri.edu; Mohan Krishnamurthy (mkrishna@arb.ca.gov) [mkrishna@arb.ca.gov]; Mridul Gautam (mgautam@wvu.edu) [mgautam@wvu.edu]; Munday, Dave (dave.munday@horiba.com) [dave.munday@horiba.com]; Nelson, Brian [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fee03a4337c543d8aa60277da00c63ae-Nelson, Brian]; Ng, Henry K [hkng@Central.UH.EDU]; NICHOLAS.BELLOVARY@sgs.com; Oliver Chang (ochang@arb.ca.gov) [ochang@arb.ca.gov]; Paolo Di Martino (paolo.di.martino@iav-usa.com) [paolo.di.martino@iav-usa.com]; Paul Rieger (prieger@arb.ca.gov) [prieger@arb.ca.gov]; Richard.frazee@avl.com; rick.rooney@horiba.com; Rob Wilson [rwilson@sensors-inc.com]; Robert C. Anderson (robert.anderson@tsi.com) [robert.anderson@tsi.com]; Ron Tandy - Horiba [Ron.tandy@horiba.com]; russell.graze@yahoo.com; sfritz@swri.org [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ba055250cec142c89919582ddefd83e6-sfritz@swri.org]; Sonny Moore (smoore@mtlcorp.com) [smoore@mtlcorp.com]; sshakenis@wabtec.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=5636ac3c03614850b1748b4cef12c5fc-sshakenis@wabtec.com]; Steve Mitchell (steven.j.mitchell@emdiesels.com) [steven.j.mitchell@emdiesels.com]; Sun, Ruonan [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=9974424e49a74e8aafda9705a313dc1a-Sun, Ruonan]; Thomas Lanni Ex. 6 Personal Privacy (PP) Tim Johnson (tim.johnson@tsi.com) [tim.johnson@tsi.com]; Todd Carpenter [Todd.Carpenter@avl.com]; Valerie Bossoutrot Ph. D. (valerie.bossoutrot@airliquide.com) [valerie.bossoutrot@airliquide.com]; Virendra Kumar (vkumar@eswgroup.com) [vkumar@eswgroup.com]; Wayne Sobieralski [wsobiera@arb.ca.gov]; William Robertson (wroberts@arb.ca.gov) [wroberts@arb.ca.gov]; Williamson, James AVLNA [James.Williamson@avl.com]; Yannick Cizeron (y.cizeron@ja-gastechnology.com) [y.cizeron@ja-gastechnology.com]; shirish.a.shimpi@cummins.com

Subject: EMA - EMTC, CARB, EPA & Others - July 27-28, 2016, EMTC Meeting Notice
Location: U.S. EPA; 2000 Traverwood Drive; Ann Arbor, Michigan

Start: 7/27/2016 1:00:00 PM
End: 7/28/2016 6:00:00 PM
Show Time As: Tentative

Recurrence: (none)

TO: Engine Emissions Measurement & Testing Committee (EMA Members, CARB, EPA & Others)

CC: Timothy A. French

FROM: Shirish Shimpi

DATE: June 20, 2016

RE: **July 27-28, 2016, EMTC Meeting Notice**

EMA will convene a two-day meeting of the Engine Emissions Measurement and Testing Committee on Wednesday and Thursday, July 27 and 28, 2016, at EPA's Offices in Ann Arbor, Michigan. An agenda will be circulated prior to the meeting.

Following are the meeting details:
DATE: Wednesday, July 27, 2016
TIME: 9:00 a.m. – 5:00 p.m.
Thursday, July 28, 2016
9:00 a.m. – 2:00 p.m.

LOCATION: EPA Office
2000 Traverwood Drive
Ann Arbor, Michigan

Conference call access and webcast information is being provided for those who are not able to attend in person.

Following are the call-in details:

DATE: Wednesday, July 27, 2016
TIME: 8:00 a.m. – 4:00 p.m. (Chicago time)
Thursday, July 28, 2016
8:00 a.m. – 1:00 p.m. (Chicago time)

Ex. 6 Personal Privacy (PP)

To join the web conference, please click on the following link: https://epawebconferencing.acms.com/emtcmeeting/

If you have any questions, please do not hesitate to contact me.

Shirish A. Shimpi, Ph. D.
Director
Emissions Development
Cummins Inc.
Mail Code 50180
1900 McKinley Ave
Columbus, Indiana 47201
Office: (812) 377-7532
Ex. 6 Personal Privacy (PP)

Andjelka Vujovic
Truck & Engine Manufacturers Association
333 West Wacker Drive • Suite 810
Chicago, Illinois • 60606
(312) 929-1973 direct • (312) 929-1975 fax
avujovic@emamail.org

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Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 6/1/2016 11:16:41 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Timothy A. French [TFrench@clpchicago.com]

Subject: Vocational Discussion
Location: Matt will call Tim French's office

Start: 6/2/2016 9:30:00 PM
End: 6/2/2016 10:00:00 PM
Show Time As: Busy

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 5/31/2016 10:15:08 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]; Timothy A. French [TFrench@clpchicago.com]

Subject: Discuss Vocational
Location: Matt will call Tim French

Start: 6/1/2016 10:30:00 PM
End: 6/1/2016 11:00:00 PM
Show Time As: Busy

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 5/17/2016 12:19:16 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; tblubaugh@emamail.org

Subject: General
Location: Matt will call Tim

Start: 5/18/2016 6:00:00 PM
End: 5/18/2016 7:00:00 PM
Show Time As: Busy

Recurrence: (none)

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 5/5/2016 8:07:06 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Jackie M Yeager [jackie.m.yeager@cummins.com]; Gary C Salemme [gary.c.salemme@cummins.com]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; James Tamm (james.tamm@dot.gov) [james.tamm@dot.gov]; Mitchell, George [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d0fbd740a76d4abab36090575cae0c6f-Mitchell, G]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]
CC: Matthew Psota [matthew.psota@cummins.com]; Coralie.Cooper@dot.gov
BCC: AA-Room-Office-N170-ConfRoom/AA-OTAQ-OFFICE [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=user34418b82]

Subject: Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6
Location: AA-Room-Office-N170-ConfRoom/AA-OTAQ-OFFICE

Start: 5/10/2016 4:30:00 PM
End: 5/10/2016 5:00:00 PM
Show Time As: Busy

Telecon w/ Cummins on MY2016 ISX FTP cert values, Personal Phone / Ex. 6

Appointment

From: EMA [ema@emamail.org]
Sent: 4/27/2016 3:37:27 PM
To: EMA [ema@emamail.org]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: May 10, 2016, Conference Call – GHG Phase 2
Attachments: 2016 05 10 CVEC Conference Call – GHG Phase 2 (2).pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 5/10/2016 3:00:00 PM
End: 5/10/2016 4:30:00 PM
Show Time As: Busy

Recurrence: (none)

TO:	CVEC GHG Subcommittee Matt Spears, EPA
CC:	Commercial Vehicle and Engine Committee Timothy A. French
FROM:	Timothy A. Blubaugh
DATE:	April 27, 2016
RE:	**May 10, 2016, Conference Call – GHG Phase 2**

Please join this conference call of EPA and EMA. Following our meeting on April 25th, the primary purpose of the call is to discuss issues related to the GHG Phase 2 vocational vehicle program.

Following is the call-in information:

DATE: Tuesday, May 10, 2016
TIME: 10:00 a.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFEREN
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ? Suite 810
Chicago, Illinois ? 60606
(312) 929-1972 direct ? (312) 929-1975 fax
tblubaugh@emamail.org

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TO: CVEC GHG Subcommittee
Matt Spears, EPA

CC: Commercial Vehicle and Engine Committee
Timothy A. French

FROM: Timothy A. Blubaugh

DATE: April 27, 2016

RE: **May 10, 2016, Conference Call – GHG Phase 2**

Please join this conference call of EPA and EMA. Following our meeting on April 25th, the primary purpose of the call is to discuss issues related to the GHG Phase 2 vocational vehicle program.

Following is the call-in information:

DATE:	Tuesday, May 10, 2016
TIME:	10:00 a.m. (Chicago time)
DIAL IN #:	Personal Phone / Ex. 6
CONFERENCE ID:	
CHAIR:	Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/16/2016 7:04:36 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Moulis, Charles [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=d9ba8bd68b3c4fb28b767e15aef54d61-Moulis, Charles]; Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Timothy A. French [TFrench@clpchicago.com]

Subject: Phase 2 Items, Matt will call Tim
Location: Matt's office

Start: 4/18/2016 9:00:00 PM
End: 4/18/2016 10:00:00 PM
Show Time As: Busy

Recurrence: (none)

Does this time work?

Appointment

From: Spears, Matthew [/O=EXCHANGELABS/OU=EXCHANGE ADMINISTRATIVE GROUP (FYDIBOHF23SPDLT)/CN=RECIPIENTS/CN=FF938823F859485E94AE7EAB5F45C201-SPEARS, MATT]
Sent: 4/8/2016 5:16:23 PM
To: Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Timothy A. Blubaugh [TBlubaugh@emamail.org]

Subject: General
Location: Matt will call Tim: 312-929-1972

Start: 4/11/2016 7:00:00 PM
End: 4/11/2016 8:00:00 PM
Show Time As: Busy

Appointment

From: Jackie M Yeager [jackie.m.yeager@cummins.com]
Sent: 4/4/2016 8:42:31 PM
To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; Brian C Mormino [brian.c.mormino@cummins.com]; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Jon A Dickson [jon.a.dickson@cummins.com]; Kaslavage Charles [charles.kaslavage@volvo.com]; Scott.Mundy@allisontransmission.com; greg.mann@allisontransmission.com; ROBERT M MERRION [Robert.Merrion@allisontransmission.com]
CC: Thomas Manley [Thomas.Manley@HMMUSA.COM]; MikeRosbury@eaton.com

Subject: Phase 2 Collaboration Meeting
Attachments: Untitled Attachment; Untitled Attachment; Untitled Attachment; Joining Skype for Business Meetings (External).pdf
Location: US toll-free Personal Phone / Ex. 6 and Skype Meeting

Start: 4/7/2016 7:00:00 PM
End: 4/7/2016 8:00:00 PM
Show Time As: Tentative

Recurrence: Weekly
Occurs on Thursday every other week from 3:00 PM to 4:00 PM effective 4/7/2016 until 12/22/2016.

Background:

(New invitation with updated Skype details)

Joint sessions to exchange information on the development and validation of engine/powertrain test cycles and information going into the vehicle simulation for Phase 2.

Teleconference call-in number:

See phone numbers below
Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

→ Join Skype Meeting

This is an online meeting for Skype for Business, the professional meetings and communications app formerly known as Lync.

Join by phone

Personal Phone / Ex. 6

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Personal Phone / Ex. 6

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Skype Advanced

Audio for this Skype for Business meeting is available using a computer or the phone dial-in bridge. Cummins Skype Advanced users should select "Use Skype for Business (full audio and video experience)" when using their PCs to connect to the meeting audio. Cummins Skype Standard users should select "Don't Join Audio" and dial into the phone bridge.

Appointment

To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Brian C Mormino [brian.c.mormino@cummins.com]; Jon A Dickson [jon.a.dickson@cummins.com]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Gary C Salemme [gary.c.salemme@cummins.com]; tom.sloane@paccar.com; Cortney.Guzlas@Navistar.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Matthew.Hunkler@Navistar.com; Manik Narula [manik.narula@cummins.com]; erin.luke@paccar.com; debbie.gordon@allisontransmission.com; MihaiDorobantu@eaton.com; Jeffrey.shultz@allisontransmission.com; david.gardner@navistar.com; David.Majors@Navistar.com; MatthewRBusdiecker@eaton.com; ErikDykes@eaton.com; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; He Yuesheng [yuesheng.he@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; Marley Jeffrey [jeff.marley@volvo.com]; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Miller Marc [marc.miller@volvo.com]; donald.keski-hynnila@daimler.com; aaron.neuman@daimler.com; gerald.freitag@daimler.com; anirban.sett@daimler.com; steve.berry@volvo.com; tblubaugh@emamail.org; david.kayes@daimler.com; Mark.Siddall@HMMUSA.COM; LIN_GEORGE@cat.com; inderpal.singh@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; Scott.Mundy@allisontransmission.com

CC: Thomas Manley [Thomas.Manley@HMMUSA.COM]

Attachments: Joining Skype for Business Meetings (External).pdf

Start: 4/28/2016 7:00:00 PM
End: 4/28/2016 8:00:00 PM
Show Time As: Busy

Recurrence: (none)

Background:

(New invitation with updated Skype details)

Joint sessions to exchange information on the development and validation of engine/powertrain test cycles and information going into the vehicle simulation for Phase 2.

Teleconference call-in number:

See phone numbers below
Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.

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Appointment

To: Jackie M Yeager [jackie.m.yeager@cummins.com]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; tom.sloane@paccar.com; Manik Narula [manik.narula@cummins.com]; Mark.Siddall@HMMUSA.COM; ErikDykes@eaton.com; debbie.gordon@allisontransmission.com; He Yuesheng [yuesheng.he@volvo.com]; Marley Jeffrey [jeff.marley@volvo.com]; Ricart-Ugaz, Laura M [Laura.Ricart@Navistar.com]; david.kayes@daimler.com; inderpal.singh@daimler.com; Gary C Salemme [gary.c.salemme@cummins.com]; david.gardner@navistar.com; Brian C Mormino [brian.c.mormino@cummins.com]; MatthewRBusdiecker@eaton.com; tblubaugh@emamail.org; Miller Marc [marc.miller@volvo.com]; dan.kieffer@paccar.com [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=512a76233b7347fd98a7c35c810644e7-dan.kieffer@paccar.com]; Jeffrey.shultz@allisontransmission.com; Jon A Dickson [jon.a.dickson@cummins.com]; Charmley, William [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=fb1828fb00af42ffb68b9e0a71626d95-Charmley, William]; aaron.neuman@daimler.com; Kaslavage Charles [charles.kaslavage@volvo.com]; David.Majors@Navistar.com; Anthony Greszler (anthony.greszler@volvo.com) [anthony.greszler@volvo.com]; LIN_GEORGE@cat.com; MihaiDorobantu@eaton.com; Costi Nedelcu [Costi.Nedelcu@PACCAR.com]; Matthew.Hunkler@Navistar.com; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; donald.keski-hynnila@daimler.com; Mark Malowicki [Mark.Malowicki@PACCAR.com]; Cortney.Guzlas@Navistar.com; Scott.Mundy@allisontransmission.com; anirban.sett@daimler.com; gerald.freitag@daimler.com; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; steve.berry@volvo.com; erin.luke@paccar.com

CC: Thomas Manley [Thomas.Manley@HMMUSA.COM]; MikeRosbury@eaton.com

Attachments: Joining Skype for Business Meetings (External).pdf

Start: 5/19/2016 7:00:00 PM
End: 5/19/2016 8:00:00 PM
Show Time As: Tentative

Recurrence: (none)

Background:

(New invitation with updated Skype details)

Joint sessions to exchange information on the development and validation of engine/powertrain test cycles and information going into the vehicle simulation for Phase 2.

Teleconference call-in number:

See phone numbers below
Skype information:
New non-Cummins attendees will need to install the Skype for Business web app plug-in. See the attached instructions.
Joining Skype for Business Meetings (External).pdf

→ Join Skype Meeting

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Appointment

From: EMA [ema@emamail.org]
Sent: 1/26/2016 9:46:49 PM
To: EMA [ema@emamail.org]; Dekraker, Paul [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f6a13a3fabff4b39879e1b52f819f267-Dekraker, Paul]; Newman, Kevin [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=c437d53e27ad40c18eae08f9b9daf09d-Newman, Kevin]; Sanchez, James [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=bda5afdc21da4149b352b6423214f268-Sanchez, James]; Spears, Matthew [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=ff938823f859485e94ae7eab5f45c201-Spears, Matt]; Zhang, Houshun [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=20d3335476a844589aa56c835783af57-Zhang, Houshun]; Timothy A. Blubaugh [TBlubaugh@emamail.org]
CC: Brakora, Jessica [/o=ExchangeLabs/ou=Exchange Administrative Group (FYDIBOHF23SPDLT)/cn=Recipients/cn=f1e8d3758a574ca29ab19bc2e2b49e58-Brakora, Jessica]

Subject: FW: February 2, 2016, Conference Call – Phase 2 GEM
Attachments: 2016 02 02 GEM TF Conference Call - Phase 2 GEM.pdf
Location: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Start: 2/2/2016 9:00:00 PM
End: 2/2/2016 10:00:00 PM
Show Time As: Busy

We will listen to EMA members, such as Daimler, Navistar, Volvo, and Paccar, for their first cut feedbacks on use of our new released debugging version of GEM.

-----Original Appointment-----
From: EMA [mailto:ema@emamail.org]
Sent: Tuesday, January 26, 2016 4:36 PM
To: EMA; Zhang, Houshun; Timothy A. Blubaugh
Subject: February 2, 2016, Conference Call – Phase 2 GEM
When: Tuesday, February 02, 2016 3:00 PM-4:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

When: Tuesday, February 02, 2016 3:00 PM-4:00 PM (UTC-06:00) Central Time (US & Canada).
Where: Dial-In#: Personal Phone / Ex. 6 Chair: Tim Blubaugh

Note: The GMT offset above does not reflect daylight saving time adjustments.

+~+~+~+~+~+~+~+~+~+

TO: GEM Task Force
Houshun Zhang, EPA

CC: CVEC GHG Subcommittee
FROM: Timothy A. Blubaugh
DATE: January 26, 2016
RE: **February 2, 2016, Conference Call – Phase 2 GEM**

Please join this conference call of EMA and EPA. The purpose of the call is to discuss the most recent GEM updates.

Following is the call-in information:

DATE: Tuesday, January 2, 2016
TIME: 3:00 p.m. (Chicago time)
DIAL IN #: Personal Phone / Ex. 6
CONFERENCE ID:
CHAIR: Tim Blubaugh

If you have any questions or comments, please do not hesitate to contact me.

Timothy A. Blubaugh
Truck & Engine Manufacturers Association
333 West Wacker Drive ▪ Suite 810
Chicago, Illinois ▪ 60606
(312) 929-1972 direct ▪ (312) 929-1975 fax
tblubaugh@emamail.org

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2016 02 02 GEM
TF Conference C...