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Environmental Technology Verification

Test Report of Mobile Source Emission Control Devices

Baumot
BA-B Diesel Particulate Filter with Pre-Catalyst

Prepared by

Southwest Research Institute

RTI International

Under a Cooperative Agreement with
U.S. Environmental Protection Agency

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THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

U.S. Environmental Protection Agency

ETV Joint Verification Statement

TECHNOLOGY TYPE:	**MOBILE DIESEL ENGINE AIR POLLUTION CONTROL**
APPLICATION:	**CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY DIESEL PARTICULATE FILTERS**
TECHNOLOGY NAME:	**BA-B DIESEL PARTICULATE FILTER WITH PRE-CATALYST**
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The U.S. Environmental Protection Agency (EPA) created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. The ETV Program seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

The ETV Program works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permitters, and other interested parties; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Air Pollution Control Technology Center (APCT Center), which is one of six centers under the ETV Program, is operated by RTI International[1] (RTI) in cooperation with EPA's National Risk Management Research Laboratory. The APCT Center has evaluated the performance of an emission control system consisting of a diesel particulate filter (DPF) with pre-catalyst.

[1] RTI International is a trade name of Research Triangle Institute.

ENVIRONMENTAL TECHNOLOGY VERIFICATION TEST DESCRIPTION

All tests were performed in accordance with the *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* and the *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Baumot for the BA-B System*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management and QA; procedures for product selection and auditing of the test laboratories; and the test reporting format.

The mobile diesel engine air pollution control technology was tested in October 2011 at Southwest Research Institute. The performance verified was the percentage of emissions reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) relative to the performance of the same baseline engine without the technology in place. Operating conditions were documented, and ancillary performance measurements also were made. A summary description of the ETV test is provided in **Table 1**.

Table 1. Summary of the Environmental Technology Verification Test

Test type	Highway Transient Federal Test Procedure
Engine family	XCEXH0359BAM
Engine make–model year	Cummins – 1999 ISB 215
Service class	Highway, medium heavy-duty diesel engine
Engine rated power	215 hp at 2700 rpm
Engine displacement	5.9 L, inline six cylinder
Technology	Baumot BA-B 1114
Technology description	Diesel particulate filter with pre-catalyst
Test cycle or mode description	One cold-start and multiple hot-start tests according to FTP test for baseline engine, degreened, and aged systems
Test fuel description	Ultra-low-sulfur diesel fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO_x, HC, and CO
Ancillary measurements	CO_2, NO, NO_2 (by calculation), soluble organic fraction of PM, exhaust backpressure, exhaust temperature, and fuel consumption

Note: CO_2 = carbon dioxide, FTP = Federal Test Procedure, hp = horsepower, NO = nitric oxide, NO_2 = nitrogen dioxide,
ppm = parts per million, rpm = revolutions per minute.

Beginning of table description. Table 1 is titled Summary of the Environmental Technology Verification Test. The table lists the type of test conducted, the critical and ancillary measurements taken, the characteristics of the test engine, and the technology undergoing verification testing. End of table description.

VERIFIED TECHNOLOGY DESCRIPTION

The Baumot BA-B technology is a diesel engine retrofit device for light, medium, and heavy heavy-duty diesel on-highway engines for use with commercial ultra-low-sulfur diesel fuel (ULSD) conforming to 40 *Code of Federal Regulations* 86.1313-2007. The BA-B particulate filter is composed of a pre-catalyst on a metal basis and wall-flow monolith, both of which are coated with a precious metal oxidation catalyst. The 1114 unit is the BA-B variant specifically designed for use with engines with output of approximately 214-335 horsepower and displacement up to 11 liters.

This verification statement describes the performance of the tested technology on the diesel engine and fuels

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identified in Table 1, and applies only to the use of the Baumot BA-B system on highway engines fueled by ULSD (15 parts per million [ppm] or less) fuel.

The monitoring and notification system that was functionally tested and used with this technology includes a sensor for exhaust gas backpressure.

VERIFICATION OF PERFORMANCE

The Baumot BA-B system achieved the reduction in tailpipe emissions shown in **Table 2** compared to baseline operation without the system installed on the test engine. In Table 2, “degreened” refers to a system with 25-124 hours of accumulated run time while “aged” refers to a system with over 1000 hours of accumulated run time. Additionally, the functional test results indicated proper operation of the monitoring and warning system for four of the five errors tested; the error code corresponding to a hose or pipe breakage or damage to the filter was not triggered successfully.

Table 2. Verified Emissions Reductions

System Type	Fuel	PM Mean Emissions Reduction (%)	NO_x Mean Emissions Reduction (%)	HC Mean Emissions Reduction (%)	CO Mean Emissions Reduction (%)	PM 95% Confidence Limits on the Emissions Reduction (%)	NO_x 95% Confidence Limits on the Emissions Reduction (%)	HC 95% Confidence Limits on the Emissions Reduction (%)	CO 95% Confidence Limits on the Emissions Reduction (%)
Degreened	ULSD	96	2.1	90	90	95 to 96	0.57 to 3.6	84 to 96	86 to 93
Aged	ULSD	97	2.7	94	93	97 to 97	1.4 to 4.0	88 to 99	89 to 97

Beginning of table description. Table 2 is titled Verified Emissions Reductions. The table describes the verified emissions reduction percentages for the degreened and aged systems for particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide. 95% confidence limits for these reductions are also listed. End of table description.

The APCT Center quality manager has reviewed the test results and quality control (QC) data and has concluded that the data quality objectives given in the generic verification protocol and test/QA plan have been attained. APCT Center QA staff have conducted technical assessments of the test laboratory procedures and of the data handling. These assessments confirm that the ETV tests were conducted in accordance with the EPA-approved test/QA plan.

This verification statement verifies the emissions characteristics of the Baumot BA-B system for the stated application. Extrapolation outside that range should be done with caution and an understanding of the scientific principles that control the performance of the technology. This verification focuses on emissions. Potential technology users may obtain other types of performance information from the manufacturer.

In accordance with the generic verification protocol, this verification statement is valid, commencing on the date below, indefinitely for application of the Baumot BA-B system within the range of applicability of the statement.

signed by Cynthia Sonich-Mullin *5/30/2012*
Cynthia Sonich-Mullin Date
Director
National Risk Management Research Laboratory
Office of Research and Development
United States Environmental Protection Agency

signed by Jason Hill *4/30/2012*
Jason Hill Date
Director
Air Pollution Control Technology Center
RTI International

NOTICE: ETV verifications are based on an evaluation of technology performance under specific, predetermined criteria and the appropriate quality assurance procedures. EPA and RTI make no express or implied warranties as to the performance of the technology and do not certify that a technology will always operate as verified. The end user is solely responsible for complying with any and all applicable federal, state, and local requirements. Mention of commercial product names does not imply endorsement.

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Environmental Technology Verification Report

Mobile Source Emission Control Devices

Baumot
BA-B
Diesel Particulate Filter with Pre-Catalyst

Prepared by

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Southwest Research Institute

EPA Cooperative Agreement No. CR83416901-0

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Notice

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute, with partial funding from Cooperative Agreement No. CR83416901-0 with the U.S. Environmental Protection Agency (EPA). The document has been submitted to RTI's and EPA's peer and administrative reviews and has been approved for publication. Mention of corporation names, trade names, or commercial products does not constitute endorsement or recommendation for use of specific products.

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Foreword

Established by the U.S. Environmental Protection Agency (EPA), the Environmental Technology Verification (ETV) Program is designed to accelerate the development and commercialization of new or improved technologies through third-party verification and reporting of performance. The goal of the ETV Program is to verify the performance of commercially ready environmental technologies through the evaluation of objective and quality-assured data to provide potential purchasers and permitters with an independent, credible assessment of the technology they are buying or permitting.

The Air Pollution Control Technology Center (APCT Center) is part of EPA's ETV Program and is operated as a partnership between RTI International (RTI) and EPA. The APCT Center verifies the performance of commercially ready air pollution control technologies. Verification tests use approved protocols, and verified performance is reported in verification statements signed by EPA and RTI officials. RTI contracts with Southwest Research Institute (SwRI) to perform verification tests on engine emissions control technologies.

Retrofit air pollution control systems used to control emissions from mobile diesel engines are among the technologies evaluated by the APCT Center. The APCT Center has developed (and EPA has approved) the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* to provide guidance on the verification testing of specific products that are designed to control emissions from diesel engines.

The following report reviews the performance of the Baumot BA-B system, comprising a diesel particulate filter with pre-catalyst. ETV testing of this technology was conducted in October 2011 at SwRI. All testing was performed in accordance with an approved test/quality assurance plan that implements the requirements of the generic verification protocol at the test laboratory.

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Availability of Report

Copies of this verification report are available from the following:

- RTI International
  Discovery & Analytical Sciences
  P.O. Box 12194
  Research Triangle Park, NC 27709-2194

- U.S. Environmental Protection Agency
  Air Pollution Prevention and Control Division (E343-02)
  109 T.W. Alexander Drive
  Research Triangle Park, NC 27711

This verification report is also available on the following EPA Web sites:

- http://www.epa.gov/etv/vt-apc.html#msd (pdf format)
- http://www.epa.gov/ncepihom/

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Acronyms/Abbreviations

2-D	Type 2 diesel fuel
ºC	degrees Celsius
ºF	degrees Fahrenheit
APCT Center	Air Pollution Control Technology Center
ASTM	American Society for Testing and Materials
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
DPF	diesel particulate filter
EPA	U.S. Environmental Protection Agency
ETV	environmental technology verification
FTP	Federal Test Procedure
g	gram(s)
g/bhp-hr	grams per brake horsepower-hour
g/kWhr	grams per kilowatt-hour
HC	hydrocarbon(s)
hp	horsepower
ID	identification
in. Hg	inch(es) mercury
kg	kilograms
kg/kWhr	kilograms per kilowatt hour
kPa	kilopascals
kWhr	kilowatt hour
L	liter(s)
lb/bhp-hr	pounds per brake horsepower-hour
lb-ft	pound foot (feet)
MHDDE	medium heavy-duty diesel engine
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides

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PM	particulate matter
ppm	parts per million
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SOF	soluble organic fraction
SwRI	Southwest Research Institute
ULS	ultra-low-sulfur
ULSD	ultra-low-sulfur diesel

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Acknowledgments

The authors acknowledge the support of all of those who helped plan and conduct the verification activities. In particular, we would like to thank Mr. Michael Kosusko, Project Officer, and Mr. Robert Wright, Quality Manager, both of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all Baumot personnel who supported the test effort.

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For more information on verification testing of mobile sources air pollution control devices, contact the following:

Mr. Jason Hill
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Phone: (919) 541-7443
E-mail: apctvc@rti.org
ETV Program Web site: http://www.epa.gov/etv

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1.0 Introduction

This Environmental Technology Verification (ETV) report reviews the performance of the BA-B system, comprising a diesel particulate filter (DPF) technology with pre-catalyst submitted for testing by Baumot North America. ETV testing of this technology was conducted during a series of tests in October 2011 by Southwest Research Institute (SwRI), under contract with the Air Pollution Control Technology Center (APCT Center).

The APCT Center is operated by RTI International[*] (RTI) in partnership with the U.S. Environmental Protection Agency's (EPA's) ETV program. The objective of the APCT Center and the ETV program is to verify, with high-quality data, the performance of air pollution control technologies, including those designed to control air emissions from diesel engines. With the assistance of a technical panel of experts assembled for the purpose, RTI has established the APCT Center program area specifically to evaluate the performance of diesel exhaust catalysts, particulate filters, SCR systems, fuels additives, and engine modification control technologies for mobile diesel engines. Based on the activities of this technical panel, the *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* [1] was developed. This protocol was chosen as the best guide to verify the immediate performance effects of the BA-B system. To determine these effects, emissions results from a heavy-duty highway diesel engine were compared to emissions results obtained operating the same engine with the same fuel, but with the BA-B technology installed. The specific test/quality assurance (QA) plan addendum for the ETV test of the technology submitted by Baumot North America was developed and approved in April 2011.[2] The goal of the test was to measure the emissions control performance of the BA-B system and its emissions reduction relative to an uncontrolled engine.

Section 2.0 of this report describes the technology. ***Section 3.0*** documents the procedures and methods used for the test and the conditions under which the test was conducted. ***Section 4.0*** summarizes and discusses the results of the test. ***Section 5.0*** presents the references used to compile this ETV report.

This report contains only summary data and the verification statement. Complete documentation of the test results is provided in a separate test report[3] and an internal audit of data quality report.[4] These reports include the raw test data from product testing and supplemental testing, equipment calibration results, and QA and quality control (QC) activities and results. Complete documentation of QA and QC activities and results, raw test data, and equipment calibration results are retained in SwRI's files for 7 years.

The verification statement applies only to the use of the BA-B system on highway engines. This statement is applicable to engines fueled only by ultra–low-sulfur diesel (ULSD) (15 parts per million [ppm] or less) fuel.

[*] RTI International is a trade name of Research Triangle Institute.

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2.0 Product Description

The Baumot BA-B technology, shown installed in **Figure 1**, is a diesel engine retrofit device for light, medium, and heavy heavy-duty diesel on-highway engines for use with commercial ultra–low-sulfur diesel fuel (ULSD) conforming to 40 *Code of Federal Regulations* (*CFR*) 86.1313-2007.[5] The BA-B particulate filter is composed of a pre-catalyst on a metal basis and wall-flow monolith, both of which are coated with a precious metal oxidation catalyst. The 1114 unit is the BA-B variant specifically designed for use with engines with output of approximately 214-335 horsepower and displacement up to 11 liters.

Baumot provided a "degreened" BA-B 1114 unit that had seen 107 hours of service on a 1997 MAN model D2865LOH09 engine using German standard diesel fuel (10-50 ppm sulfur). The unit had serial number 1114100033 and a June 2010 date of manufacture.

Figure 1. The Baumot BA-B system installed for emissions tests.

Baumot provided an "aged" BA-B 1114 unit that had seen 1,093 hours of service on a 2001 DAF model WS268M engine using German standard diesel fuel (10-50 ppm sulfur). The unit had serial number 0000006586 and a May 2010 date of manufacture.

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3.0 Test Documentation

The ETV testing took place during October 2011 at SwRI under contract to the APCT Center. Testing was performed in accordance with the following:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* [1]
- *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines* [6]
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Baumot for the BA-B System.*[2]

The applicant reviewed the generic verification protocol and test/QA plan and had an opportunity to review the test-specific addendum prior to testing.

3.1 Engine Description

ETV verification testing was performed on a 1999 Cummins ISB 215 in-line, 6-cylinder, direct injected, turbocharged medium heavy-duty diesel engine (MHDDE), serial number 56541396, provided by SwRI. The rated power of the 5.9-liter (L) engine was expected to have a nominal rated power of 215 horsepower (hp) at 2700 revolutions per minute (rpm), and a rated torque of 420 pound feet (lb-ft) at 1600 rpm. The EPA engine family identification (ID) was XCEXH0359BAM. This engine was built in January 1999. Engine fuel injection management was electronically controlled. The test fuel was an ULSD that met specifications in 40 CFR 86.1313-2007.[5]

Table 1 provides the engine ID details, and **Figure 2** and **Figure 3** shows the ID plate from the engine.

Table 1. Engine Identification Information

Engine serial number	56541396
Date of manufacture	January 1999
Make	Cummins
Model year	1999
Model	ISB 215
Engine displacement and configuration	5.9 L, inline six cylinder
Service class	Highway, medium heavy-duty diesel engine
EPA engine family identification	XCEXH0359BAM (Engine Family Box OH-10)
Certification standards (g/bhp-hr)	HC = 1.3, CO = 15.5, NO_x = 4.0, PM = 0.1
Rated power (nameplate)	215 hp at 2700 rpm
Rated torque (nameplate)	420 lb-ft at 1600 rpm
Certified emission control system	Cummins CPL 2617
Aspiration	Turbo air to air
Fuel system	Electronic direct injection

Note: CO = carbon monoxide, g/bhp-hr = grams per brake horsepower-hour, HC = hydrocarbons, NO_x = nitrogen oxides, PM = particulate matter.

Beginning of table description. Table 1 is titled Engine Identification Information. The table lists the test engine's characteristics including engine serial number; date of manufacture; make, model, and model year; engine displacement and configuration; service class; performance characteristics; and standard emissions control, aspiration, and fuel systems. End of table description.

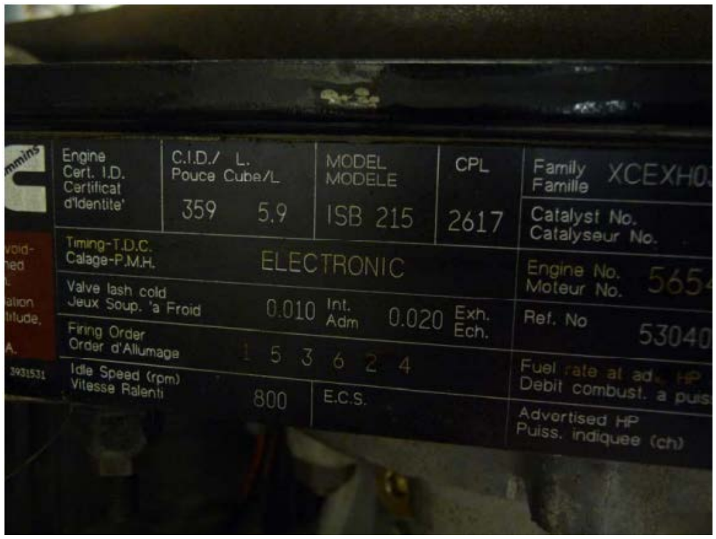

Figure 2. Identification label for 1999 Cummins ISB 215 showing engine model.

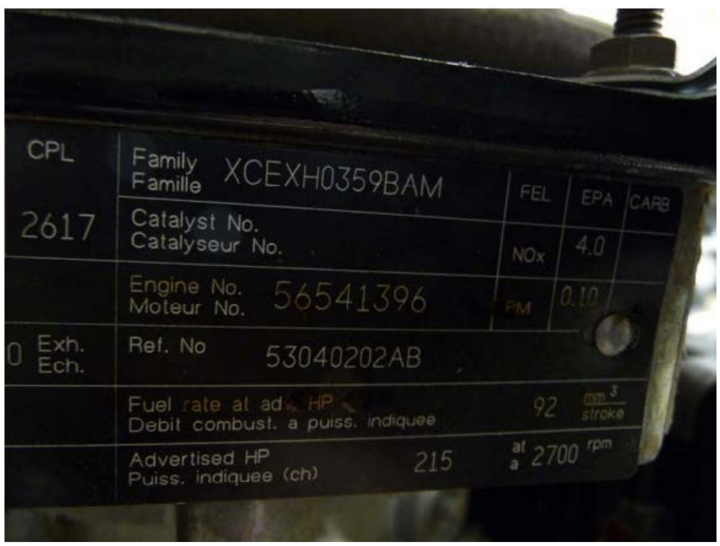

Figure 3. Identification label for 1999 Cummins ISB 215 showing engine family and serial numbers.

3.2 Engine Fuel Description

All emissions testing was conducted with ULSD fuel meeting the 40 CFR 86.1313-2007 specification for emissions certified fuel.[5] Selected fuel properties from the supplier's analyses are summarized in **Table 2**. All testing was conducted using fuel from a single batch, identified as ZG2821HW10.

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Table 2. Selected Fuel Properties and Specifications

Item	ASTM CFR Specification[a]	Type 2-D CFR Specification[a]	Diesel 2007 ULS Test Fuel
Cetane number	D613	40–50	45.2
Cetane index	D976	40–50	45.8
Distillation range:	—	—	—
Initial boiling point, ºC (ºF)	D86	171.1–204.4 (340–400)	178 (353)
10% point, ºC (ºF)	D86	204.4–237.8 (400–460)	209 (409)
50% point, ºC (ºF)	D86	243.3–282.2 (470–540)	256 (493)
90% point, ºC (ºF)	D86	293.3–332.2 (560–630)	314 (597)
End point, ºC (ºF)	D86	321.1–365.6 (610–690)	340 (644)
Gravity (American Petroleum Institute)	D287	32–37	35.6[b]
Total sulfur, ppm	D2622	7–15	10[c]
Hydrocarbon composition:	—	—	—
Aromatics (minimum), %	D5186	27	28[e]
Olefins, saturates %	D5186	Not applicable[d]	72[e]
Flash point (minimum), ºC (ºF)	D93	54.4 (130)	67.8 (154)
Viscosity, centistokes at 40ºC	D445	2.0–3.2	2.5

Note: ºC = degrees Celsius, ºF = degrees Fahrenheit, 2-D = Type 2 diesel fuel, ASTM = American Society for Testing and Materials, CFR = Code of Federal Regulations, ULS = ultra–low sulfur.

[a] 40 CFR 86.1313(b)(2) for heavy-duty diesel engines.[5]

[b] Measured per ASTM D4052.

[c] Measured per ASTM D5453; this method is an acceptable substitute for ASTM D2622.

[d] Remainder of the hydrocarbons.

[e] Measured per ASTM D1319.

Beginning of table description. Table 2 is titled Selected Fuel Properties and Specifications. The table lists the fuel specifications enumerated in the Code of Federal Regulations and the actual values for the fuel used during the verification test. The listed specifications include the cetane number, cetane index, distillation range, gravity, total sulfur content, hydrocarbon composition, flash point, and viscosity. The fuel used for the test met all the specifications. End of table description.

3.3 Functional Tests

Functional tests were performed on the aged BA-B unit's Bau-Dat exhaust backpressure monitoring system. Although functional testing of exhaust backpressure monitoring and notification/warning systems is not required under the verification protocol, this functinal testing was performed to demostrate the warning systems of the Bau-Dat. Results from the functional tests are given in **Table 3**. The table shows the tasks that were performed to force a diagnostic code or trigger an alarm, the timing for system's diagnostic warning and alarm indications (lights), and passing criteria for the system's diagnostic events. Table 3 also includes the observations and comments provided by the test personnel. Error code 31, corresponding to a hose or pipe breakage or damage to the filter, could not be triggered successfully. Error codes 32 (no pressure build up) and 33 (temperature remaining constant) did not trigger while the engine idled for twenty minutes, but they were triggered when the engine was run through the transient cycle for ten minutes. Error codes 34 and 36 triggered as expected under the test conditions specified in the test-specific addendum.[2]

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Table 3. Results from Functional Tests of the Bau-Dat Monitoring System

HOSE OR PIPE BREAKAGE OR DAMAGE TO FILTER					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC CODES**	**PASS CRITERIA**	**OBSERVED EVENTS**	**COMMENTS**
Start engine and allow exhaust backpressure to increase over 0 mbar					
Detach pressure hose from filter inlet		Alert 31 on display	Alert message 31	**Did not get Alert message 31 to appear**	**Ran engine other than idle - several attempts**
Re-attach hose		No alert on display	Alert off		
Shut off engine					
NO PRESSURE AFTER SWITHCING SYSTEM POWER					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC CODES**	**PASS CRITERIA**	**OBSERVED EVENTS**	**COMMENTS**
Engine off, disconnect pressure hose from filter inlet					
Start engine	Run idle 10 min	Alert 32 on display	Alert message 32 within 10 minutes	**Alert message 32 flashed on display at 10 minutes**	**Had to run engine other than idle**
Re-attach hose		No alert on display	Alert off	**Alert message off**	
Shut off engine					
CONSTANT TEMPERATURE AFTER SWITCHING SYSTEM POWER					
TASK	**TIME/EVENTS**	**VIEW DIAGNOSTIC CODES**	**PASS CRITERIA**	**OBSERVED EVENTS**	**COMMENTS**
Engine off, remove temperature sensor from filter inlet					
Start engine	Run idle 10 min	Alert 33 on display	Alert message 33 within 10 minutes	**Alert message 33 flashed on display at 10 minutes**	**Had to run engine other than idle**
Insert temperature sensor		No alert on display	Alert off	**Alert message off**	
Shut off engine					

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Table 3 (continued). Results from Functional Tests of the Bau-Dat Monitoring System

BROKEN TEMPERATURE SENSOR

TASK	TIME/EVENTS	VIEW DIAGNOSTIC CODES	PASS CRITERIA	OBSERVED EVENTS	COMMENTS
Engine off, remove electrical connector from temperature sensor					
Start engine		Alert 34 on display	Alert message 34	**Alert message 34 flashed on display at approximately 30 seconds**	
Re-attach sensor wire		No alert on display	Alert off	**Alert message off**	
Shut off engine					

UPPER PRESSURE THRESHHOLD

TASK	TIME/EVENTS	VIEW DIAGNOSTIC CODES	PASS CRITERIA	OBSERVED EVENTS	COMMENTS
Engine off, disconnect pressure hose from filter inlet					
Install pressure calibrator onto hose					
Apply pressure at 250 mbar	Wait 5 seconds	Alarm light and buzzer	Alarm light and buzzer in 5 sec	**Alert message 36 flashed, both lights lit solid, no buzzer at approx 5 sec**	
Continue	Wait 60 seconds	Both alarm lights flash and buzzer	Both alarm lights flash - buzzer in 60 sec	**Alert message 36 flashed, both lights flashed, intermittent buzzer at 60 sec**	
Continue	Wait added 120 seconds	Alert 36 on display, both alarm lights and constant buzzer	Alert 36, alarm lights, constant buzzer after 120 sec	**Alert message 36 flashed, both lights flashed, constant buzzer at 120 sec**	
Remove calibrator from hose and connect to filter					
Start engine		No alert, no lights, no buzzer	All off	**All off**	**Did not need to run engine**

3.4 Summary of Emissions Measurement Procedures

The ETV tests consisted of baseline uncontrolled tests and tests with the control technology installed. Engine operation and emissions sampling adhered to techniques developed by EPA in 40 CFR, Part 86, Subpart N.[7] Emissions were measured over a single cold-start and triplicate hot-start runs of the highway transient test cycle for the baseline, degreened BA-B, and aged BA-B exhaust configurations.

The 1999 Cummins ISB 215 engine was operated in an engine dynamometer test cell, with exhaust sampled using full-flow dilution constant volume sampling techniques to measure regulated emissions of hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM), along with carbon dioxide (CO_2) and nitric oxide (NO). Nitrogen dioxide (NO_2) emissions were determined as the difference between NO_x and NO emissions. Gaseous emission levels were corrected for dilution air ambient (background) levels. Emissions of HC, CO, CO_2, NO, and NO_x were measured using a Horiba MEXA-7200 analyzer bench. The NO analyzer did not have a NO_2/NO converter. PM emissions were determined from the net weight gain of a pair of Pallflex T60A20 media filters used in series.

Soluble organic fraction (SOF) of the PM emissions was determined from the particulate-laden filters from the emission tests. The SOF was extracted using toluene/ethanol solvent and a Soxhlet apparatus. To determine the mass of SOF, the filter set was reweighed after the extraction process. The weight difference between loaded and extracted conditions of the filters represented the mass of SOF.

In addition to results presented in this report, raw data were gathered at the rate of one series of measurements per second over each test to record the engine speed, torque value, concentration of selected emissions, exhaust temperature, and various pressures. **Figure 4** depicts the sampling system and related components. The system is designed to comply with the requirements of 40 CFR, Part 86.[7]

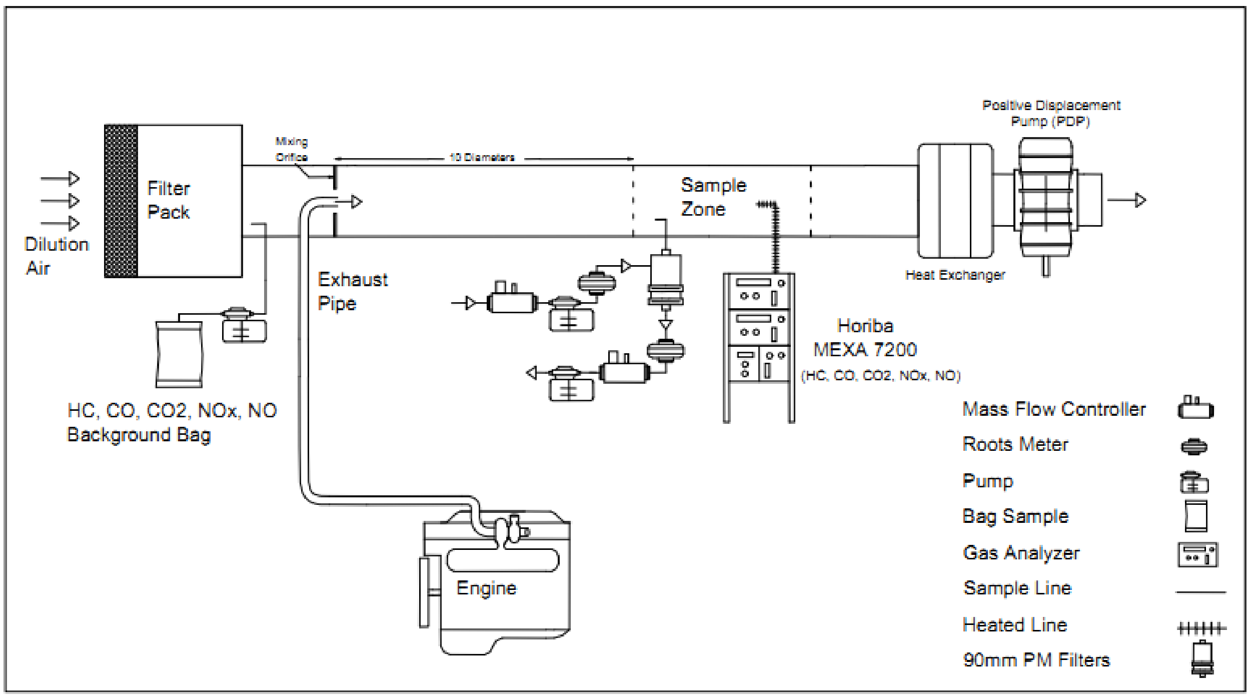

Figure 4. Schematic of emissions sampling system at SwRI.

The verification protocol requires that the emissions from engines used for verification testing must not exceed 110% of the certification standards for that engine category.[1] For MY 1998-2003 non-urban bus engines, these certification standards are defined in EPA's on-highway engine family box OH-10. Furthermore, the Office of Transportation and Air Quality assumes 5% reduction in PM emissions due to the use of ULSD fuel.

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The criteria established to indicate the test engine was acceptable and that verification testing could proceed were that the baseline emissions from the engine using ULSD fuel could not exceed 110% of OH-10 (1.1 x OH-10) for HC, CO, and NO_x, and also could not exceed 110% of [(OH-10)-5%], or (1.045 x OH-10) for PM. Certification standards for OH-10 are HC 1.3 g/bhp-hr, CO 15.5 g/bhp-hr, NO_x 4.0 g/bhp-hr, and PM 0.1 g/bhp-hr. **The adjusted levels the test engine must have met were HC 1.43 g/bhp-hr, CO 17.05 g/bhp-hr, NO_x 4.4 g/bhp-hr, and PM 0.1045 g/bhp-hr.**

Table 4 presents the required emissions performance of the test engine, as well as the certification standards and baseline results for comparison.

Table 4. Test Engine Baseline Emissions Requirement for 1999 Cummins ISB 215

—	HC (g/kWhr)	HC (g/bhp-hr)	CO (g/kWhr)	CO (g/bhp-hr)	NO_x (g/kWhr)	NO_x (g/bhp-hr)	PM (g/kWhr)	PM (g/bhp-hr)
OH-10[a]	1.7	1.3	20.8	15.5	5.4	4.0	0.1	0.1
Acceptance criteria	1.92	1.43	22.86	17.05	5.9	4.4	0.1401	0.1045
Baseline results	0.252	0.188	1.97	1.47	5.11	3.81	0.126	0.094

Note: g/bhp-hr = grams per brake horsepower-hour, g/kWhr = grams per kilowatt-hour.

[a] Certification standards for EPA highway engine family box OH-10 for 1998-2003 non-urban bus engines.

Beginning of table description. Table 4 is titled Test Engine Baseline Emissions Requirement for 1999 Cummins ISB 215. The table lists the certified emissions rates for engine category OH-10, to which the Cummins ISB 215 test engine belongs; the allowable acceptance criteria for maximum emissions for this category; and the actual results for the baseline Cummins ISB 215 used during the test. The pollutants listed are hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter, with units given in both grams per kilowatt hour and grams per brake horsepower-hour. The baseline engine met the acceptance criteria. End of table description.

3.5 Deviations from the Test/QA Plan

All of the verification data are within compliance for testing as specified in 40 CFR, Part 86, Subpart N.[7] However, one hot-start transient test for the baseline configuration was not used in the verification data set due to exceeding a sampling temperature limit. Baseline testing required a fourth hot-start test to make up for a PM sample filter over-temperature condition (>52 °C) during the second hot-start test. No equipment malfunction was noted and no corrective action report was submitted. Repeating the hot-start portion of an FTP is allowed according to 40 CFR 86.1336-84. If any test equipment malfunctions during the hot-start, the cycle is completed and the engine is shut down for a twenty-minute soak. If the malfunction is corrected before the soak period ends, the hot-start tests may be re-run. After the second hot-start test, corrective action was taken by reducing the double dilution system's sample flow by approximately 4 percent. According to 40 CFR 86.1337-96, sample flowrates can be adjusted to desired rates before a cold-start or hot-start test begins.

3.6 Documented Test Conditions

Engine Performance

Figure 5 shows torque map information measured on the 1999 Cummins ISB 215 engine using the ULSD fuel.

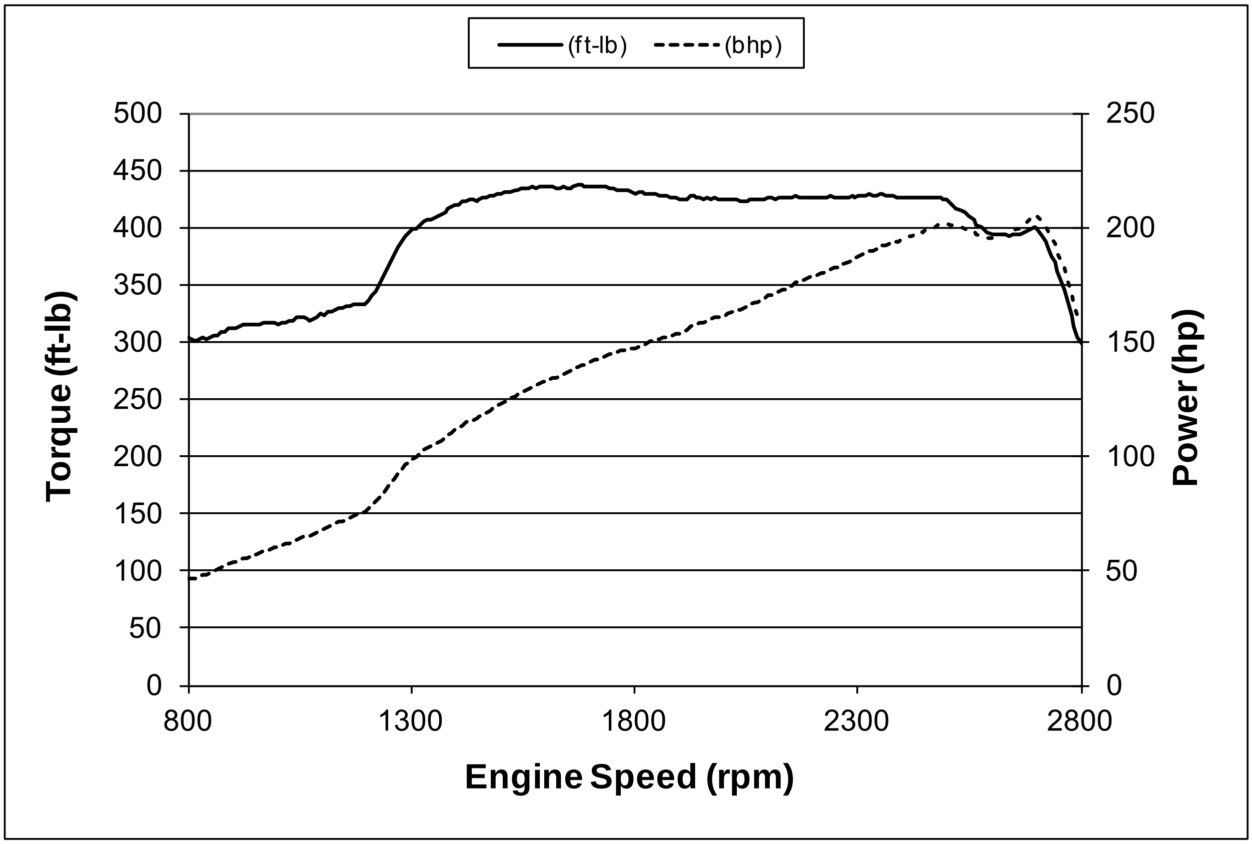

Figure 5. Torque map of 1999 Cummins ISB 215 engine using ULSD fuel.

Engine Exhaust Backpressure and Exhaust Temperature

The engine backpressure for the 1999 Cummins ISB 215 engine was set in accordance with the engine manufacturer's specifications for the baseline configuration. The backpressure was adjusted to the same specification after installation of the degreened and aged devices. Maximum exhaust backpressure levels for transient Federal Test Procedure tests on the BA-B systems are given in **Table 5**. The aged BA-B systems had significantly increased exhaust backpressure over the transient test cycle relative to the degreened BA-B system.

Temperature measurements were made in the exhaust system of the Cummins engine at the inlet and outlet of the BA-B. Average inlet and outlet temperatures over the transient test cycle, shown in Table 5, were 423 ºF (217 ºC) and 462 ºF (239 ºC), respectively.

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Table 5. Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine[a]

Test Number	Test Type	Test Date	Maximum Exhaust Back-pressure (kPa)	Maximum Exhaust Back-pressure (in. Hg)	Average Device Inlet Temperature (°C)	Average Device Inlet Temperature (°F)	Average Device Exhaust Temperature (°C)	Average Device Exhaust Temperature (°F)
1396-586-C1	Cold-Start	10/12/11	7.59	2.24	—	—	209.51	409.11
1396-588-H1	Hot-Start	10/12/11	7.69	2.27	—	—	218.54	425.38
1396-592-H3	Hot-Start	10/12/11	7.79	2.30	—	—	218.50	425.29
1396-594-H4	Hot-Start	10/12/11	7.86	2.32	—	—	218.93	426.08
—	—	**Average**	**7.73**	**2.28**	—	—	216.37	421.47

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Back-pressure (kPa)	Maximum Exhaust Back-pressure (in. Hg)	Average Device Inlet Temperature (°C)	Average Device Inlet Temperature (°F)	Average Device Exhaust Temperature (°C)	Average Device Exhaust Temperature (°F)
1396-604-C1	Cold-Start	10/14/11	5.35	1.58	209.61	409.30	215.17	419.31
1396-606-H1	Hot-Start	10/14/11	5.59	1.65	216.82	422.28	242.47	468.45
1396-608-H2	Hot-Start	10/14/11	5.69	1.68	217.65	423.77	243.15	469.66
1396-610-H3	Hot-Start	10/14/11	5.82	1.72	217.35	423.22	243.15	469.66
—	—	**Average**	**5.61**	**1.66**	**215.36**	**419.64**	**235.98**	**456.77**

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	Test Date	Maximum Exhaust Back-pressure (kPa)	Maximum Exhaust Back-pressure (in. Hg)	Average Device Inlet Temperature (°C)	Average Device Inlet Temperature (°F)	Average Device Exhaust Temperature (°C)	Average Device Exhaust Temperature (°F)
1396-619-C1	Cold-Start	10/17/11	7.11	2.10	212.15	413.86	218.97	426.15
1396-621-H1	Hot-Start	10/17/11	7.28	2.15	221.29	430.33	247.99	478.37
1396-623-H2	Hot-Start	10/17/11	7.45	2.20	221.56	430.81	248.84	479.92
1396-625-H3	Hot-Start	10/17/11	7.48	2.21	222.34	432.21	249.61	481.29
—	—	**Average**	**7.33**	**2.17**	**219.33**	**426.80**	**241.35**	**466.43**

Note: in. Hg = inches mercury, kPa = kilopascals.

[a] Baseline engine did not have a DPF installed, the baseline exhaust temperature results refer to the engine exhaust temperature.

Beginning of table description. Table 5 is titled Engine Exhaust Backpressure and Average Device Inlet/Outlet Temperature. The table lists the maximum exhaust backpressure, average device inlet temperature, and average device exhaust temperature for each individual cold-start and hot-start test run for the baseline, degreened, and aged systems. Results are given in both metric and U.S. common units. End of table description.

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Figure 6 shows the inlet temperature over time for the degreened device, and **Figure 7** shows the inlet temperature over time for the aged device. In both figures, the hot-start profile is the average of the three hot-start tests.

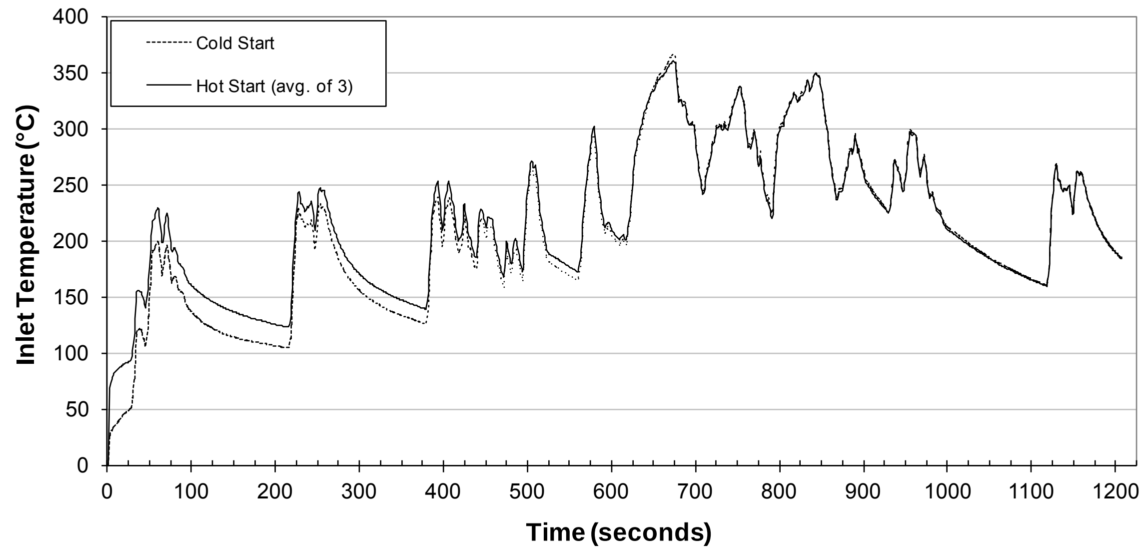

Figure 6. Inlet temperature profile of degreened BA-B system.

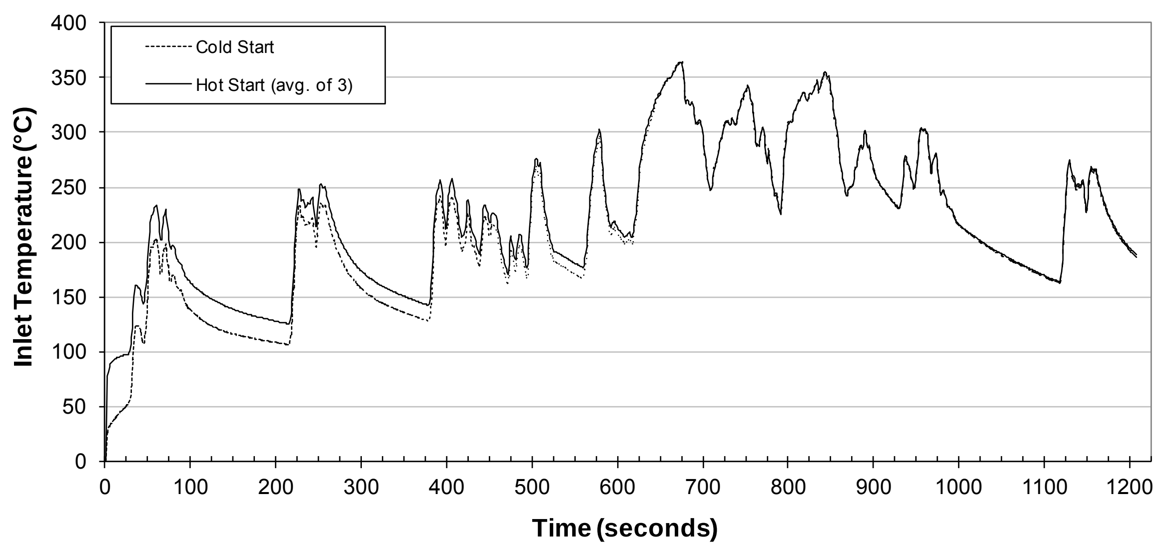

Figure 7. Inlet temperature profile of aged BA-B system.

Soluble Organic Fraction

On each test, the particulate material was tested for SOF. **Table 6** reports the results. Due to very low PM accumulations with the BA-B systems, accurate SOF results could not be obtained for the degreened or aged devices.

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Table 6. Particulate Characterization—Soluble Organic Fraction from Each Test

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Text Type	PM (g)	PM (% SOF)
1396-586-C1	Cold-Start	1.28	54
1396-588-H1	Hot-Start	1.27	35
1396-592-H3	Hot-Start	1.27	34
1396-594-H4	Hot-Start	1.27	37

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Text Type	PM (g)	PM (% SOF)
1396-604-C1	Cold-Start	0.196	a
1396-606-H1	Hot-Start	0.0199	a
1396-608-H2	Hot-Start	0.0425	a
1396-610-H3	Hot-Start	0.0302	a

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Text Type	PM (g)	PM (% SOF)
1396-619-C1	Cold-Start	0.0411	a
1396-621-H1	Hot-Start	0.0532	a
1396-623-H2	Hot-Start	0.0544	a
1396-625-H3	Hot-Start	0.0123	a

Note: g = grams.

[a] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 6 is titled Particulate Characterization—Soluble Organic Fraction from Each Test. The table lists the mass of particulate matter emissions in grams and the percent soluble organic fraction from each individual cold-start and hot-start test for the baseline, degreened, and aged systems. End of table description.

Brake-Specific Fuel Consumption

The fuel consumption was not measured directly during the engine testing. Rather, a calculated "carbon-balance" fuel consumption rate was determined based on the measured exhaust flow rate and the carbon content (i.e., the CO and the CO_2) in the exhaust gas analysis. The weighted brake-specific fuel consumption (BSFC) calculations are similar to the weighted emissions calculations explained in Section 4.0. **Table 7** shows the weighted BSFC calculations. **Table 8** summarizes the results of these calculations and compares the fuel consumption during the baseline runs with that measured during the tests with the BA-B units installed. The BA-B systems did not have a substantial effect on fuel consumption.

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Table 7. Brake-Specific Fuel Consumption (by Carbon Balance)

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
1396-586-C1	Cold-Start	10/12/2011	0.438	0.266	—	—
1396-588-H1	Hot-Start	10/12/2011	0.434	0.264	0.434	0.264
1396-592-H3	Hot-Start	10/12/2011	0.430	0.261	0.431	0.262
1396-594-H4	Hot-Start	10/12/2011	0.429	0.261	0.430	0.262
—	—	—	—	Mean	0.432	0.263

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
1396-604-C1	Cold-Start	10/14/2011	0.433	0.263	—	—
1396-606-H1	Hot-Start	10/14/2011	0.424	0.258	0.425	0.259
1396-608-H2	Hot-Start	10/14/2011	0.423	0.257	0.424	0.258
1396-610-H3	Hot-Start	10/14/2011	0.425	0.258	0.426	0.259
—	—	—	—	Mean	0.425	0.259

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	Test Date	BSFC (lb/bhp-hr)	BSFC (kg/kWhr)	Weighted BSFC (lb/bhp-hr)	Weighted BSFC (kg/kWhr)
1396-619-C1	Cold-Start	10/17/2011	0.435	0.264	—	—
1396-621-H1	Hot-Start	10/17/2011	0.425	0.258	0.427	0.259
1396-623-H2	Hot-Start	10/17/2011	0.425	0.258	0.426	0.259
1396-625-H3	Hot-Start	10/17/2011	0.424	0.258	0.425	0.258
—	—	—	—	Mean	0.426	0.259

Note: lb/bhp-hr = pounds per brake horsepower-hour, kg/kWhr = kilograms per kilowatt hour.

Beginning of table description. Table 7 is titled Brake-Specific Fuel Consumption (by Carbon Balance). The table lists the calculated results for brake-specific fuel consumption for each individual cold-start and hot-start test for the baseline, degreened, and aged systems. The mean weighted brake-specific fuel consumption is also listed for each system. Results are shown in both U.S. common and metric units. End of table description.

Table 8. Summary of Fuel Consumption Reductions

Device type	Fuel	% Reduction	95% Confidence Limits
Degreened	ULSD	1.5	0.28 to 2.7
Aged	ULSD	1.3	0.12 to 2.5

Beginning of table description. Table 8 is titled Summary of Fuel Consumption Reductions. The table lists the percent fuel reduction with ULSD fuel for the degreened and aged systems. 95% confidence limits for the percent reductions are also provided. End of table description.

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4.0 Summary and Discussion of Emissions Results

Table 9 reports the emissions from the highway transient Federal Test Procedure (FTP) tests that were conducted: baseline; with a degreened BA-B system installed; and with an aged BA-B system installed. The concentration measurements were converted to units of total grams per test for most species, with CO_2 (kilograms [kg]) as the exception. The work values in units of kilowatt hour (kWhr) and brake horsepower-hour (bhp-hr) are also shown in these tables to document the integrated measured power during each test period. Additionally, the PM samples from the highway FTP tests with the BA-B systems had accumulations too low for accurate SOF analysis.

Table 9. Highway FTP Emissions Data

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NOx (g)	NO (g)	NO_2[a] (g)	NO_2/NO_X (%)	HC (g)	CO (g)	CO_2 (kg)	Work (kWhr [bhp-hr])
1396-586-C1	Cold-Start	1.28	54	59.1	51.0	8.16	13.8	3.18	27.3	8.58	10.2 (13.6)
1396-588-H1	Hot-Start	1.27	35	50.2	43.1	7.09	14.1	2.39	19.2	8.46	10.1 (13.6)
1396-592-H3	Hot-Start	1.27	34	50.3	42.4	7.91	15.7	2.42	18.5	8.36	10.1 (13.5)
1396-594-H4	Hot-Start	1.27	37	50.7	42.6	8.17	16.1	2.52	18.6	8.36	10.1 (13.5)

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NOx (g)	NO (g)	NO_2[a] (g)	NO_2/NO_X (%)	HC (g)	CO (g)	CO_2 (kg)	Work (kWhr [bhp-hr])
1396-604-C1	Cold-Start	0.196	b	56.8	39.0	17.8	31.4	0.935	9.08	8.51	10.2 (13.6)
1396-606-H1	Hot-Start	0.0199	b	49.5	29.3	20.2	40.8	0.148	0.978	8.31	10.1 (13.6)
1396-608-H2	Hot-Start	0.0425	b	49.8	29.1	20.7	41.5	0.116	0.876	8.29	10.1 (13.6)
1396-610-H3	Hot-Start	0.0302	b	49.6	29.3	20.4	41.0	0.155	0.863	8.33	10.1 (13.6)

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test Number	Test Type	PM (g)	PM (% SOF)	NOx (g)	NO (g)	NO_2[a] (g)	NO_2/NO_X (%)	HC (g)	CO (g)	CO_2 (kg)	Work (kWhr [bhp-hr])
1396-619-C1	Cold-Start	0.0411	b	56.3	28.3	28.0	49.7	0.652	7.26	8.54	10.1 (13.6)
1396-621-H1	Hot-Start	0.0532	b	48.9	17.6	31.3	64.1	0.0690	0.552	8.31	10.1 (13.5)
1396-623-H2	Hot-Start	0.0544	b	49.4	17.5	31.9	64.5	0.0990	0.339	8.30	10.1 (13.5)
1396-625-H3	Hot-Start	0.0123	b	49.3	17.5	31.8	64.5	0.0610	0.266	8.27	10.1 (13.5)

Note: g = grams.

[a] NO_2 calculated as $NO_X - NO$.

[b] SOF analysis was completed, but the PM sample's accumulation was too low to give accurate results.

Beginning of table description. Table 9 is titled Highway FTP Emissions Data. The table provides the pollutant emissions results from the individual cold-start and hot-start test runs for the baseline, degreened, and aged systems. Results are provided for the following: PM in grams and the PM % soluble organic fraction; NOx, NO, and NO2 in grams; NO2/NOx ratio as a percentage; HC in grams; CO in grams; CO2 in kilograms; and work in both kilowatt hours and break horsepower-hours. End of table description.

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For each pollutant/hot-start test combination, the transient composite-weighted emissions per work brake horsepower-hour (bhp-hr) were then calculated following the fractional calculation for highway engines as follows:

$$\left(E_{COMP}\right)_m = \frac{\frac{1}{7} \bullet E_{COLD} + \frac{6}{7} \bullet \left(E_{HOT}\right)_m}{\frac{1}{7} \bullet W_{COLD} + \frac{6}{7} \bullet \left(W_{HOT}\right)_m} \qquad \text{(Eq. 1)}$$

where

E_{COMP} = composite emissions rate, g/bhp-hr
m = one, two, or three hot-start tests
E_{COLD} = cold-start mass emissions level, g
E_{HOT} = hot-start mass emissions level, g
W_{COLD} = cold-start bhp-hr
W_{HOT} = hot-start bhp-hr

These composite-weighted emissions rates are shown in **Table 10** and **Table 11** and were used to calculate the mean and standard deviations for the baseline and controlled emissions rates. These data were, in turn, used to calculate mean emissions reductions and 95% confidence limits. These calculations are based on the generic verification protocol[1] and test/QA plan addendum.[2]

Table 10. Composite-Weighted Emissions Rates (U.S. Common Units)

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.0936	3.79	3.26	0.534	14.1	0.184	1.50	624
Hot-Start #2	0.0938	3.80	3.22	0.586	15.4	0.187	1.46	619
Hot-Start #3	0.0937	3.83	3.23	0.602	15.7	0.193	1.46	619

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00332	3.72	2.26	1.46	39.3	0.0192	0.157	613
Hot-Start #2	0.00475	3.74	2.25	1.49	39.9	0.0172	0.151	612
Hot-Start #3	0.00397	3.73	2.26	1.47	39.5	0.0196	0.150	615

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2[a] (g/bhp-hr)	NO_2/NO_x (%)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Hot-Start #1	0.00380	3.69	1.41	2.28	61.8	0.0112	0.111	616
Hot-Start #2	0.00388	3.72	1.41	2.31	62.2	0.0131	0.0980	615
Hot-Start #3	0.00121	3.71	1.41	2.31	62.1	0.0107	0.0934	614

Note: g/bhp-hr = grams per work brake horsepower-hour.

[a] NO_2 calculated as NO_x−NO.

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Beginning of table description. Table 10 is titled Composite-Weighted Emissions Rates (U.S. Common Units). The table provides the composite-weighted emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per brake horsepower-hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per brake horsepower-hour. End of table description.

Table 11. Composite-Weighted Emissions Rates (Metric Units)

Baseline with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.126	5.08	4.37	0.716	14.1	0.247	2.01	837
Hot-Start #2	0.126	5.10	4.32	0.786	15.4	0.251	1.96	830
Hot-Start #3	0.126	5.14	4.33	0.807	15.7	0.259	1.96	830

Degreened Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00445	4.99	3.03	1.96	39.3	0.0257	0.211	822
Hot-Start #2	0.00637	5.02	3.02	2.00	39.9	0.0231	0.202	821
Hot-Start #3	0.00532	5.00	3.03	1.97	39.5	0.0263	0.201	825

Aged Baumot BA-B with ULSD Fuel on a 1999 Cummins ISB 215 Test Engine

Test	Exhaust PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2[a] (g/kWhr)	NO_2/NO_x (%)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Hot-Start #1	0.00510	4.95	1.89	3.06	61.8	0.0150	0.149	826
Hot-Start #2	0.00520	4.99	1.89	3.10	62.2	0.0176	0.131	825
Hot-Start #3	0.00162	4.98	1.89	3.10	62.1	0.0143	0.125	823

Note: g/kWhr = grams per kilowatt-hour.

[a] NO_2 calculated as $NO_x - NO$.

Beginning of table description. Table 11 is titled Composite-Weighted Emissions Rates (Metric Units). The table provides the composite-weighted emissions rates for each individual hot-start test of the baseline, degreened, and aged systems. Results are provided for the following: exhaust PM, NOx, NO, and NO2 in grams per kilowatt hour; the NO2/NOx ratio as a percentage; and HC, CO, and CO2 in grams per kilowatt hour. End of table description.

The mean combined emissions rates presented below in **Table 12** and **Table 13** are the key values for the verification test. The first line shows the baseline engine results; the emissions in all categories are below the Table 4 threshold.

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Table 12. Summary of Verification Test Data (U.S. Common Units): Mean Combined Weighted Emission Value

Device Type	Fuel	PM (g/bhp-hr)	NO_x (g/bhp-hr)	NO (g/bhp-hr)	NO_2 (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	CO_2 (g/bhp-hr)
Baseline	ULSD	0.0937	3.81	3.23	0.574	0.188	1.47	621
Degreened	ULSD	0.00401	3.73	2.25	1.47	0.0186	0.153	614
Aged	ULSD	0.00296	3.71	1.41	2.30	0.0117	0.101	615

Note: g/bhp-hr = grams per work brake horsepower-hour.

Beginning of table description. Table 12 is titled Summary of Verification Test Data (U.S. Common Units): Mean Combined Weighted Emission Value. The table lists the mean combined weighted emission rates for the baseline, degreened, and aged systems. Results are provided for PM, NOx, NO, NO2, HC, CO, and CO2 in grams per brake horsepower-hour. End of table description.

Table 13. Summary of Verification Test Data (Metric Units): Mean Combined Weighted Emission Value

Device Type	Fuel	PM (g/kWhr)	NO_x (g/kWhr)	NO (g/kWhr)	NO_2 (g/kWhr)	HC (g/kWhr)	CO (g/kWhr)	CO_2 (g/kWhr)
Baseline	ULSD	0.126	5.11	4.34	0.770	0.252	1.97	832
Degreened	ULSD	0.00538	5.00	3.02	1.98	0.0250	0.205	823
Aged	ULSD	0.00397	4.97	1.89	3.08	0.0157	0.135	825

Note: g/kWhr = grams per kilowatt-hour.

Beginning of table description. Table 13 is titled Summary of Verification Test Data (Metric Units): Mean Combined Weighted Emission Value). The table lists the mean combined weighted emission rates for the baseline, degreened, and aged systems. Results are provided for PM, NOx, NO, NO2, HC, CO, and CO2 in grams per kilowatt hour. End of table description.

Table 14 summarizes the emissions reductions that were achieved by the use of the BA-B systems. These are the "verified emissions reductions" reported in Table 2 of the ETV Joint Verification Statement.

Table 14. Summary of Verification Test Emissions Reductions

System Type	Fuel	PM Mean Emissions Reduction (%)	NO_x Mean Emissions Reduction (%)	HC Mean Emissions Reduction (%)	CO Mean Emissions Reduction (%)	PM 95% Confidence Limits on the Emissions Reduction (%)	NO_x 95% Confidence Limits on the Emissions Reduction (%)	HC 95% Confidence Limits on the Emissions Reduction (%)	CO 95% Confidence Limits on the Emissions Reduction (%)
Degreened	ULSD	96	2.1	90	90	95 to 96	0.57 to 3.6	84 to 96	86 to 93
Aged	ULSD	97	2.7	94	93	97 to 97	1.4 to 4.0	88 to 99	89 to 97

Beginning of table description. Table 14 is titled Summary of Verification Test Emissions Reductions. The table describes the emissions reduction percentages from the verification tests of the degreened and aged systems. Results are presented for particulate matter, nitrogen oxides, hydrocarbons, and carbon monoxide. 95% confidence limits for these reductions are also listed. End of table description.

In summary, the BA-B systems significantly reduced PM, HC, and CO emissions but only slightly reduced NO_x emissions. In comparing the aged to the degreened results, the 95% confidence limits for the percent reduction of NO_x, HC, and CO overlapped each other, while a very slight improvement in PM reduction was measured for the aged system relative to the degreened system. With the BA-B systems in place, the soluble organic fraction of the PM emissions was too low to quantify. The BA-B systems did not have a substantial effect on CO_2 emissions or fuel consumption, but did increase NO_2:NO_x ratio.

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4.1 Quality Assurance

The ETV of the BA-B system with ULSD fuel for heavy-duty highway diesel engines was performed in accordance with the approved test/QA plan[6] and the test-specific addendum.[2] An internal audit of data quality conducted by SwRI personnel[4] included the review of equipment, procedures, record keeping, data validation, analysis, and reporting. Preliminary, in-process, and final inspections, and a review of 10% of the data, showed that the requirements stipulated in the test/QA plan[5] were achieved. The SwRI, APCT Center, and EPA quality managers reviewed the test results and the QC data and concluded that the data quality objectives given in the generic verification protocol were attained. RTI QA staff conducted an audit of SwRI's technical systems in March 2010 and found no deficiencies that would adversely impact the quality of results at that time. The equipment was appropriate for the verification testing, and it was operating satisfactorily.

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5.0 References

1. RTI International. 2002. *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines.* Research Triangle Park, NC, January. Available at: http://www.epa.gov/etv/pubs/05_vp_devrev.pdf (accessed November 28, 2011).
2. RTI International. 2011. *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Baumot for the BA-B System.* Research Triangle Park, NC, April 2011.
3. Southwest Research Institute. 2011. *Environmental Technology Verification: Baumot North America BA-B Diesel Particulate Filter Technology.* Final Report. San Antonio, TX, November.
4. Southwest Research Institute. 2011. *Audit of Data Quality for Environmental Technology Verification - Baumot North America BA-B Diesel Filter Technology.* San Antonio, TX, December.
5. 40 CFR, Part 86.1313-2007 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Fuel Specifications), Table N07-2. Available at: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=73cf95a92e6738b2e5dab5c2172074ef&rgn=div8&view=text&node=40:19.0.1.1.1.8.1.20&idno=40 (accessed November 28, 2011).
6. RTI International. 2011. *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines.* Research Triangle Park, NC, March. Available at: http://www.epa.gov/nrmrl/std/etv/pubs/600etv11004.pdf (accessed November 28, 2011).
7. 40 CFR, Part 86 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines), Subpart N. Available at: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=73cf95a92e6738b2e5dab5c2172074ef;rgn=div6;view=text;node=40%3A19.0.1.1.1.8;idno=40;cc=ecfr (accessed November 28, 2011).

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