

# Environmental Technology Verification

## Test Report of Mobile Source Emission Control Devices

Cummins Emission Solutions & Cummins Filtration  
Diesel Oxidation Catalyst and Closed Crankcase Ventilation System

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



## ETV Joint Verification Statement

<b>TECHNOLOGY TYPE:</b>	<b>MOBILE DIESEL ENGINE AIR POLLUTION CONTROL</b>
<b>APPLICATION:</b>	<b>CONTROL OF EMISSIONS FROM MOBILE DIESEL ENGINES IN HIGHWAY USE BY DIESEL OXIDATION CATALYST (DOC) AND CLOSED CRANKCASE VENTILATION (CCV) SYSTEM</b>
<b>TECHNOLOGY NAME:</b>	<b>201350N DOC PLUS COALESCER BREATHER CV5061200 AND CRANKCASE DEPRESSION REGULATOR (CDR) VALVE 395587500</b>
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The U.S. Environmental Protection Agency (EPA) has 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. ETV 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.

ETV works in partnership with recognized standards and testing organizations; stakeholder groups, which consist of buyers, vendor organizations, permittees, 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 Verification Center (APCT Center), one of six centers under the ETV Program, is operated by RTI International (RTI), in cooperation with EPA's National Risk

Management Research Laboratory. The APCT Center has evaluated the performance of an emissions control system consisting of a precious metal diesel oxidation catalyst and diesel particulate filter for highway diesel engines.

## ETV TEST DESCRIPTION

All tests were performed in accordance with the *Test/QA Plan for the Verification Testing of Diesel Exhaust Catalysts, PM Filters, and Engine Modification Technologies for Highway and Nonroad Use Diesel Engines* and the *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Cummins Emission Solutions & Cummins Filtration for the 201350N DOC + Coalescer Breather CV5061200*. These documents are written in accordance with the applicable generic verification protocol and include requirements for quality management, QA, procedures for product selection, auditing of the test laboratories, and test reporting format.

The mobile diesel engine air pollution control technology was tested January 10-12, 2007, at Southwest Research Institute. The performance verified was the percentage emission reduction achieved by the technology for particulate matter (PM), nitrogen oxides (NO<sub>x</sub>), 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 were also made. A summary description of the ETV test is provided in Table 1.

**Table 1. Summary Description of the ETV Test**

Test type	Highway Transient Federal Test Procedure (FTP)
Engine family	YCEXH0661MAH
Engine make–model year	Cummins – 2000 ISM 350 ESP
Service class	Highway, heavy heavy-duty diesel engine
Engine rated power	350 hp at 2100 rpm
Engine displacement	10.8 L, inline six-cylinder
Technology	201350N DOC plus coalescer breather CV5061200 and crankcase depression regulator (CDR) valve 395587500
Technology description	Diesel oxidation catalyst (DOC) and closed crankcase ventilation (CCV)
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 (ULSD) fuel with 15 ppm sulfur maximum
Critical measurements	PM, NO <sub>x</sub> , HC, and CO
Ancillary measurements	CO <sub>2</sub> , NO, NO <sub>2</sub> (by calculation), soluble organic fraction (SOF) of PM, exhaust backpressure, exhaust temperature, and fuel consumption

## VERIFIED TECHNOLOGY DESCRIPTION

The Cummins Emission Solutions & Cummins Filtration’s 201350N precious metal diesel oxidation catalyst (DOC) and closed crankcase ventilation (CCV) system, consists of the DOC plus the coalescer breather CV5061200 and crankcase depression regulator (CDR) valve 395587500. This verification statement describes the performance of the tested technology on the diesel engine and fuels identified in Table 1, and applies only to the use of the 201350N DOC plus coalescer breather

CV5061200 and CDR valve 395587500 on highway engines fueled only by ULSD (15 ppm or less) fuel.

## VERIFICATION OF PERFORMANCE

The 201350N DOC plus coalescer breather CV5061200 and CDR valve 395587500 achieved the reduction in tailpipe emissions shown in Table 2 compared to baseline operation without the DOC+CCV system.

**Table 2. Verified Emissions Reductions**

Device type	Fuel	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
		PM	NO <sub>x</sub>	HC	CO	PM	NO <sub>x</sub>	HC	CO
Degreened	ULSD	31	2.8	80	71	27 to 34	2.0 to 3.7	75 to 86	70 to 73
Aged	ULSD	30	0.68	68	60	26 to 34	– <sup>a</sup>	62 to 73	59 to 61

<sup>a</sup> The emission reduction cannot be distinguished from zero with 95% confidence.

The APCT Center QA officer has reviewed the test results and quality control data and has concluded that the data quality objectives given in the generic verification protocol and test/QA plan have been attained. EPA and APCT Center QA staff have conducted technical assessments of the test laboratory 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 201350N DOC plus coalescer breather CV5061200 and CDR valve 395587500 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 201350N DOC plus coalescer breather CV5061200 and CDR valve 395587500 within the range of applicability of the statement.

*Original signed by S. Gutierrez*      7/16/07

Sally Gutierrez      Date  
Director  
National Risk Management Research Laboratory  
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*Original signed by A. R. Trenholm*      7/3/07

Andrew R. Trenholm      Date  
Director  
Air Pollution Control Technology  
Verification Center

# **Environmental Technology Verification Report**

## **Mobile Source Emission Control Devices**

**Cummins Emission Solutions & Cummins Filtration  
Closed Crankcase Ventilation System  
(201350N Precious Metal Diesel Oxidation Catalyst Plus  
Coalescer Breather CV5061200 and Crankcase  
Depression Regulator Valve 395587500)**

Prepared by

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EPA Cooperative Agreement No. CR831911-01-1

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June 2007

## **Notice**

This document was prepared by RTI International (RTI) and its subcontractor, Southwest Research Institute (SwRI), with partial funding from Cooperative Agreement No. CR83191101-1 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.

## Foreword

The Environmental Technology Verification (ETV) Program, established by the U.S. Environmental Protection Agency (EPA), 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 in order to provide potential purchasers and permittees an independent, credible assessment of the technology they are buying or permitting.

The Air Pollution Control Technology Verification Center (APCT Center) is part of the 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 emission control technologies.

Retrofit air pollution control devices used to control emissions from mobile diesel engines are among the technologies evaluated by the APCT Center. The APCT Center developed (and EPA 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 Cummins Emission Solutions & Cummins Filtration closed crankcase ventilation system, consisting of the Cummins coalescer breather CV5061200 and crankcase depression regulator (CDR) valve 395587500, and Cummins 201350N precious metal diesel oxidation catalyst. ETV testing of this technology was conducted in January 10-12, 2007, at SwRI. All testing was performed in accordance with an approved test/QA plan that implements the requirements of the generic verification protocol at the test laboratory.

## **Availability of Report**

Copies of this verification report are available from:

- RTI International  
Engineering and Technology Unit  
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

Web site: <http://www.epa.gov/etv/verifications/verification-index.html> (pdf format)



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## Acronyms/Abbreviations

APCT Center	Air Pollution Control Technology Verification Center
ASTM	American Society for Testing and Materials
bhp	brake horsepower
bhp-hr	brake horsepower-hour
BSFC	brake-specific fuel consumption
C-B	carbon balance
CCV	closed crankcase ventilation
CDR	crankcase depression regulator
CFR	Code of Federal Regulations
cm	centimeter(s)
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
Cummins	Cummins Emission Solutions & Cummins Filtration
CVS	constant volume sampler
DOC	diesel oxidation catalyst
EPA	U.S. Environmental Protection Agency
ETV	environmental technology verification
FEL	family emission limits
ft	foot (feet)
FTP	Federal Test Procedure
g	gram(s)
HC	hydrocarbon(s)
HD	heavy duty
hp	horsepower
in.	inch(es)
kW	kilowatt(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
lb-ft	pound foot (feet)
m	meter(s)

mm	millimeter(s)
N	newton(s)
N-m	newton-meter
NO	nitric oxide
NO <sub>2</sub>	nitrogen dioxide
NO <sub>x</sub>	nitrogen oxides
OTAQ	Office of Transportation and Air Quality
Pa	pascal(s)
PDP	positive displacement pump
PM	particulate matter
ppm	parts per million by volume
QA	quality assurance
QC	quality control
rpm	revolutions per minute
RTI	RTI International
SOF	soluble organic fraction of the particulate matter
SOP	standard operating procedure
SwRI	Southwest Research Institute
ULSD	ultra-low sulfur diesel

## **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 Michael Kosusko, project manager, and Paul Groff, quality assurance manager, both of the U.S. Environmental Protection Agency's (EPA's) National Risk Management Research Laboratory in Research Triangle Park, NC. We would also like to acknowledge the assistance and participation of all Cummins Emission Solutions & Cummins Filtration personnel who supported the test effort.

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## Section 1.0 Introduction

This report reviews the performance of the 201350N precious metal diesel oxidation catalyst (DOC) and closed crankcase ventilation (CCV) system, consisting of the Cummins coalescer breather CV5061200 and crankcase depression regulator (CDR) valve 395587500, submitted for testing by Cummins Emission Solutions & Cummins Filtration (Cummins). Environmental technology verification (ETV) testing of this technology was conducted January 10-12, 2007, during a series of tests by Southwest Research Institute (SwRI), under contract with the Air Pollution Control Technology Verification Center (APCT Center). The APCT Center is operated by RTI International (RTI)<sup>†</sup> in partnership with the U.S. Environmental Protection Agency's (EPA) 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, 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*<sup>1</sup> was developed. This protocol was chosen as the best guide to verify the immediate performance effects of the Cummins DOC+CCV technology. 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 DOC+CCV technology installed. The specific test/quality assurance (QA) plan addendum for the ETV test of the technology submitted by Cummins was developed and approved in November 2006.<sup>2</sup> The goal of the test was to measure the emissions control performance of the DOC+CCV technology and its emissions reduction relative to an uncontrolled engine.

A description of the Cummins DOC+CCV technology is presented in Section 2. Section 3 documents the procedures and methods used for the test and the conditions under which the test was conducted. The results of the test are summarized and discussed in Section 4, and references are presented in Section 5.

This report contains only summary data and the verification statement. Complete documentation of the test results is provided in a separate test report<sup>3</sup> and audit of data quality report.<sup>4</sup> 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/QC activities and results, raw test data, and equipment calibration results are retained in SwRI's files for 7 years.

This verification report describes the performance of the tested technology on the diesel engine identified in Table 1, and applies only to the use of the 201350N DOC plus coalescer breather CV5061200 and CDR valve 395587500 on highway engines fueled only by ULSD (15 ppm or less) fuel.

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<sup>†</sup> RTI International is a trade name of Research Triangle Institute.

## **Section 2.0**

### **Product Description**

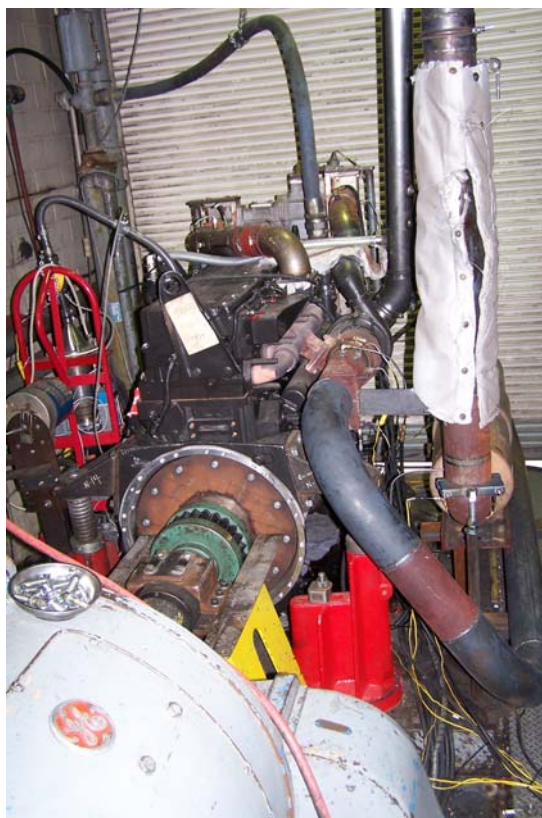
The Cummins DOC+CCV system, shown in Figure 1, consists of a DOC and coalescing filter. Emissions were quantified with separate degreened and aged DOC+CCV system components.

Each DOC+CCV system included a DOC, Cummins Part No. 201350N, manufactured by Johnson Matthey Inc., and a set of coalescing components to re-route the engine's crankcase ventilation. Installation of the CCV hardware prevents crankcase effluents from reaching the atmosphere. Prior to closing the crankcase, baseline tests quantified the engine's crankcase mass-rate particulate emissions or "blowby" in accordance with SwRI procedure 07-043<sup>5</sup>. The coalescing hardware is designed to capture blow-by mist, and route any gaseous remainder into the turbocharger air intake pipe. Two identical CCV coalescing filter housings and filter elements were provided as degreened and aged units, with one crankcase depression regulator (CDR) valve used in all DOC+CCV work. The components intended for degreening arrived clean and new. In contrast, the aged filter element and housing were notably seasoned with oil and arrived in a sealed plastic bag. Figure 2 shows the main components of the CCV system, the CDR valve (Part: 395587500) and filter housing (Part: CV5061200), with the coalescing filter element shown exposed for the photograph.

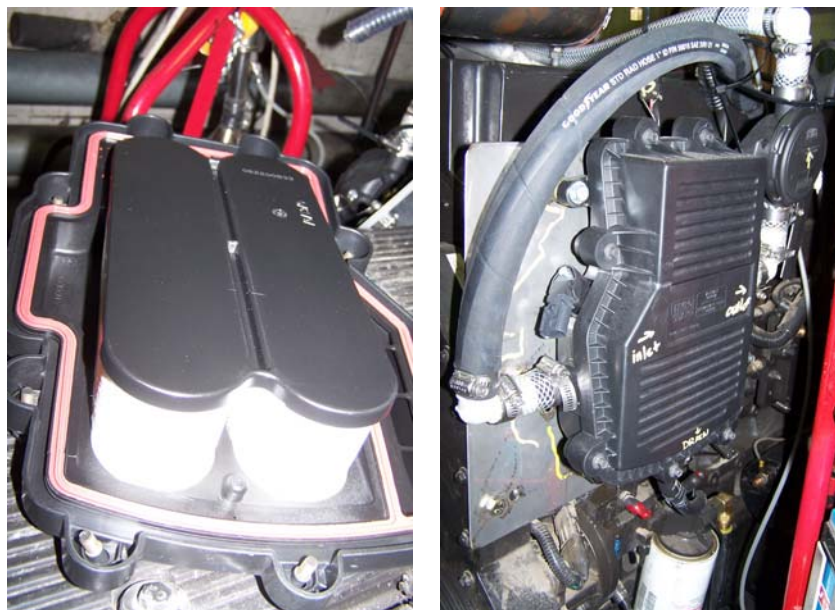
Cummins provided a new DOC to be degreened at SwRI prior to verification. This DOC's label showed serial number 306, EPA Sample 6, July 2006. The 25-hour degreening process included five repetitions of the two-step sequence consisting of 0.5 hours at the engine's no-load, low idle condition, followed by 4.5 hours at the declared peak torque speed, with a partial load applied to achieve a minimum DOC inlet temperature of 450 °C.

Cummins also provided an "aged" DOC unit that had seen 2700 hours of service on a 2003 Cummins ISM 330 ESP engine, installed on a Class 8 truck operated within a 200 mile radius of Oconomowoc, WI. The "aged" DOC was labeled with serial number 115, EPA Sample 7, April 2005.

The degreened and aged DOC units were identically sized, 45-inch long, cylindrical-shaped canisters, designed as mufflers weighing nominally 60 pounds. They had a 5-inch diameter flange at each opening, and the 11-inch DOC brick was located near the canister's midpoint. For evaluating emissions, each DOC in turn was mounted 150 inches downstream of the turbocharger, replacing the baseline exhaust spool-pipe.



**Figure 1. Engine shown in emissions test cell with Cummins DOC+CCV installed on engine.**



**Figure 2. Closed crankcase ventilation system components.**



## **Section 3.0**

### **Test Documentation**

The ETV testing took place during January 2007 at SwRI under contract to the APCT Center. Testing was performed in accordance with:

- *Generic Verification Protocol for Diesel Exhaust Catalysts, Particulate Filters, and Engine Modification Control Technologies for Highway and Nonroad Use Diesel Engines*<sup>1</sup>
- *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*<sup>6</sup>
- *Test-Specific Addendum to ETV Mobile Source Test/QA Plan for Cummins Emission Solutions & Cummins Filtration for the 201350N DOC + Coalescer Breather CV5061200 and CDR Valve 3958700*<sup>2</sup>

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

#### **3.1 Engine Description**

The ETV testing was performed on a six-cylinder, 10.8 liter, 2000 model year Cummins ISM350 highway heavy heavy-duty diesel engine (SN: 35010881) borrowed from EPA. The nameplate rating of this model engine is 260 kW (350 bhp) in “prime” power service at 2100 rpm. The test engine had about 215 hours of operation accumulated on it before arriving at SwRI.

Table 1 provides the engine identification details and Figure 3 shows the identification plates from the engine and its electronic control module.

#### **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.<sup>7</sup> 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 EM-5989-F.

**Table 1. Engine Identification Information**

Engine serial number	35010881
Date of manufacture	June 2000
Make	Cummins
Model year	2000
Model	ISM 350 ESP
Engine displacement and configuration	10.8 L, inline six-cylinder
Service class	Highway heavy heavy-duty diesel engine
EPA engine family identification	YCEXH0661MAH
Certification standards (g/hp-hr)	HC 1.30/CO 15.50/NO <sub>x</sub> 4.00/PM 0.100
Rated power (nameplate)	350 hp at 2100 rpm
Rated torque (calculated from nameplate power)	1350 lb-ft at 1200 rpm
Certified emission control system	Typical exhaust
Aspiration	Turbo-charged
Fuel system	Electronically controlled fuel injection



**Figure 3. Identification labels for 2000 Cummins ISM350 engine and its electronic control module.**

**Table 2. Selected Fuel Properties and Specifications**

Item	Code of Federal Regulations (CFR) Specification <sup>a</sup>		Test Fuel
	ASTM	Type 2D	EM-5989-F
Cetane number	D613	40–50	44.4
Cetane index	D976	40–50	n/a <sup>b</sup>
Distillation range:			
Initial boiling point, °C (°F)	D86	171–204 (340–400)	192 (377)
10% Point, °C (°F)	D86	204–238 (400–460)	214 (417)
50% Point, °C (°F)	D86	243–282 (470–540)	260 (500)
90% Point, °C (°F)	D86	293–332 (560–630)	311 (592)
End point, °C (°F)	D86	321–366 (610–690)	337 (638)
Gravity (American Petroleum Institute)	D287	32–37	35.2 <sup>c</sup>
Specific gravity	–	–	0.849 <sup>c</sup>
Total sulfur, ppm	D2622	7-15	10 <sup>d</sup>
Hydrocarbon composition:			
Aromatics (minimum), %	D5186	27 <sub>f</sub>	29.5 <sup>e</sup>
Paraffins, naphthenes, and olefins, %	D5186		70.5 <sup>e</sup>
Flash point (minimum), °C (°F)	D93	54 (130)	77 (170)
Viscosity, centistokes at 40 °C	D445	2.0–3.2	2.5

<sup>a</sup> 40 CFR 86.1313-2007(b)(2) for the year 2007 and beyond for heavy-duty diesel engines.

<sup>b</sup> n/a=not applicable

<sup>c</sup> Measured per ASTM D4052.

<sup>d</sup> Measured per ASTM D5453; this method is an acceptable substitute for ASTM D2622.

<sup>e</sup> Measured per ASTM D1319.

<sup>f</sup> Remainder of the hydrocarbons.

### 3.3 Summary of Emissions Measurement Procedures

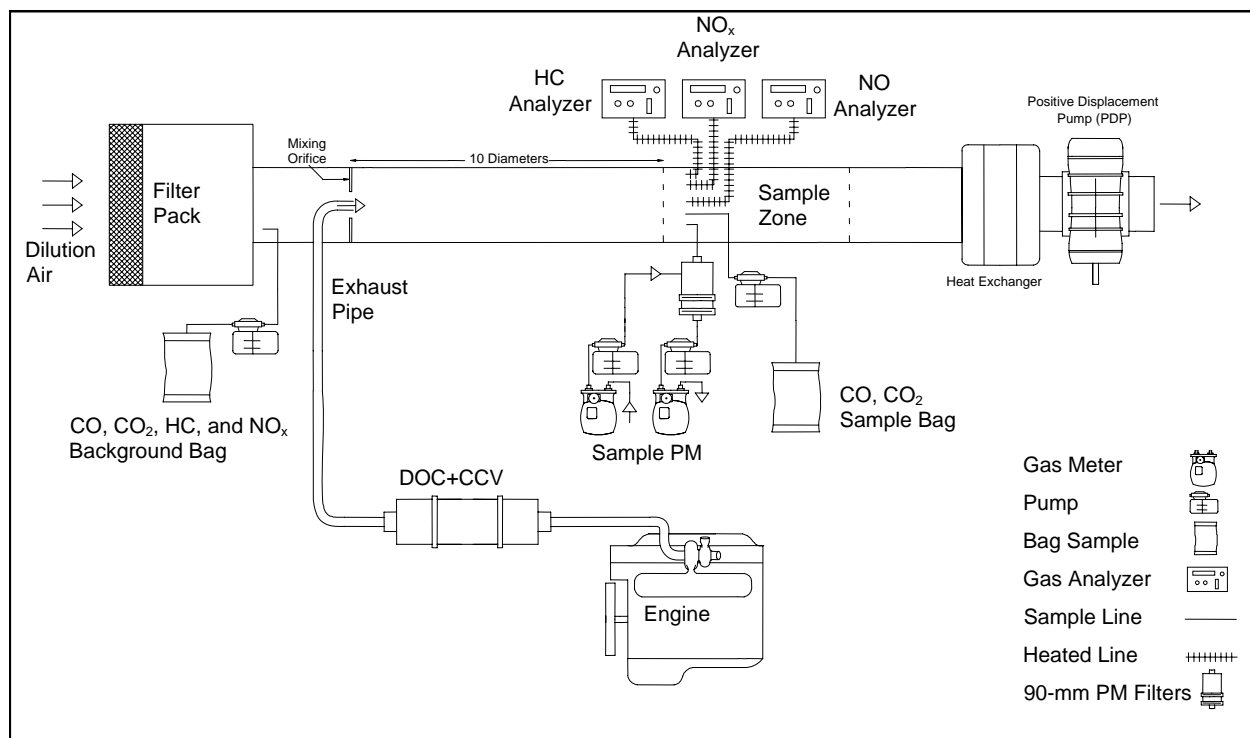
The ETV tests consisted of baseline uncontrolled tests and tests with the control technology installed. Engine operation and emissions sampling adhered to techniques developed by EPA in 40 CFR, Part 86, Subpart N.<sup>8</sup> Emissions were measured over multiple runs of the highway transient test cycle for the baseline, degreened DOC+CCV, and aged DOC+CCV exhaust configurations.

The statement of work called for one cold-start test and three hot-start tests for the baseline, degreened, and aged conditions. When running the first hot start test of the baseline engine, the NO<sub>x</sub> values were slightly depressed, suggesting a possible sensor problem that would invalidate the test. With the engine still in the test cell, SwRI chose to run a fourth hot-start test. After reviewing the data, there was no evidence of a sensor problem. All four hot-start tests were valid, and data from all four were used in calculating the emissions reductions. A fourth hot-start test was added to the degreened and aged conditions to keep the data sets uniform.

When the engine was configured in an open-loop configuration, the crankcase effluent was routed through a sample filter to allow the collection of the total crankcase particulate. When the engine was configured in a closed-loop configuration, the crankcase effluent was routed through

the coalescer filter before being directed into the intake of the engine. Baseline emissions included both open crankcase and tailpipe emissions. Control technology tests were conducted with a closed crankcase.

The Cummins ISM350 engine was operated in an engine dynamometer test cell, with exhaust sampled using full-flow dilution constant volume sampling (CVS) techniques to measure regulated emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and particulate matter (PM), plus nitric oxide (NO). The nitrogen dioxide (NO<sub>2</sub>) levels are expressed as the difference between measured NO<sub>x</sub> and NO levels for each run. 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.<sup>8</sup>



**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.<sup>9</sup> For 1998-2003 non-urban bus engines, the certification standards are defined in EPA's on-highway engine family box OH-10<sup>9</sup>. Furthermore, the Office of Transportation and Air Quality (OTAQ) assumes 5% reduction in PM emissions due to the use of ULSD fuel.

Therefore, the criteria established to indicate that the test engine was acceptable and that the 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<sub>x</sub>, and also could not

exceed 110% of [(OH-10)-5%], or (1.045 x OH-10) for PM. Table 3 presents the required emission performance of the test engine, as well as the certification standards and baseline results for comparison. Open crankcase emissions are included when calculating emissions reductions, but are not included when evaluating whether the engine meets the certification standards for verification testing to proceed.

**Table 3. Test Engine Baseline Emissions Requirement for 2000 Cummins ISM350**

	HC		CO		NOX		PM	
	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr	g/kWh	g/hp-hr
OH-10	1.74	1.30 <sup>a</sup>	20.79	15.50 <sup>a</sup>	5.36	4.00 <sup>a</sup>	0.130	0.100 <sup>a</sup>
Acceptance criteria	1.92	1.43	22.86	17.05	5.90	4.40	0.140	0.105
Baseline results	0.34	0.26	1.06	0.79	5.18	3.86	0.090	0.069

<sup>a</sup> Certification standards for EPA highway engine family box OH-10 for 1998-2003 non-urban bus engines.

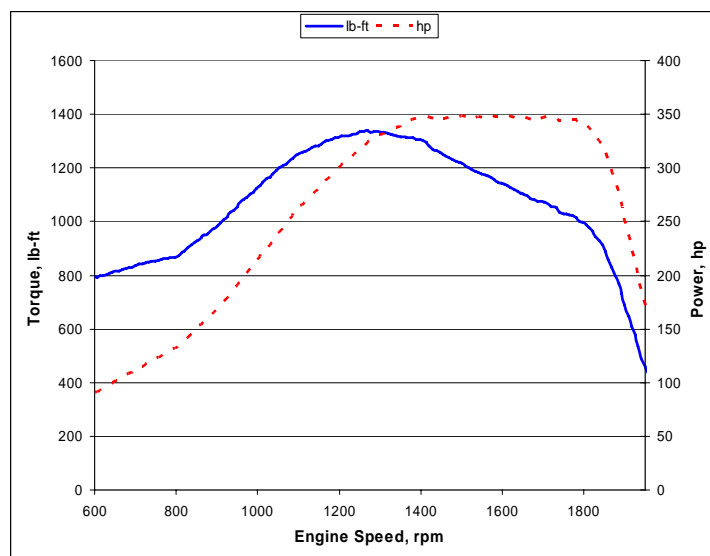
### 3.4 Deviations from the Test/QA Plan

There were no deviations from the test/QA plan. A minimum of three tests was specified in the test-specific addendum, but the applicant has the option of conducting additional tests to narrow the 95% confidence interval. As long as the data from all valid tests are used in calculating the emissions, the addition of a fourth hot-start test is not considered a deviation.

### 3.5 Documented Test Conditions

#### *Engine Performance*

Figure 5 shows torque map information measured on the 2000 Cummins ISM350 engine using the ULSD fuel.



**Figure 5. Torque map of 2000 Cummins ISM350 engine using ULSD fuel.**

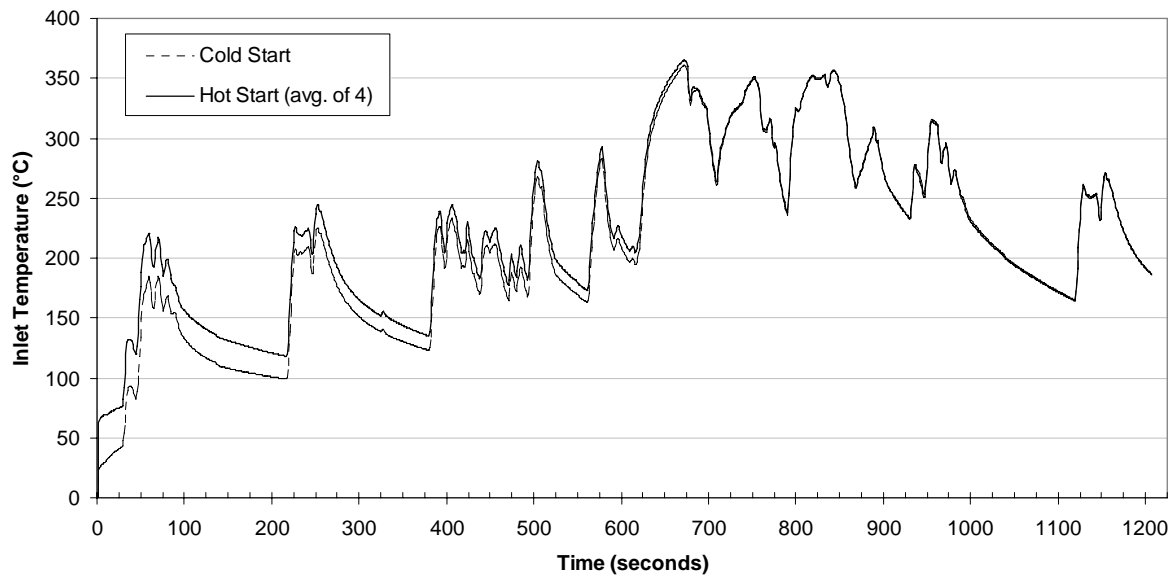
## Engine Exhaust Backpressure and Exhaust Temperature

The engine backpressure for the 2000 Cummins ISM350 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 backpressure observed during testing, reported in Table 4, did not exceed the manufacturer's specifications.

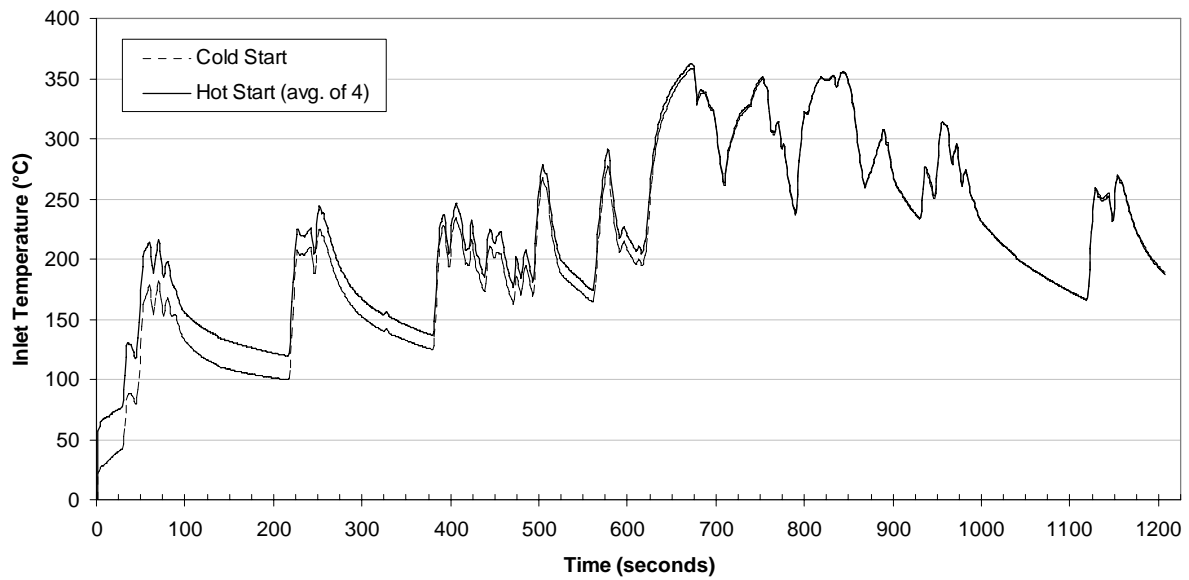
Temperature measurements were made in the exhaust system of the Cummins engine at the inlet and outlet of the DOC within 1 inch (2.54 cm) of the flange openings. Average inlet and outlet temperatures over the transient test cycle, shown in Table 4, were 427 °F (220 °C) and 444 °F (229 °C), respectively. 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 four hot-start tests.

**Table 4. Engine Exhaust Backpressure and DOC Inlet/Exhaust Temperature**

Test Number	Test Type	Test Date	Maximum Exhaust Backpressure		Average DOC Inlet Temperature		Average DOC Exhaust Temperature	
			kPa	in. Hg	°C	°F	°C	°F
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
B-881-C3	Cold Start	01/10/07	8.5	2.5	Not measured (no device in place)			
B-881-H1	Hot Start	01/10/07	8.5	2.5				
B-881-H2	Hot Start	01/10/07	8.5	2.5				
B-881-H3	Hot Start	01/10/07	8.5	2.5				
B-881-H4	Hot Start	01/10/07	8.5	2.5				
Average			8.5	2.5				
Degreened DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-6-C1	Cold Start	01/11/07	10.2	3.0	212.1	413.8	214.9	418.9
JM-6-H1	Hot Start	01/11/07	10.2	3.0	220.7	429.2	231.9	449.4
JM-6-H2	Hot Start	01/11/07	10.5	3.1	221.8	431.3	233.6	452.5
JM-6-H3	Hot Start	01/11/07	10.5	3.1	222.6	432.7	234.0	453.2
JM-6-H4	Hot Start	01/11/07	10.2	3.0	221.9	431.5	233.3	451.9
Average			10.2	3.0	219.8	427.7	229.5	445.2
Aged DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-7-C1	Cold Start	01/12/07	9.8	2.9	211.8	413.3	214.2	417.5
JM-7-H1	Hot Start	01/12/07	9.8	2.9	222.4	432.3	231.8	449.3
JM-7-H2	Hot Start	01/12/07	9.8	2.9	221.8	431.2	231.2	448.2
JM-7-H3	Hot Start	01/12/07	10.5	3.1	220.7	429.3	230.8	447.5
JM-7-H4	Hot Start	01/12/07	10.5	3.1	221.3	430.3	231.4	448.5
Average			10.2	3.0	219.6	427.3	227.9	442.2



**Figure 6. Inlet temperature profile of degreened DOC+CCV**



**Figure 7. Inlet temperature profile of aged DOC+CCV**

### ***Soluble Organic Fraction***

On each test, the particulate matter was tested for soluble organic fraction (SOF). Table 5 reports the results.

**Table 5. Particulate Characterization – Soluble Organic Fraction (SOF) from Each Test**

Test Description	Test Number	PM, g/hp-hr	SOF, % of PM
Baseline (Without DOC+CCV)	B-881-C3	1.69	39.6
	B-881-H1	1.89	30.2
	B-881-H2	1.98	27.3
	B-881-H3	1.97	29.6
	B-881-H4	1.98	33.0
With Degreened DOC+CCV	JM-6-C1	1.22	20.3
	JM-6-H1	1.29	20.1
	JM-6-H2	1.37	19.6
	JM-6-H3	1.36	17.0
	JM-6-H4	1.31	16.5
With Aged DOC+CCV	JM-7-C1	1.32	16.4
	JM-7-H1	1.34	13.3
	JM-7-H2	1.35	16.1
	JM-7-H3	1.33	13.5
	JM-7-H4	1.33	16.3



### Brake Specific Fuel Consumption

The fuel consumption was not measured directly during the engine testing. Rather, a calculated “carbon-balance” (C-B) fuel consumption rate was determined based on the measured exhaust flow rate and the carbon content (i.e., the CO and the CO<sub>2</sub>) in the exhaust gas analysis. The weighted BSFC calculations are similar to the weighted emissions calculations explained in Section 4.0. Table 6 shows the weighted BSFC calculations. Table 7 summarizes the results of these calculations and compares the fuel consumption during the baseline runs with that measured during the tests with the DOC+CCV units installed.

**Table 6. Brake-Specific Fuel Consumption (by Carbon Balance)**

Test Number	Test Type	Test Date	BSFC		Weighted BSFC	
			lb/bhp-hr	kg/kWh	lb/bhp-hr	kg/kWh
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine						
B-881-C3	Cold Start	1/10/2007	0.375	0.228		
B-881-H1	Hot Start	1/10/2007	0.360	0.219	0.362	0.220
B-881-H2	Hot Start	1/10/2007	0.358	0.218	0.361	0.219
B-881-H3	Hot Start	1/10/2007	0.358	0.218	0.360	0.219
B-881-H4	Hot Start	1/10/2007	0.358	0.218	0.360	0.219
Mean					0.361	0.219
Degreened DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine						
JM-6-C1	Cold Start	1/11/2007	0.372	0.226		
JM-6-H1	Hot Start	1/11/2007	0.354	0.215	0.356	0.217
JM-6-H2	Hot Start	1/11/2007	0.353	0.215	0.356	0.216
JM-6-H3	Hot Start	1/11/2007	0.355	0.216	0.357	0.217
JM-6-H4	Hot Start	1/11/2007	0.354	0.215	0.356	0.217
Mean					0.356	0.217
Aged DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine						
JM-7-C1	Cold Start	1/12/2007	0.369	0.224		
JM-7-H1	Hot Start	1/12/2007	0.356	0.216	0.358	0.218
JM-7-H2	Hot Start	1/12/2007	0.354	0.215	0.356	0.216
JM-7-H3	Hot Start	1/12/2007	0.354	0.215	0.356	0.217
JM-7-H4	Hot Start	1/12/2007	0.354	0.215	0.356	0.216
Mean					0.356	0.217

**Table 7. Summary of Fuel Consumption Reductions**

Device Type	Fuel	% Reduction	95% Confidence Limits
Degreened	ULSD	1.2	0.71 to 1.7
Aged	ULSD	1.2	0.63 to 1.8

## Section 4.0

### Summary and Discussion of Emission Results

Table 8 reports the emissions from the tests that were conducted: baseline, with a degreened DOC+CCV installed, and with an aged DOC+CCV installed. The concentration measurements were converted to units of total grams per test for all species. The “bhp from work” (the integrated measured power during each test period) values are also shown in these tables.

**Table 8. Emissions Data**

Test Number	Test Type	Blow-by PM	Exhaust PM	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>a</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>	Work
		g					%	g	g	kg	kWh (bhp-hr)
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine											
B-881-C3	Cold Start	0.126	1.563	112	104	7.79	6.94	5.24	23.8	13.2	18.4 (24.6)
B-881-H1	Hot Start	0.209	1.680	92.6	84.2	8.39	9.06	6.22	19.0	12.8	18.5 (24.8)
B-881-H2	Hot Start	0.219	1.759	92.6	83.9	8.67	9.36	6.49	18.6	12.6	18.4 (24.6)
B-881-H3	Hot Start	0.237	1.737	91.2	82.5	8.65	9.48	6.64	18.9	12.6	18.3 (24.6)
B-881-H4	Hot Start	0.233	1.750	92.1	83.3	8.76	9.51	6.73	18.7	12.6	18.3 (24.5)
Degreened DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine											
JM-6-C1	Cold Start	— <sup>b</sup>	1.224	106	86.5	19.6	18.5	1.35	10.2	13.0	18.2 (24.4)
JM-6-H1	Hot Start	— <sup>b</sup>	1.291	88.7	72.8	15.9	17.9	1.20	4.78	12.4	18.2 (24.4)
JM-6-H2	Hot Start	— <sup>b</sup>	1.365	88.8	73.8	15.0	16.9	1.18	4.63	12.4	18.2 (24.5)
JM-6-H3	Hot Start	— <sup>b</sup>	1.363	89.2	74.6	14.6	16.3	1.22	4.89	12.5	18.3 (24.5)
JM-6-H4	Hot Start	— <sup>b</sup>	1.312	89.8	75.7	14.1	15.7	1.26	4.73	12.4	18.2 (24.4)
Aged DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine											
JM-7-C1	Cold Start	— <sup>b</sup>	1.317	108	99.2	8.55	7.94	1.88	5.00	12.8	17.8 (24.2)
JM-7-H1	Hot Start	— <sup>b</sup>	1.338	90.6	85.0	5.60	6.19	1.86	8.24	12.4	17.9 (24.3)
JM-7-H2	Hot Start	— <sup>b</sup>	1.347	91.0	85.6	5.41	5.94	2.03	8.14	12.4	17.9 (24.4)
JM-7-H3	Hot Start	— <sup>b</sup>	1.325	91.2	85.8	5.41	5.94	2.23	8.05	12.5	18.0 (24.5)
JM-7-H4	Hot Start	— <sup>b</sup>	1.329	91.0	86.2	4.88	5.36	2.14	8.27	12.4	18.0 (24.4)

<sup>a</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.

<sup>b</sup> Blow-by PM routed through CCV.

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

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

where

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

These composite-weighted emissions rates are shown in Tables 9 and 10 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<sup>1</sup> and test/QA plan addendum.<sup>2</sup>

**Table 9. Composite Weighted Emission Rates (U.S. Common Units)**

Test Number	Total PM <sup>a</sup>	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>b</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
	g/bhp-hr				%	g/bhp-hr		
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
B-881-H1	0.075	3.85	3.52	0.336	8.71	0.246	0.794	519
B-881-H2	0.079	3.87	3.53	0.347	8.95	0.256	0.786	516
B-881-H3	0.079	3.83	3.48	0.347	9.05	0.262	0.798	516
B-881-H4	0.079	3.87	3.52	0.351	9.08	0.266	0.792	516
Degreened DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-6-H1	0.053	3.74	3.06	0.672	18.0	0.050	0.228	512
JM-6-H2	0.055	3.73	3.09	0.642	17.2	0.049	0.222	511
JM-6-H3	0.055	3.74	3.12	0.625	16.7	0.051	0.231	513
JM-6-H4	0.053	3.77	3.16	0.610	16.2	0.052	0.226	512
Aged DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-7-H1	0.055	3.83	3.58	0.248	6.48	0.077	0.320	514
JM-7-H2	0.055	3.84	3.60	0.241	6.27	0.083	0.316	511
JM-7-H3	0.054	3.83	3.59	0.240	6.26	0.089	0.312	512
JM-7-H4	0.054	3.83	3.61	0.222	5.79	0.086	0.320	511

<sup>a</sup> Total PM = Exhaust PM + Blow-by PM

<sup>b</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.

**Table 10. Composite Weighted Emission Rates (Metric Units)**

Test Number	Total PM <sup>a</sup>	NO <sub>x</sub>	NO	NO <sub>2</sub> <sup>b</sup>	NO <sub>2</sub> /NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
	g/kWh				%	g/kWh		
Baseline with ULSD Fuel on a 2000 Cummins ISM350 Engine								
B-881-H1	0.101	5.16	4.720	0.451	8.71	0.330	1.06	696
B-881-H2	0.106	5.19	4.734	0.465	8.95	0.343	1.05	692
B-881-H3	0.105	5.14	4.667	0.465	9.05	0.351	1.07	692
B-881-H4	0.106	5.19	4.720	0.471	9.08	0.357	1.06	692
Degreened DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-6-H1	0.070	5.02	4.104	0.901	18.0	0.067	0.306	687
JM-6-H2	0.074	5.00	4.144	0.861	17.2	0.066	0.298	685
JM-6-H3	0.074	5.02	4.184	0.838	16.7	0.068	0.310	688
JM-6-H4	0.071	5.06	4.238	0.818	16.2	0.070	0.303	687
Aged DOC+CCV with ULSD Fuel on a 2000 Cummins ISM350 Engine								
JM-7-H1	0.074	5.14	4.801	0.333	6.48	0.103	0.429	689
JM-7-H2	0.074	5.15	4.828	0.323	6.27	0.111	0.424	685
JM-7-H3	0.073	5.14	4.814	0.322	6.26	0.119	0.418	687
JM-7-H4	0.073	5.14	4.841	0.298	5.79	0.116	0.429	685

<sup>a</sup> Total PM = Exhaust PM + Blow-by PM<sup>b</sup> NO<sub>2</sub> calculated as NO<sub>x</sub> - NO.

The mean composite weighted emission rates from Tables 11 and 12 are the key values for the verification test. Table 13 summarizes that information. The first line shows the baseline engine results; the emissions in all categories are below the Table 3 threshold.

**Table 11. Summary of Verification Test Data (U.S. Common Units)**

Device Type	Fuel	Mean Composite Weighted Emission Value				
		Total PM <sup>a</sup>	NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
		g/bhp-hr				
Baseline	ULSD	0.078	3.86	0.257	0.793	517
Degreened	ULSD	0.054	3.75	0.0504	0.227	512
Aged	ULSD	0.055	3.83	0.0836	0.317	512

<sup>a</sup> Total PM = Exhaust PM + Blow-by PM**Table 12. Summary of Verification Test Data (Metric Units)**

Device Type	Fuel	Mean Composite Weighted Emission Value				
		Total PM <sup>a</sup>	NO <sub>x</sub>	HC	CO	CO <sub>2</sub>
		g/kWh				
Baseline	ULSD	0.104	5.17	0.345	1.06	693
Degreened	ULSD	0.072	5.02	0.0676	0.304	687
Aged	ULSD	0.073	5.14	0.112	0.425	687

<sup>a</sup> Total PM = Exhaust PM + Blow-by PM

Table 13 summarizes the emissions reductions that were achieved by the use of the DOC+CCV. These are the “verified emissions reductions” reported in Table 2 of the ETV Joint Verification Statement.

**Table 13. Summary of Verification Test Emission Reductions**

Device Type	Fuel	Mean Emissions Reduction (%)				95% Confidence Limits on the Emissions Reduction (%)			
		PM <sup>a</sup>	NO <sub>x</sub>	HC	CO	PM <sup>a</sup>	NO <sub>x</sub>	HC	CO
Degreened	ULSD	31	2.8	80	71	27 to 34	2.0 to 3.7	75 to 86	70 to 73
Aged	ULSD	30	0.68	68	60	26 to 34	– <sup>b</sup>	62 to 73	59 to 61

<sup>a</sup> PM = Exhaust PM + Blow-by PM

<sup>b</sup> The emission reduction cannot be distinguished from zero with 95% confidence.

## 4.1 Quality Assurance

The environmental technology verification of the DOC+CCV with ULSD fuel for heavy-duty highway diesel engines was performed in accordance with the generic verification protocol<sup>1</sup>, the test-specific addendum<sup>2</sup>, and the approved test/QA plan<sup>6</sup>. An audit of data quality included the review of equipment, personnel qualifications, 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 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. EPA and RTI QA staff conducted audits of SwRI’s technical and quality systems in April 2002 and found no deficiencies that would adversely impact the quality of results. The equipment was appropriate for the verification testing, and it was operating satisfactorily. SwRI’s technical staff was well qualified to perform the testing and conducted themselves in a professional manner.

## Section 5.0 References

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8. 40 CFR, Part 86 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines), Subpart N.
9. RTI International. 2003. *Generic Verification Protocol for Determination of Emissions Reductions from Selective Catalytic Reduction Control Technologies for Highway, Nonroad, and Stationary Use Diesel Engines*. Research Triangle Park, NC, September. Available: [http://www.epa.gov/etv/pdfs/vp/05\\_vp\\_emissions.pdf](http://www.epa.gov/etv/pdfs/vp/05_vp_emissions.pdf).
10. 40 CFR §86.091-11 (Protection of Environment: Control of Emissions from New and In-Use Highway Vehicles and Engines, Emission standards for 1991 and later model year diesel heavy-duty engines). Available: <http://www.epa.gov/epahome/cfr40.htm> (updated June 26, 2006).