New York State Energy Research and Development Authority

Evaluation of On-Board Real-Time Particulate Emissions Measurement Technologies

Final Report

May 2011

No. 11-25

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EVALUATION OF ON-BOARD REAL-TIME PARTICULATE EMISSIONS MEASUREMENT TECHNOLOGIES

Final Report

Prepared for the

NEW YORK STATE
ENERGY RESEARCH AND
DEVELOPMENT AUTHORITY

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Energy. Innovation. Solutions.

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
bhp	brake horsepower
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
CV	Coefficient of Variation
CVS	constant volume sampling
DOC	diesel oxidation catalyst
DOES2	Dynamic Dilution On/Off-Road Exhaust Emissions Sampling System
DPF	diesel particulate filter
DSNY	City of New York Department of Sanitation
EC/OC	elemental carbon/organic carbon
ECM	Electronic Control Module
ECS	Emission Control Systems
EPA	U.S. Environmental Protection Agency
ERMS	Environment Canada's Emissions Research and Measurement Section
EVC	Environment Canada
generic protocol	*Generic In-Use Test Protocol for Non-Road Equipment*
HDFTP	Heavy Duty Federal Test Procedure
LFE	laminar flow element
NO	nitric oxide
NOx	oxides of nitrogen
NYSERDA	New York State Energy Research and Development Authority
NYSDEC	New York State Department of Environmental Conservation
PAG	Project Advisory Group
PEMS	portable emissions measurement system
PM	particulate matter
QA	quality assurance
QA/QC	quality assurance and quality control
RH	relative humidity
rpm	revolutions per minute
SCFM	standard cubic feet per minute
SMPS	TSI Scanning Mobility Particle Sizer
Southern	Southern Research Institute
THC	total hydrocarbons
UC-R	University of California—Riverside
ULSD	Ultra Low Sulfur Diesel
WVU	West Virginia University

EXECUTIVE SUMMARY

INTRODUCTION

To evaluate the impacts of various types of emission control technologies, fuels, and operating strategies on PM emissions used in equipment in the mobile source sector, there is an urgent need to have viable, validated, accurate, portable, and cost effective measurement technologies to provide real-time PM emissions measurements while equipment is in-use. In-use PM measurement can help address several issues, including:

- The ability to verify PM emission reductions resulting from large scale implementation programs for diesel retrofits, engine repowers, and vehicle replacement, and to measure the impacts and effectiveness of these programs
- Verification of proper installation and actual effectiveness of control technologies implemented under tighter emission reduction regulations. This may include the development of compliance or inspection and maintenance programs that may be planned in conjunction with these and other regulations
- Efforts to develop more accurate emissions inventories to help guide State Implementation Programs, future regulations, implementation programs (such as diesel retrofits), research and development program development, and other actions.

This demonstration and evaluation effort identified portable emission monitoring systems (PEMS) that may be applicable to real-world, real-time measurement of PM emissions from diesel and other mobile emission sources, and subjected them to an independent evaluation program in both a controlled laboratory and in-use settings. The program consisted of the following primary activities:

- Reviewing the state of the art in PM PEMS technologies and the assessing the feasibility of implementing these technologies for in-use PM measurement primarily on diesel equipment and vehicles
- Testing and evaluating the feasible of PM PEMS technologies (including measurement and sampling systems together) on diesel engines in the laboratory under steady state and transient conditions in comparison to a standard reference method
- Testing and evaluating the feasible of PM PEMS technologies on diesel engines in the field under real-world in-use operating conditions and in comparison to a standard reference method; and
- Evaluating instrument installation requirements, practicality, reliability, and costs.

Table 3-1 summarizes specifications for the eight PM measurement instruments that participated in the evaluation program.

Table S-1. Specifications for Selected PM Measurement Instruments

Make/ Model	Detection Method	Sampling Method	Type of PM Measured	Applicable Particle Sizes	Sampling Rate	Reported Units
Artium LII-200	Laser-induced incandescence	Direct raw exhaust	Soot only	10—100 nm	20 Hz	Soot Mass Concentration (ppb)
AVL 483 Soot Sensor	Photo acoustic soot sensor	Direct sample of raw exhaust with proprietary probe	Soot only	Not specified	1 Hz	Soot Mass Concentration (mg/m^3)
Dekati DMM-230	Particle charging, inertial and electrical mobility classification	Dilution required	Full spectrum	0—1200 nm	1 Hz	Total PM Mass Concentration (mg/m^3)
Dekati ETaPS	Particle charging	Direct raw exhaust	Full spectrum	Not specified	Continuous; < 1 Hz	Volts
TSI DustTrak 8520	Laser photometry	Dilution required	Full spectrum	100—10,000 nm	1 Hz	Total PM Mass Concentration (mg/m^3)
TSI EAD 3070A	Corona charging and current detection	Dilution required	Full spectrum	10—1000 nm	3.75 Hz	Aerosol Diameter Concentration (mm/cm^3)
TSI EEPS 3090	Electrostatic charging and particle mobility sizing	Raw exhaust, diluter likely required	Full spectrum	5.6—560 nm	10 Hz	Particles/cm^3
Control Sistem Micro-PSS	Gravimetric—Filter Sample Weight	Direct Sample of raw exhaust with integrated partial flow dilution tunnel	Full spectrum	N/A	N/A	Total PM Mass

TEST PROCEDURES

Independent evaluation of measurement technologies in a controlled setting allows for the direct comparison of results from each technology to a reference method. Laboratory testing was completed at Environment Canada, using standard EPA reference test methods based on both 40 CFR 1065 and 40 CFR 86 requirements. Testing was completed on a Caterpillar C11 diesel engine equipped with a diesel particulate filter (DPF) at a variety of engine operating condition, including three steady state load conditions (10, 24, and 70 % of maximum load) as well as the heavy duty federal test procedure (HDFTP). In addition, the PM-PEMS and reference methods were used while sampling emissions at engine out, DPF-out, and at partially controlled emission condition achieved by blending engine out and DPF out exhaust streams for these engine loading conditions.

In-use testing was completed using an on-road diesel box van operated at Environment Canada. Environment Canada's DOES2 (dynamic dilution, on- and off-road, exhaust emissions sampling system), a field portable, 40 CFR 86 compliant, partial fltestow dilution sampling system served as the field reference method for gravimetric PM emissions sampling and measurement.

RESULTS

A summary of testing results is provided in Table S-2, with PEMS systems sorted according to their level of comparison vs. the reference standard (40 CFR 1065) in the laboratory evaluation. The instrument results are classified according to the following criteria:

Sorting Criteria	Indicator in Table S-2
< 25 % mean of differences vs. reference OR no statistically significant difference at 3 of 4 engine operating test conditions/cycles	░
25-50% mean of differences vs. reference	▒
>50% mean of differences vs. reference	▓

The summary table provides the mean of the differences for all test conditions or cycles (i.e., 10%, 24%, and 70% max power, HDFTP), and is defined as follows:

$$\Delta_{\text{mean},x} = \frac{\Delta_{10\%,x} + \Delta_{24\%,x} + \Delta_{70\%,x} + \Delta_{\text{FTP},x}}{4}$$

Where: x = exhaust test condition being evaluated (DPF-out, engine-out, or intermediate);

$\Delta_{10\%,x}$ = the difference between the PM-PEMS determined mass emission rate and the reference method determined mass emission rate at engine operating condition = 10% of maximum power at exhaust condition x.

It should be noted that Table S-2 provides a summary level view of performance in comparison to a specific reference, via averaging of the differences of the PM-PEMS and 1065 laboratory reference method at each operating condition into a single value. Analysis of performance of each instrument at each test condition was completed, including assessment of the statistical significance of any differences, which provides a more detailed insight into the performance of the systems.

As shown in Table S-2, several instruments performed reasonably well, in comparison with the 1065 reference at certain conditions. Nevertheless, aside from the Dekati DMM, no instrument performed well at all conditions and PM emission levels. In several instances, the performance of the instrument at a single test condition negatively affects the mean as reflected in the summary results above, such as the Dekati ETaPS and TSI EEPS, which performed poorly at one test condition (e.g. 70% max power) at the specified PM emissions level (e.g. DPF out or engine out), but generally well at others.

Table S-2. Summary of PM-PEMS comparison vs. 40 CFR 1065 Reference

	Mean Difference vs. Reference (40CFR 1065)		
PM-PEMS	**DPF Out**	**Intermediate PM**	**Engine Out**
Artium	90%	76%	78%
AVL	54%[a]	36%	42%
Dekati DMM	69%[a]	21%	41%[a]
Dekati ETAPS	106%	59%	77%[a,b]
Control Sistem	336%	26%[a]	18%
TSI Dustrak	191%	49%	60%
TSI EAD	86%	51%	62%
TSI EEPS	48%[a,b]	40%	55%

[a] Rating assigned based on statistical significance of differences vs. reference—3 of 4 test conditions indicated no statistically significant difference between PM-PEMS and reference (1065).

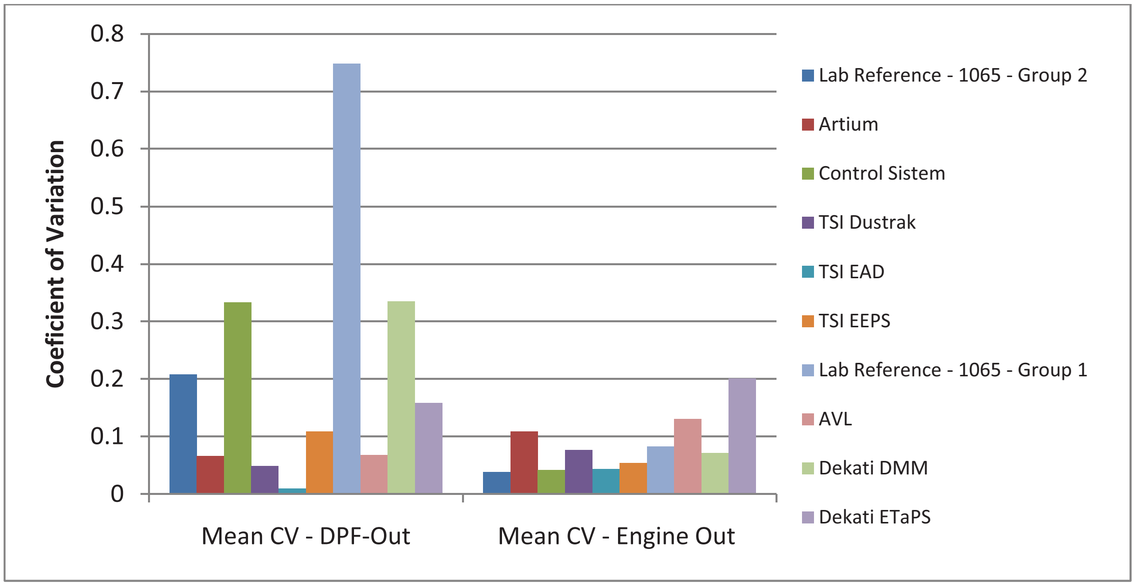
[b] High mean of differences primarily caused by a single test condition with large difference (>100%).

Additionally, comparisons of performance of the systems vs. reference elemental carbon measurements were performed. Several of the instruments are either designed to measure only soot, the elemental carbon fraction of the PM emissions, or were set up using heated sample conditioning systems to remove the organic PM fraction. Several instruments generally compared more favorably vs. the elemental carbon reference than the 1065 reference.

The repeatability of the PM-PEMS was also evaluated. The coefficient of variation (CV) was used as an indication of the repeatability of measurement over a series of repeated test runs. For each instrument, CV was compared vs. the 1065 reference method CV at each test condition. Overall, nearly all instruments had CVs that were comparable with the CVs of the reference method, or better. As shown in Figure S-1, CVs for the PM-PEMS measuring DPF-out PM emissions were significantly better than the 1065 reference. Note that Figure S-1 groups each PM-PEMS with laboratory reference results for the specific group with which it was tested. At engine out conditions, most CVs are comparable to the reference method. As a result, it is apparent that the repeatability of these instruments is excellent.

Because emission measurements were completed at both engine out and DPF out conditions, an assessment of the ability of the PM-PEMS to determine the PM emission reduction achieved by the DPF was also completed. PM emissions were reduced by over 90% based on the 1065 reference results. Nearly all instruments, except for the TSI EAD, measured an emissions reduction within 5% of the reference level.

Figure S-1. PM PEMS Mean CV Comparison



In-use evaluations of PM-PEMS systems showed similar results to the laboratory evaluations, with the exception of DPF out conditions. This is primarily due to the limitations of the reference test method used (portable 40 CFR 86)—which is at or near detection limits, and whose PM sample collection method affects the type and quantity of PM mass collected on the sample filter. As a result, PM-PEMS evaluations for in-use DPF out conditions should be used with caution, as should comparisons vs. PM-PEMS measuring soot only. The TSI Dustrak DRX results showed no statistically significant differences vs. the in-use reference method at both engine out and DPF out. The TSI EAD also showed no significant difference at DPF out conditions. All other PM-PEMS showed statistically significant differences vs. the references at all conditions during in-use testing.

Installation requirements, operator labor, data processing requirements, and short term (during testing only) reliability were documented and are discussed in the report. In general, all PM-PEMS had similar installation requirements, although the Control Sistem Micro-PSS required more effort to install and additional equipment (a continuous flow rate input signal) to operate. Generally, all PEMS worked very well, and required a relatively short time and minimum effort to properly set-up and operate . All instruments generally were reliable, with only a few minor instances requiring adjustments or loss of data. The Artium LII, however, was determined after the test to have a faulty calibration which potentially impacted its performance.

Finally, the PM-PEMS displayed a capability to provide second by second PM emission rates, with excellent comparison between PEMS, which can be useful in evaluation the impacts of transient operations on PM emissions, something not possible with filter based sampling and analysis.

CONCLUSIONS

Overall, the PM-PEMS evaluated here, more often than not, showed statistically significant differences vs. the reference methods used, an indication of poor correlation with the references. As a result, an overall recommendation may be to use the PM-PEMS with caution if selected as a direct replacement for 40 CFR 1065 emission testing procedures.

This test program does show that nearly all of the PM-PEMS evaluated, including the lower cost TSI Dustrak and Dekati ETaPS, can be successfully used in the evaluation of the performance of emission control devices, such as diesel particulate filters. The use of these PM-PEMS for relative emission comparisons is warranted.

Based on the test results the PEMS units demonstrated the ability to perform real-time measurement of PM emissions, and can provide additional PM emission information beyond total PM mass emissions. The ability of the instruments to measure particle size and particle number provides additional capability that traditional PM measurement methods (e.g. filter based sampling and gravimetric analysis) cannot.

It must be noted that the comparisons to a particulate emissions reference method are specific to that reference method and the setup of the PM-PEMS systems themselves. Such comparisons not only depend on the PM-PEMS performance, but on the selection of the reference method used. As evidenced by the test results for the two references used (40 CFR 1065 and 86), the PM mass emissions measured by the reference depend upon a variety of conditions, including but not limited to sampling temperature, face velocity, ambient or test cell conditions, and particulate makeup (elemental vs. organic carbon). In addition, the sampling systems used by the PEMS systems may be set up differently (e.g. the use of high temperature heated sample conditioning systems), influencing the results of any comparison.

Ultimately, the application of the PM-PEMS depends on the type of particulate information that is being sought and the reference measurement technique required, if one is specified. The PM-PEMS systems evaluated can be used for a variety of applications, but must be selected based on the information desired.

1.0 INTRODUCTION

Southern Research Institute (Southern) was contracted by the New York State Energy Research and Development Authority (NYSERDA) to implement a project to demonstrate and evaluate the performance of in-use particulate matter (PM) portable emission measurement systems (PEMS). The intent was to identify systems which may be applicable to real-world measurement of PM emissions from diesel and other mobile emission sources while operating in normal duty.

In the past few years, several PM measurement instrument vendors have developed unique technologies aimed at real-time and in-use PM measurement. These technologies use a variety of techniques to determine PM mass, particle size distribution, or particle number. Techniques used by these manufacturers include:

- Light scattering
- Laser induced incandescence
- Gravimetric microbalances
- Photoacoustic sensors
- Particle charging and flux measurement
- PM combustion and detection

Many of these technologies have not been independently evaluated and compared to reference standards in real-world applications beyond the laboratory. In many cases, these new instruments provide data outputs that may not be direct correlations to PM mass. Some of the instruments measure soot, some provide measurement of particle size and number, some measure mass directly, and some provide outputs of volts or amps, which can theoretically, be correlated with PM mass, size, or number. In addition, the costs, accuracy claims, portability, required sampling systems, ruggedness, power requirements, and other aspects of these technologies cover a very wide range. All of these technologies, however, may be feasible for in-use real-time measurements, but a lack of validated performance data prevents appropriate technologies from being selected and adapted widely.

Several recent studies have looked at real-time and on-board PM measurement technologies in comparison to reference methods. These include the *Evaluation of Portable Emissions Measurement Systems for Inventory Purposes and the Not-To-Exceed Heavy-Duty Diesel Engine Regulation* (University of California - Riverside CE-CERT, 2006) performed by the University of California—Riverside (UC-R) and the Coordinating Research Council's (CRC) E-66-3 project (Coordinating Research Council, Inc., 2006) and the U.S. Environmental Protection Agency (EPA) Measurement Allowance Program (U.S. Environmental Protection Agency, 2005). Previous studies typically focused on the performance of the PM analyzers, and did not focus on in-use measurement performance, including sampling systems. Both the UC-R and the CRC projects served as a significant resource for the feasibility analysis and test planning for this NYSERDA project. This project included several new technologies not previously evaluated and included sampling systems and in-field performance evaluations.

The program consisted of the following primary tasks:

- Review of the state of the art in PM PEMS technologies and the analysis of the feasibility of implementing these technologies for in-use PM measurement primarily on diesel equipment and vehicles
- Testing and evaluation of feasible PM PEMS technologies (including measurement and sampling systems together) on diesel engines in the laboratory under steady state and transient conditions for comparison to a standard reference method
- Testing and evaluation of feasible PM PEMS technologies on diesel engines in the field under real-world in-use operating conditions and comparison to a standard reference method
- Evaluation of instrument installation requirements, practicality, reliability, and costs.

1.1. PURPOSE

Particulate matter emissions from mobile sources contribute to air quality concerns and have been shown to have significant negative health effects resulting from particle inhalation. As concern over mobile source PM emissions has grown, several programs and regulations have been put into place by federal, state, and local authorities to:

- Quantify emissions of mobile source PM and other pollutants from the existing vehicle fleet and develop accurate emission inventories
- Develop, implement, and evaluate PM emission control strategies for new and existing engines
- Regulate the emissions of PM from new and existing engines; and
- Determine the health impacts of PM and the key constituents causing these impacts.

There are currently a number of efforts occurring throughout the nation aimed at reducing PM emissions from diesel and other engines. Rigorous studies have been performed using diesel engines in the laboratory on engine dynamometers. Information regarding diesel equipment duty cycles, and their impacts on engine emissions, however, is limited. This is noted by the lack of data regarding PM emissions from vehicles during their normal operation, the effectiveness of control devices in real duty cycles and applications, and the engine operating characteristics and duties that result in significant PM emissions. Without a validated, accurate, and cost effective means of evaluating real-time in-use PM emissions, regulators, program managers, and researchers have needed to:

- Rely on very small amounts of available real-world emission data;
- Develop and implement costly emissions testing programs; or
- Rely on certification level data based on integrated gravimetric PM filter data collected during controlled laboratory studies.

Although engines are certified at specific emission levels when new, the emissions from the engine while in-use may change drastically based on factors such as the actual duty cycle, age, engine maintenance status, control devices, operators, and other factors. These are typically observed only under real-world conditions. In addition, laboratory certifications of PM emissions are based on gravimetric analysis of diluted exhaust samples collected on filters over an integrated time frame. The gravimetric method does not allow for evaluation of transients and the impacts, emission levels, or characteristics of PM that occur at different points during transient operations. Also, to further enable study of PM emission characteristics and relations to health impacts, several real-time PM measurement technologies have the ability to determine PM size or number as an alternative to, or in addition to, PM mass emissions.

To evaluate the impacts of various types of equipment on PM emissions in the mobile source sector, there is an urgent need to have viable, validated, accurate, portable, and cost effective measurement technologies to provide real-time PM emissions measurements while equipment is in-use. In-use PM measurement can help address several issues, including:

- The ability to verify PM emission reductions resulting from large scale implementation programs for diesel retrofits, engine repowers, and vehicle replacement, and to measure the impacts and effectiveness of these programs
- Verification of proper installation and actual effectiveness of control technologies implemented under tighter emission reduction regulations. This may include the development of compliance or inspection and maintenance programs that may be planned in conjunction with these and other regulations
- Efforts to develop more accurate emissions inventories to help guide State Implementation Programs, future regulations, implementation programs (such as diesel retrofits), research and development program development, and other actions.

This demonstration and evaluation effort identified systems that may be applicable to real-world, real-time measurement of PM emissions from diesel and other mobile emission sources, and subjected them to an independent evaluation program in both a controlled laboratory and in an in-use settings.

1.2. PARTICIPANTS, ROLES, AND RESPONSIBILITIES

PM measurement technology vendors provided their instruments and technicians to set up and operate the equipment, to ensure that the technology was operating properly during testing. Southern staff served as an independent third party to collect, manage, and evaluate all performance data in conformance with acceptable quality assurance (QA) standards and approved test plans. A focused Project Advisory Group (PAG) was developed to guide the program and provide technical input, review, and approval. Participants on the project Advisory Group included participants from the following entities: Cummins, Ford, New York State Department of Environmental Conservation (NYSDEC), NYSERDA, California Air Resources Board (CARB), Environment Canada, West

Virginia University (WVU), University of California-Riverside, the U.S. EPA, and Caterpillar. Southern used Environment Canada's Emissions Research and Measurement Section (ERMS) to host and conduct the laboratory and field evaluations. Responsibilities of each participant included:

Southern Research Institute:

- Developed and documented the test strategy
- Coordinated the execution of all laboratory and field testing activities
- Procured a diesel engine and vehicle for laboratory and field evaluations (with Environment Canada)
- Collected data after each test from the operators of the PM PEMs instruments
- Evaluated, validated, and quality-assured data collected, i.e., data quality assurance and quality control (QA/QC)
- Analysis and reporting; and
- Project management, including managing the PAG.

Environment Canada:

- Hosted laboratory and field evaluations
- Facilitated the shipping and receiving of all test equipment
- Facilitated all laboratory and field testing activities, including,
    - Preparation and conditioning of the dilution tunnel and reference PM sampling systems
    - Diesel engine and vehicle procurement
    - Procurement of fuel for testing
    - Equipment installation assistance, and
    - Operation of the laboratory and field reference methods; as well as
- Correlation of the in-use reference method equipment with the laboratory reference method prior to field evaluations.

PM measurement technology vendors:

- Provided their PM measurement technology equipment, sampling system, and ancillary equipment, as necessary
- Provided technicians to set up and operate their equipment, as needed, to ensure that the technology is operating properly during testing
- Provided spreadsheet or algorithm used to process data and results into required units
- Provided the raw emission data files to Southern staff immediately following each test run
- Provided calculated PM mass emission results to Southern staff.

Figure 1-1 provides an organizational schematic.

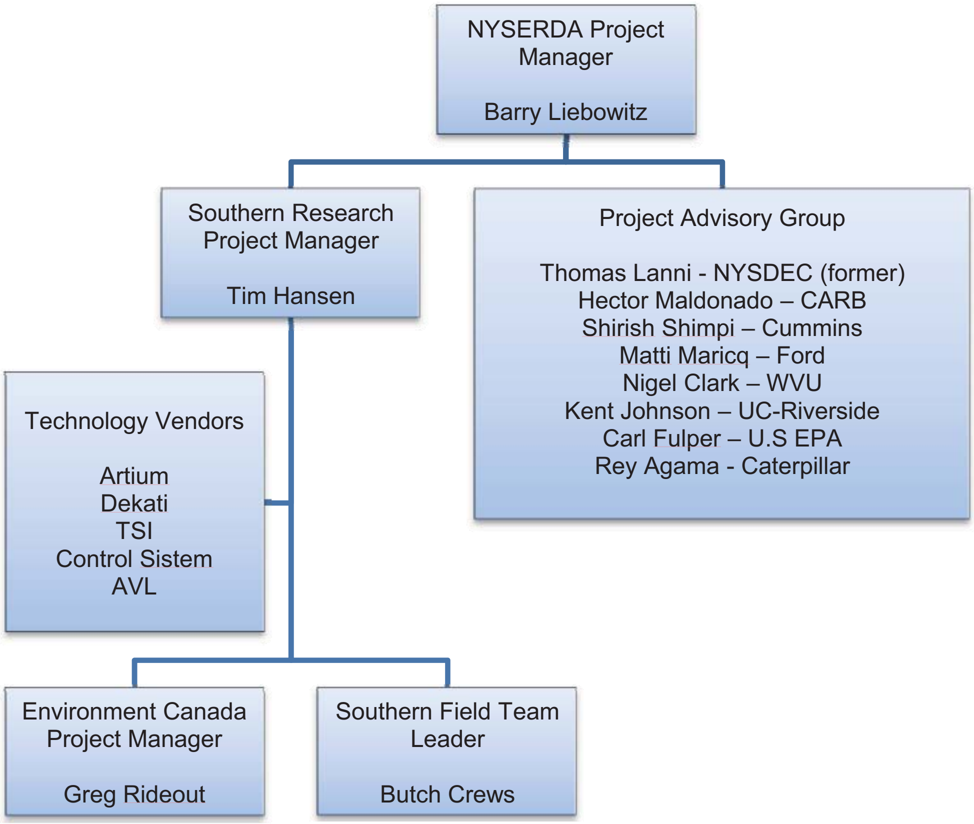


Figure 1-1. Project Organization

2.0 TECHNOLOGY EVALUATIONS

2.1. FEASIBILITY EVALUATION

2.1.1. Overview

Southern performed a systematic evaluation of the feasibility of these technologies to determine those that are most suitable for evaluation. The objectives of the feasibility study were to:

- Identify potential real-time and on-board PM measurement technologies currently available or in near-commercial stages, and obtain specifications for these technologies
- Evaluate the feasibility of these technologies in multiple in-use testing scenarios
- Select the most promising technologies for inclusion in the second major phase of the project: laboratory evaluations.

Southern performed literature reviews and contacted technology vendors, interested stakeholders, past program managers, and others to identify potential PM measurement technologies that are available or in a near commercial stage. Table 2-1 lists the PM measurement technology instruments that were evaluated in the feasibility analysis, as well as some basic specifications for each instrument.

Table 2-1. PM Measurement Technologies Evaluated in the Feasibility Study

Make/ Model	Detection Method	Sampling Method	Type of PM Measured	Applicable Particle Sizes	Sampling Rate	Accuracy or Repeatability
Artium LII-200	Laser-induced incandescence	Direct sample of raw exhaust into laser cell	Soot only	10—100 nm	20 Hz	± 5 % of reading
AVL 483 Micro Soot Sensor	Photoacoustic sensor	Direct sampling of raw exhaust with proprietary probe	Soot only	Not specified	100 Hz with < 1 s rise time	± 3 % in diluter ranges likely to be used in this test series
Cambustion DMS-50	Electrical mobility spectrometer	Raw exhaust through probe-mounted primary and secondary diluters	Full spectrum	5—560 nm	1 Hz	Size: ± 5 %; Number: ± 10 %
Cambustion DMS-500	Electrical mobility spectrometer	Raw exhaust through primary and secondary diluters	Full spectrum	5—2500 nm	1 Hz	Size: ± 5 % between 5—300 nm, ± 10 % above 300 nm; Number: ± 10 %
Clean Air Technologies CATI Montana	Laser light scattering (opacity)	Direct raw exhaust	Not specified	Not specified	1 Hz	Not specified

Make/ Model	Detection Method	Sampling Method	Type of PM Measured	Applicable Particle Sizes	Sampling Rate	Accuracy or Repeatability
Dekati DMM-230	Particle charging, inertial and electrical mobility classification	Dilution required	Full spectrum	0—1200 nm	1 Hz	Not specified
Dekati ETaPS	Particle charging	Full flow	Full spectrum	Not specified	Continuous; < 1 Hz	Not specified
Horiba Mexa 1000SPCS	Condensation particle counter	Diluter likely required	Full spectrum	Not specified	10 Hz	Not specified
Horiba Mexa 1370PM	Furnace pyrolysis and gas analysis of dilution tunnel-collected standard quartz particulate filters	Dilution tunnel (either portable or laboratory) required	Full spectrum	Likely 10—2500 nm	n/a—integrated sample	Not specified
Matter Engineering LQ 1-DC	Corona charging and current measurement	Very high dilution required; ≈ 5,000: 1	Full spectrum	Not specified	0.3333 (1 sample / 3 seconds)	± 15 % of reading
Sensors PPMD	Incremental weight gain causes frequency change of quartz-crystal microbalance	Full-flow raw exhaust with integral diluter	Full spectrum	≈ 10—2500 nm	1 Hz	Not specified
Thermo Scientific TEOM 1105	Gravimetric filter	Diluter likely required	Full spectrum	Not specified	< 1 Hz	Not specified
TSI DustTrak 8520	Laser photometry	Diluter likely required	Full spectrum	100—10,000 nm	1 Hz	Not specified
TSI EAD 3070A	Corona charging and current detection	Diluter required	Full spectrum	10—1000 nm	3.75 Hz	Not specified
TSI EEPS 3090	Electrostatic charging and particle mobility sizing	Raw exhaust, diluter likely required	Full spectrum	5.6—560 nm	10 Hz	Not specified
TSI SMPS 3936, 3080	Scanning mobility particle sizer with spectrometer	Raw exhaust, diluter likely required	Full spectrum	10—1000 nm	0.033 (1 sample/ 30 seconds)	Not specified

2.1.2. Technology Feasibility Evaluation Criteria

In order to evaluate the feasibility of each technology for laboratory and field testing, Southern identified rating criteria that technologies should meet to ensure their ability to function in field applications and provide accurate data. Each of the criteria was then assigned an associated weighting factor. The criteria were developed based on the goals of the NYSERDA project, and include:

- analytes
- stated performance capabilities
- operating requirements
- calibration and maintenance

- size
- complexity
- power requirements
- data outputs and acquisition
- cost

For inclusion in this test program, candidate PM PEMS instruments must be commercially available or in near-commercial stages, and must meet the following requirements for portability:

- To be small, lightweight, and easy to install
- To work with a low power consumption so that tests of at least three hours can be run either with a small generator or a set of batteries
- To measure or calculate the real-time mass of PM in the engine exhaust.

These requirements are based on those set forth in the European Union's *Portable Emission Measurement Systems (PEMS) Heavy-Duty Pilot Programme Final Project Plan 2007-2008* (European Union, 2007).

Table 2-2 provides the individual criteria and ranges for each. Past testing experience, the realities of field work, existing test data, and the potential spectrum of participating monitors formed the basis for each criterion range. Reviewers from Southern used the following procedure for ranking the monitoring technologies:

- enter background information, equipment lists, and other data in the appropriate table cells
- review the range for each criterion with respect to the PM measurement technology specifications and enter the appropriate ranking
- calculate the appropriate weighted ranking for each criterion based on the provided weighting factors; and
- develop an overall instrument rating by summing the weighted ranks.

Low scores imply that the monitor should be assigned a high priority for testing.

The primary intent of the multiplier, or weighting factor, is to quantify the relative importance of each criterion. For example, sample rates greater than once per second have a large multiplier because near real-time sampling rates (once per second or faster) are an essential project requirement.

The weighting factors also allow for varying the emphasis between the 0, 1, and 2 base ranks. For example, PM particle sizes of interest for diesel engines are generally between 10 and 1500 nanometers. A measurement technology capable of responding to all PM in this size range would receive a "0" ranking. Technologies with narrower ranges or those that sense larger sizes are generally intended for laboratory research, product development, or screening applications. These technologies would receive a "1" ranking. A larger multiplier emphasizes the difference between the two rankings.

2.2. FEASIBILITY ANALYSIS RESULTS

Table 2-3 summarizes the particulate measurement technology rankings, sorted in order of priority for testing. Lower scores indicate a higher priority for testing.

Southern, with input from NYSERDA and the project advisory group, selected ten of the instruments evaluated in Table 2-3 for testing in laboratory conditions, as indicated by the shaded instruments. Eight instruments were originally recommended. However, due to instrument and staff availability, vendor interest, funding availability, and other issues, only six agreed to participate in the feasibility evaluation (shaded in green). In addition, with additional space availability, additional instruments that were included in the feasibility analysis—the TSI EAD and Control Sistem MicroPSS—were included in the test program after the original selections had been made.

Table 2-2. PM Measurement Technology Feasibility Rating Criteria

Manufacturer:			Model:			
Detection method:						
Analyte and sampling method criteria						
Description	**Rank Definitions**			**Base Rank**	**Multiplier**	**Final Rank**
	0	**1**	**2**			
Sample rate, r (1 Hz = 1 sample / sec; 0.1 Hz = 1 sample / 10 sec) Note: Monitor response time must be fast enough to support the sample rate	1 Hz ≤ r	1 Hz < r ≤ 0.1 Hz	0.1 Hz < r (integrated and other non-real-time samplers) 5			
Applicable particle sizes	10—1500 nm, inclusive (example: 5—2500 nm)	narrower size range (example: 5.6—560 nm; 100—10000 nm)	not specified or measured as some other parameter (example: 0—2000 μ^2 / cm^3 active surface area) 2			
Type of PM measured	full spectrum (semi-volatiles, sulfates, EC, OC, etc.)	restricted species (soot only, etc.)			5	
Mass concentration method	direct measure	cumulative, derived, or calculated	not measured or surrogate		5	
Available mass concentration span (expected value for non-road diesel engines ≈ 100 mg/m^3)	0—100 mg/m^3	narrower range with diluter or other accessory to allow span at least 0—100 mg/m^3	outside 0—100 mg/m^3 range, not measured, or surrogate 4			
Accuracy or repeatability	± 5 % of reading or better	between ± 5 % and 10 % of reading	> ± 10 % of reading or not specified 2			
Detection limit	< 1 mg/m^3 or < 1 % of span	1—5 mg/m^3 or 1—5 % of span	> 5 mg/m^3 or > 5 % of span		2	
Number		direct measure	not measured		1	
Size distributions		direct measure	not measured		1	
				Subtotal		

Table 2-2, continued. PM Measurement Technology Feasibility Rating Criteria

Manufacturer:			Model:			
Physical size, installation, ancillary equipment criteria						
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:						
Describe all onboard reagents, gases, filters, consumables, etc.:						
Rank Definitions:	**0**	**1**	**2**	**Base Rank**	**Multiplier**	**Final Rank**
Number of modules, probes, support equipment required (not including sample lines)	1-2^{a} (example: probe, main module)	3^{b} (example: probe, denuder, main module)	> 3^{c} (example: probe, stack-mounted diluter, main module, dilution / sheath air unit, power supply) 3			
Main module volume, v	v 1 ft^{3,a}	1 ft^{3} v 2 ft^{3,b}	2 ft^{3} < v^{c}		4	
Largest support module volume, v	v 1 ft^{3,a}	1 ft^{3} v 2 ft^{3,b}	2 ft^{3} < v^{c}		4	
System total weight	20 lb	20—60 lb^{a}	≥ 60 lb^{b,c} 3			
Req'd support brackets, braces for in-use tests	0—1	2	> 2		4	
Sampling method	direct, raw exhaust sampling through probe and heated sample line	requires proprietary probe, diluter or sample conditioner, denuder, specialty sample lines, etc.	full flow or other method NOTE: Rank as 0 if full flow adaptor properly fits the exhaust pipe on the equipment to be tested 2			
Vibration sensitivity	none	some	not specified		2	
Power supply voltage	12 VDC	24 VDC, 110 VAC			3	
Power supply current	< ≈ 20 A @ 12 VDC or onboard power is sufficient	20—60 A @ 12 VDC or auxiliary battery power required	≥ 60 A @ 12 VDC or temporarily mounted auxiliary generator required 3			
^{a}recommended for "small" in-use, laboratory engine, or larger ^{b}recommended for "medium" in-use, laboratory engine, or larger ^{c}recommended for "large" in-use, laboratory engine				**Subtotal**		
Operations and maintenance criteria						
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	> 12 h	2.5—12 h or operator monitoring required (such as pollutant concentration dependent)	2.5 h 2			
Calibration operations	automated	operator intervention required			3	
Level of operator intervention required for calibrations, cleaning, maintenance	none	minor (example: filter change accessible from outside the monitor enclosure)	major (example: access to inside of enclosure required for sample pump cleaning) 3			
Operator's training time	< 2 h	2—8 h	> 8 h		2	
				Subtotal		

Table 2-2, concluded. PM Measurement Technology Feasibility Rating Criteria

Manufacturer:			Model:			
Data processing and acquisition						
Rank Definitions:	**0**	**1**	**2**	**Base Rank**	**Multiplier**	**Final Rank**
Data acquisition	onboard data acquisition	external PC required	Analog outputs only; external data logger required 5			
Output files	onboard mass concentration calculations with full data stream (including supporting parameters, calibration logging, time stamps, etc.	onboard mass concentration calculations and output available (analog or digital) with limited supporting data	External mass concentration calculations or post-processing required; requires correlation with 5 other data sources (such as dynamometer CVS studies)			
				Subtotal		
Cost						
Cost	< $25,000	$25,000—$100,000	> $100,000		1	

Table 2-3. Summary of Particulate Measurement Technology Rankings

Manufacturer	Model	Analysis and sampling methods	Physical size, installation, ancillary equipment	Operations and maintenance	Data processing, output, and acquisition	Cost	Grand total	Applicability	
								Lab	Field
TSI	DustTrak 8520	15	15	13	10	0	53	Y	Y
Cambustion	DMS-50	17	27	13	10	1	68	Y	Y
Artium	LII-200	14	38	10	5	2	69	Y	Y
Dekati	ETaPS	22	17	10	20	0	69	Y	Y
Sensors	PPMD	17	19	16	15	2	69	Y	Y
Clean Air Technologies	CATI Montana	37	9	16	10	0	72	Y	Y
TSI	EEPS 3090	17	41	10	5	1	74	Y	Y
AVL	483 Soot Sensor	17	37	15	5	1	75	Y	Y
Cambustion	DMS-500	15	40	16	5	2	78	Y	
Dekati	DMM-230	18	39	15	5	1	78	Y	Y
TSI	EAD 3070A	37	29	11	15	1	93	Y	Y
Horiba	Mexa 1370PM	18	56	20	0	2	96	Y	
Thermo Scientific	TEOM 1105	17	47	18	15	2	99	Y	
Horiba	Mexa 1000SPCS	25	40	20	15	2	102	Y	
TSI	SMPS 3936, 3080	36	44	18	15	2	115	Y	
Matter Engineering	LQ 1-DC	47	32	18	20	0	117	Y	
Control Sistem	MicroPSS	NA	NA	NA	NA	NA	NA	Y	Y
Selected but did not participate in test program									
Selected and participated in test program									
Not originally selected—participated in test program									
NOTE: low scores indicate a higher priority for testing									

3.0 TEST PROGRAM DESIGN

3.1. INTRODUCTION

The testing program was designed to provide an independent assessment of the performance of the selected PM PEMS compared to standard references in both a controlled environment in the laboratory and in a real-world, in-use application. In addition, information regarding system installation and operation was documented. The program was designed to evaluate the entire PM-PEMS system, as it would be deployed for use in on-board testing. Therefore, in both laboratory and in-use testing, the systems were required to be standalone systems, with some minor exceptions.

Figure 3-1 summarizes the PM and gaseous emission measurement instrument comparisons that took place in the laboratory and field evaluations.

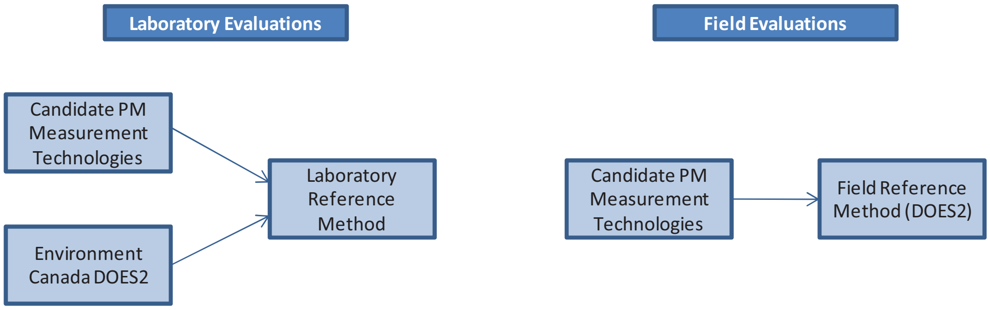


Figure 3-1. PM and Gaseous Emission Measurement Instrument Comparisons to Reference Methods

Figure 3-2 shows a general test activity schematic. The sections that follow describe the participating PM measurement technologies, the engine and vehicle selected for testing, the test procedures for the laboratory and field evaluations, the emission measurement instruments listed in Table 2-3, and the data collection and analysis procedures.

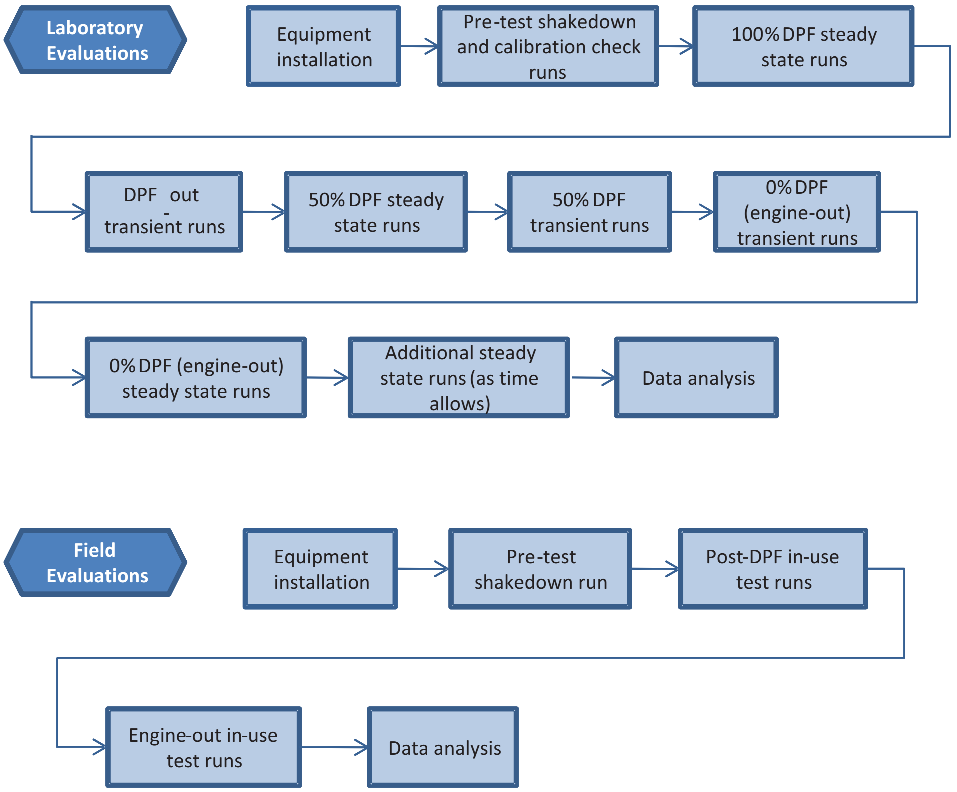


Figure 3-2. Schematic of Test Activities

Table 3-1 summarizes specifications for the eight PM measurement instruments that participated in the evaluation program.

Table 3-1. Specifications for Selected PM Measurement Instruments

Make/ Model	Detection Method	Sampling Method	Type of PM Measured	Applicable Particle Sizes	Sampling Rate	Reported Units
Artium LII-200	Laser-induced incandescence	Direct raw exhaust	Soot only	10—100 nm	20 Hz	Soot Mass Concentration (ppb)
AVL 483 Soot Sensor	Photo acoustic soot sensor	Direct sample of raw exhaust with proprietary probe	Soot only	Not specified	1 Hz	Soot Mass Concentration (mg/m^3)
Dekati DMM-230	Particle charging, inertial and electrical mobility classification	Dilution required	Full spectrum	0—1200 nm	1 Hz	Total PM Mass Concentration (mg/m^3)
Dekati ETaPS	Particle charging	Direct raw exhaust	Full spectrum	Not specified	Continuous; < 1 Hz	Volts
TSI DustTrak 8520	Laser photometry	Dilution required	Full spectrum	100—10,000 nm	1 Hz	Total PM Mass Concentration (mg/m^3)

Make/ Model	Detection Method	Sampling Method	Type of PM Measured	Applicable Particle Sizes	Sampling Rate	Reported Units
TSI EAD 3070A	Corona charging and current detection	Dilution required	Full spectrum	10—1000 nm	3.75 Hz	Aerosol Diameter Concentration (mm/cm^3)
TSI EEPS 3090	Electrostatic charging and particle mobility sizing	Raw exhaust, diluter likely required	Full spectrum	5.6—560 nm	10 Hz	Particles/cm^3
Control Sistem Micro-PSS	Gravimetric Filter Sample Weight	Direct Sample of raw exhaust with integrated partial flow dilution tunnel	Full spectrum	N/A	N/A	Total PM Mass

3.2. LAB TESTING

3.2.1. Objectives

Independent evaluation of measurement technologies in a controlled setting allows for the direct comparison of results from each technology to a reference method. Laboratory testing allows for careful control of all parameters in repeatable test sequences, such that data can be directly compared from one test to the next. The laboratory evaluation ensures that the instrument performance, from an accuracy, repeatability, and precision standpoint, can be established with a certain degree of confidence that may not be available in field evaluations due to the inherent variability in the field.

3.2.2. Test Groups

Due to physical space limitations and potential impacts of many instruments sampling simultaneously, testing was completed in two groups at two separate times. The test groups were organized as follows.

Test Group ID	Lab Testing Dates	Participating Instruments
Group 1	06/11/08—06/16/08	AVL Microsoot Sensor 483 Dekati ETaPS Dekati DMM-230
Group 2	07/23/08—07/30/08	Artium LII-200 TSI EAD 3070A TSI EEPS 3090 TSI Dustrak DRX 8533 Control Sistem Micro-PSS

3.2.3. Test Engine and Vehicle

Laboratory evaluations used a 2004 Caterpillar C11on-road diesel engine equipped with a diesel particulate filter (DPF). This engine was selected because it is a commonly used engine and it has the highest engine-out PM emission rate of the engines available in ERMS's fleet. Specifications for the C11 test engine are shown in Table 3-2. The test engine label is shown in Figure 3-3.

Table 3-2. Specifications for the Laboratory Test Engine

<table>
<tr><td>Make</td><td colspan="3">Caterpillar</td></tr>
<tr><td>Model</td><td colspan="3">C11</td></tr>
<tr><td>Model Year</td><td colspan="3">2004</td></tr>
<tr><td>Serial No.</td><td colspan="3">KCA018109</td></tr>
<tr><td>Throttle Control</td><td colspan="3">Electronic</td></tr>
<tr><td>Number of Cylinders</td><td colspan="3">Inline 6</td></tr>
<tr><td>Displacement</td><td colspan="3">11.1 liter</td></tr>
<tr><td>Maximum Power (EPA Certification)</td><td colspan="3">400 brake horsepower (bhp) @ 1800 revolutions per minute (rpm)</td></tr>
<tr><td>Control</td><td colspan="3">Electronic ACERT</td></tr>
<tr><td>Engine-Out Exhaust Pipe Diameter</td><td colspan="3">5"</td></tr>
<tr><td>Current Engine Hours</td><td colspan="3">~ 350</td></tr>
<tr><td>PM Emissions Certification Level</td><td colspan="3">2004 compliant with a required diesel oxidation catalyst (DOC)</td></tr>
<tr><td>Emissions Parameter:</td><td>EPA Certification Levels (g/bhp-hr)</td><td colspan="2">EPA Emission Standard (g/bhp-hr)</td></tr>
<tr><td>PM grams per brake horse power hour</td><td>0.094</td><td colspan="2">0.1</td></tr>
<tr><td>CO grams per brake horse power hour</td><td>1.6</td><td colspan="2">15.5</td></tr>
<tr><td>NOx grams per brake horse power hour</td><td>2.3</td><td>2.5</td><td rowspan="2">2.4
(combined)</td></tr>
<tr><td>NMHC grams per brake horse power hour</td><td>0.1</td><td>0.5</td></tr>
</table>

Figure 3-3. Test Engine Label

CAT® CATERPILLAR INC. IMPORTANT ENGINE INFORMATION / AVIS IMPORTANT 2004 KCA01809

ENGINE MODEL: C11 - DISPLACEMENT: 11.1 L - VALVE LASH: 0.38 mm INT. 0.64 mm EXH. VARIABLE VALVE ACTUATOR (V V A) 0.61mm INT.

MODELE MOTEUR: C11 -CYL.: 11.1 L - JEU SOUPAPES: ADM. 0.38 mm ECHAP. 0.64 mm MÉCANISME DE COMMANDE DE SOUPAPE VARIABLE (V V A) 0.61 mm INT.

ENGINE FAMILY FAMILY DE MOTEURS	MAX. ADV. kW (HP) kW (HP) MAXI PUBLIES	MAX. RATED SPEED (RPM) MAXI. REGIME NOMINAL tr/mn	MAXI. LOW IDLE SPEED (RPM) MAXI. REGIME RALENTI tr/mn	FUEL RATE MAX kW (mm³ /STROKE) DEBIT D'INJ. A PUIS. MAXI (mm³/STROKE) (PISTON)	MAX. INITIAL TIMING DEG. BTDC MAXI. CALAGE INITIAL D'INJ. (DEGRES) (AVANT PMH)	EXHAUST EMISSION CONT. SYS. DISPOSITIF ANTI-POLLUANT
4CPXH0680EBK	287 (385)	1800	600	239	ELECTRONIC	EM,DI,TC,ECM,CAC,CAT

THIS C11 ENGINE CONFORMS TO U.S. EPA AND CALIFORNIA REGULATIONS APPLICABLE TO 2004 MODEL YEAR NEW HEAVY DUTY DIESEL ENGINES AND HAS A PRIMARY INTENDED SERVICE APPLICATION AS A HEAVY HEAVY-DUTY ENGINE. THIS ENGINE IS NOT CERTIFIED FOR USE IN AN URBAN BUS AS DEFINED AT 40 CFR 86.093-2. SALE OF THIS ENGINE FOR USE IN AN URBAN BUS IS A VIOLATION OF FEDERAL LAW UNDER THE CLEAN AIR ACT. THIS ENGINE IS CERTIFIED TO OPERATE ON DIESEL FUEL.

Ce moteur diesel C11 essentiellement destiné à des applications de Service trés-lourdes, est conforme aux réglementations de l'Agence américaine de protection de l'environnement (EPA) et de Californie valables pour nouveaux moteurs diesel lourds construits en 2004. Ce moteur n'est pas homologué pour les bus des transports publics urbains tels que définis à l'art 40 CFR 86.093-2. La vente de ce moteur pour motoriser des bus des transports publics urbains constitue une violation de la Loi fédérale sur la propreté de l'air (Clean Air Act). Ce moteur est certifiée pour fonctionner avec le carburant diesel.

DATE OF MANUFACTURE MONTH / DE FABRICATION-MOIS: 04

7E-8050 02

CAT®

SER. NO. KCA01809 ENGINE MODEL C11
CERT NO.
MAX ALT 3048 M 10000 FT
MODIFICATION NO.
AR NO.
ECM SOFTWARE 251-5727
CORE AR 229-2631
PERF SPEC 0K-5956
DEM NO.
FLS (INTERCEPT) 12
FTS (SLOPE) -8
ADV 305 HP 227.5 kW MAX HP kW
USE SERVICE TOOL TO VERIFY CURRENT ENGINE SETTINGS 115-5852 2

3.2.4. Historical Engine Test Data

The 2004 Caterpillar C11 Engine has been used in various studies previously at the Environment Canada facility. Results of previous studies are useful in evaluating expected engine performance and emissions, and variability of engine emissions. A brief summary of engine emissions, for different time periods and different exhaust configurations is provided in Appendix A. A statistical review of the particulate emission variance is also provided in the table. All tests were completed using the same test procedures—the Heavy Duty Diesel Federal Test Procedure (HD-FTP), with sampling and analysis in accordance with 40 CFR part 86 test methods (U.S. Environmental Protection Agency, 2003).

3.2.5. Emission Control Technology

For the Caterpillar C11 engine used in the lab studies, in addition to the engine-out condition, exhaust was also routed through a commercially available Engine Control Systems (ECS) Purifilter diesel particulate filter (DPF).

This filter is a catalyzed DPF with a precious metal catalyst on a silicon carbide filter block. It is passively regenerated primarily via oxygen oxidation, requiring exhaust temperature in the 280-350°C range.

3.2.6. Test Fuel

The test fuel used for all laboratory testing was Ultra Low Sulfur Diesel (ULSD) which met American Society for Testing and Materials (ASTM) D975 standards. A single fuel batch was used during each group of tests to eliminate potential impacts of test fuel on engine performance and emissions.

3.2.7. Intermediate Particulate Loading

In order to determine the performance of the PM PEMS systems across a broad range of PM emission levels that may be encountered, testing was planned for an intermediate particulate emission level, near the midpoint between engine-out emissions and DPF-out. To achieve intermediate levels of PM emissions, ERMS installed a DPF bypass system (see Figure 3-4) that allowed a proportion of the engine exhaust to enter the DPF and a portion to bypass the DPF. Targets for achieving the intermediate emission level were to set the bypass such that approximately 50% of the exhaust went through the DPF.

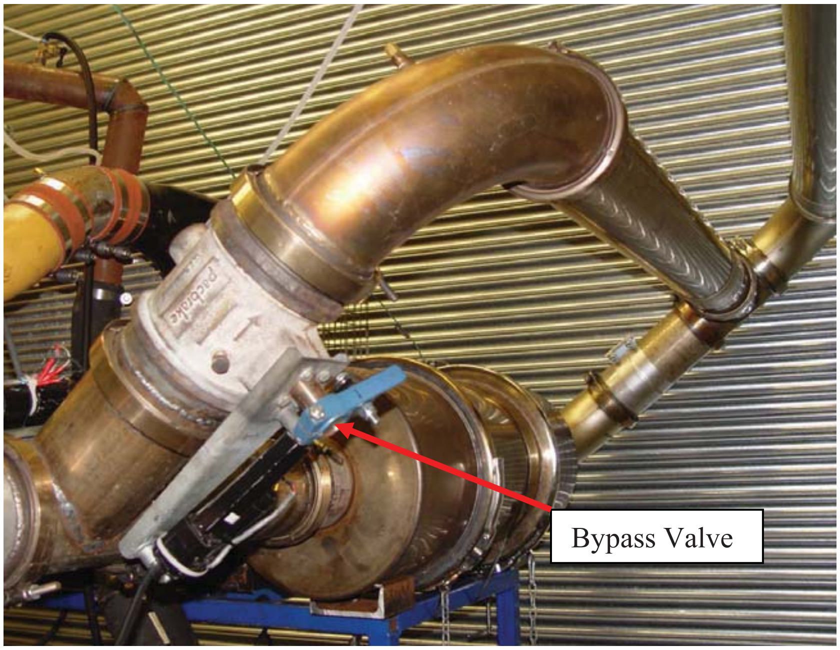


Figure 3-4. DPF Bypass Configuration

The bypass valve was installed directly after the exhaust Y-transition from the turbo. Both the bypass valve and an engine backpressure control valve were controlled by electronic servos from the engine test cell control room. ERMS used the backpressure valve to regulate the engines exhaust backpressure to manufacturer’s specifications during testing without emission control technologies. To determine the appropriate valve settings, pressure and carbon monoxide emission measurements were performed at the 100% DPF level with the regulating valves in the open position and then at the 0% DPF level with the backpressure controlled to meet manufacturer specifications. Pressure and CO measurements were taken at both conditions.

When setting the bypass valve for the intermediate PM emission levels, the backpressure valve was adjusted to create approximately the same backpressure as the 100% DPF level while adjusting the bypass so that the CO emissions would read half of the observed values between the 100% and 0% DPF measured concentration. Because the exhaust backpressure adjustment and the bypass adjustment are dependent on each other, there were some control issues with the bypass valve, and the exact setting of the bypass was somewhat variable between each test condition to meet backpressure requirements.

3.2.8. Test Procedures

3.2.8.1. Tunnel cleaning

Prior to testing, the engine exhaust transfer system was removed from the engine test cell to undergo a thorough cleaning. The transfer system was hand scrubbed and rinsed with a high pressure cleaning system to remove trace deposits of particles before the beginning of each instrument test phase. The transfer tube was then thoroughly dried and inspected before reinstallation occurred. After reassembly, the system was preconditioned by performing a series of transient and steady-state cycles. During the system preconditioning second-by-second particle concentrations were monitored by Environment Canada’s Scanning Mobility Particle Sizer (SMPS), when particulate levels remained consistent from run to run, manufacturers were allowed to setup their PM PEMs systems.

3.2.8.2. Shakedown

The test matrix included operation of the test engine for a brief period for PM PEMS instrument shakedowns prior to the start of testing. The shakedown tests allowed for vendors to check instrument general operation and allowed for corrections of dilution flow and other instrument parameters required during normal test setup. For the shakedown run, the test engine was operated at 24% of the engine’s rated power and at the intermediate PM loading condition for a short period of time (approximately five minutes). Two to three repeats of engine operation were allowed during the shakedowns.

3.2.8.3. Calibration Run

A calibration check test run was also completed to make certain reasonable data is being collected by PM-PEMS instrumentation. The calibration check test run was performed at 24% of the test engine’s rated power and at DPF-out, intermediate PM loading, and engine out conditions. Each condition was held for approximately 10 minutes. Environment Canada collected PM filters during the calibration check run and made the filter data available to vendors approximately two days after the calibration check was run, or about half way through the test program.

Vendors were then allowed to make any necessary corrections to their instrument configuration to ensure accuracy of measurements, if desired. No vendors requested the calibration run data nor made any modifications to their operation based on the data.

3.2.8.4. Instrument Installation & Setup

Once the laboratory engine setup was completed, technology vendors were allowed to begin installation of their PM PEMS. Vendors were allowed to set up instruments outside of the test cell with sample lines run from the test cell to the instruments, such that when test cell doors were closed, instrumentation could be monitored safely outside the cell. Sample lines were installed by vendors based on individual system specifications, but were primarily heated sample lines with maximum lengths of approximately five meters.

For each group of test instruments, discussions were held with all participants prior to establishing sampling locations to ensure that interferences from sample probes or other instruments on sampling systems or instruments further downstream would be minimized. Vendor representatives approved their final sampling locations in the exhaust sampling line and proceeded with installation. Environment Canada staff provided assistance with the installation of required sampling ports and fittings on the exhaust line. All sample locations were located a minimum of 10 exhaust line diameters from any disturbances (such as elbows).

All instrumentation setup and installation requirements were observed and logged by Southern staff. A log sheet of the requirements was completed for each installation and reviewed and approved by each technology vendor to ensure accuracy. Observations of instrument specifications, additional sensors, sampling systems, brackets, hangers, cables, consumables (i.e. compressed air), power consumption, and other requirements were documented. In addition, the estimated physical installation time was monitored and documented. Any changes made to the installation throughout the test program were also documented.

3.2.8.5. Test Modes and Cycles

Laboratory evaluations were performed under two conditions: steady state and transient. Steady state evaluations were completed at a series of three loads and three PM emissions conditions.

Environment Canada performed preliminary testing to determine the optimal engine conditions for PM evaluations. Environment Canada expressed concerns of venturi overheating during tests at 100% rated power. As such, 100% full rated power testing was not performed. Instead, steady state tests were performed at 1200 rpm and 10% rated power; 1800 rpm (max rated speed) and 24% rated power; and 1800 rpm and 70% rated power. Each of these load/speed combinations were repeated at three different PM emission levels: DPF-out; Intermediate Level; Engine-Out. In addition, the Heavy Duty Federal Test Procedure was run at each PM emission level. Table 3-3 summarizes the laboratory test matrix.

Table 3-3. Laboratory Test Matrix

Engine Condition	DPF-Out	Intermediate PM Loading	Engine Out
1200 RPM @ 10% Rated Power	X	X	X
1800 RPM @ 24% Rated Power	X	X	X
1800 RPM @ 70% Rated Power	X	X	X
HDFTP	X	X	X

3.2.8.6. Instrument and Sampling Locations

For laboratory evaluations, due to the number of participants and limited space, two groups of tests were performed. The analyzers, sampling systems (i.e. pumps, dilution systems, etc.) and control systems (computers and dataloggers) were primarily located outside of the test cell during all test runs. Technology vendors used sample lines running from the sampling point inside the cell to the analyzer outside of the cell. The primary exception to this was for TSI, which used a single rotating disc diluter to provide sample to three instruments—the EAD, EEPS, and Dustrak. TSI located its instruments within the test cell, but was able to monitor and control (start/stop) the instruments remotely. An example of the instrument setup and location is shown in Figure 3-5.

Figure 3-5. Lab Instrument Setup (left—inside test cell, right outside test cell)

3.2.8.7. Laboratory PM Emissions Reference Standard

Particulate emission data provided by the candidate PM measurement technologies were evaluated and compared to the laboratory reference method. The reference standards used for comparison of the measurement instruments were gravimetric filter-based particulate measurements performed by ERMS. These filter measurements were collected using two different EPA test methods—one that complies with 40 CFR Part 86 test procedures, and a sampling system that complies with 40 CFR Part 1065 test methods. A SMPS was also used during testing to provide additional data regarding particle size, etc. Finally, fired quartz filters were collected and analyzed for elemental and organic carbon fractions (EC/OC). For Environment Canada's 40 CFR Part 1065-compliant testing, the PM collection temperatures were maintained at 48 degrees +/- 5 degree Celsius, and a filter face velocity below 100 cm/second was maintained. The filter handling and weighing area is temperature and humidity controlled and has a HEPA-filtered supply air for the area. Specifications for the reference method test equipment are provided in Table 3-4.

Table 3-4. Laboratory Reference Test Instrumentation Specifications

	Parameter	Sensor Mfg	Model	Logging Frequency	Accuracy	Repeatability
Laboratory Reference Method	CO	Horiba	AIA-210 LE	1 Hz	2% of point or 1% of full scale	1% of point
	CO_2	Horiba	OPE-115			
	NOx	California Analytical Instruments	400-HCLD			
	NO	California Analytical Instruments	400-HCLD			
	THC	California Analytical Instruments	300M-HFID			
	PM filter weight	Sartorius	M5P-000V001	n/a[a]		
	Gravimetric PM filters	70 mm Emfab TX40HI20-WW (86) & 47 mm Teflon membrane (1065)		n/a	n/a	n/a
	EC/OC filters	47 mm fired Quartz—Pall Tissuquartz 2500QAT-UP plus 47 mm Teflon membrane		n/a	n/a	n/a

3.2.8.8. Additional Data Collected

The engine's exhaust flow rate was characterized by ERMS'Ss laboratory reference method via a laminar flow element (LFE). ERMS also installed a portion of their Sensors Semtech PEMS for engine data collection. Engine parameters that were logged are listed in Table 3-5.

Table 3-5. Electronic Control Module (ECM) Parameters Logged in Laboratory Evaluations

ECM Parameter	Units
Vehicle Speed	mph
Throttle Position	%
Engine Load	%
Engine Torque	lb-ft
Oil Pressure	kPa
Boost Pressure	kPa
Intake Manifold Temperature	deg F
Barometric Pressure	kPa
Engine Coolant Temperature	deg F
Oil Temperature	deg F
Fuel Rate	gal/s
Fuel Economy	mpg
Engine Speed	rpm

Engine power output, as brake horsepower (BHP), and fuel consumption were logged by ERMS during completion of all laboratory testing so that emissions could be reported in units of grams/bhp-hr and grams/gallon. Fuel consumption was calculated based on a carbon balance equation.

3.2.8.9. Lab Test Procedure Summary

A summary of the step by step lab test procedures, including pre-test efforts is provided in Table 3-6.

Table 3-6. Laboratory Evaluation Test Procedures

1	PM measurement technology vendors (or designated personnel) will deliver their spreadsheets or algorithms for calculating the final reported results to Southern staff.
2	PM measurement technology vendors (or designated personnel) will install their candidate technologies at a sampling location downstream of the DPF bypass. Southern will document installation procedures and setup conditions. The candidate systems will be installed so that they do not interfere with one another's operation.
3	ERMS staff will install and operate the DOES2 system during one test group for correlation to the laboratory reference method prior to the field study phase.
4	Synchronize all candidate technology and other instrument clocks to the laboratory reference method time.
5	Perform a short shake down steady state cycle for instrument setup and flow checks and calibration.
6	Perform a calibration check of steady state cycles for the PM instrument to verify the collection of reasonable data.
7	Perform DPF-out steady state test runs at designated engine conditions (10%, 24%, 70% max power). There will be three test runs at each engine condition. • Prior to each test run, there will be an approximately 10 minute warm-up period while ERMS staff brings the engine to a steady state load condition. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • Between each test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. • During the 20 minute soak period between test runs, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**
8	Perform the Heavy-Duty FTP transient test runs at DPF-out. There will be three transient test runs performed. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • After each transient test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. • During the 20 minute soak period after each test run, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**
9	Perform intermediate PM Loading steady state test runs at designated engine conditions (10%, 24%, 70% max power). There will be three test runs at each engine condition. • Prior to each test run, there will be an approximately 10 minute warm-up period while ERMS staff brings the engine to a steady load. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • Between each test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. • During the 20 minute soak period between test runs, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**

10	Perform the Heavy-Duty FTP transient test runs at intermediate PM Loading. There will be three transient test runs performed. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • After each transient test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. • During the 20 minute soak period after each test run, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**
11	Perform the Heavy-Duty FTP transient test runs at engine-out. There will be three transient test runs performed. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • After each transient test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. • During the 20 minute soak period after each test run, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**
12	Perform engine-out steady state test runs at designated engine conditions (10%, 24%, 70% max power). There will be three test runs at each engine condition. • Prior to each test run, there will be an approximately 10 minute warm-up period while ERMS staff brings the engine to a steady load. • Begin laboratory reference method, candidate technology, and ECM logging. When applicable, also begin DOES2 logging. • Between each test run there will be an approximately 20 minute soak period while ERMS staff change the laboratory reference method PM filter. During the 20 minute soak period between test runs, **candidate technology vendors must provide Southern staff with all raw data files for archiving.**
13	Perform any required makeup tests (replacements for invalid test runs) or perform additional steady state tests at each bypass condition (0%, 50%, and 100%) for the following engine condition: 1800 rpm and 70% rated power.
14	End of test group. PM measurement technology vendors (or designated personnel) will un-install their candidate technologies.

3.2.8.10. Recorded Parameters

Table 3-7 summarizes the parameters that were recorded during all laboratory evaluations.

Table 3-7. Summary of Parameters Recorded in the Laboratory Evaluations

Parameter	Measurement Instrument	Data Collected By	Logging Frequency	Units
PM	Laboratory Reference Method	ERMS	Integrated filter	mg
	Candidate Technologies	Technology Vendors	1 Hz, if available	Varies
EC/OC	NIOSH or similar method	ERMS	Integrated filter	mg/cm^2
CO	Laboratory Reference Method	ERMS	1 Hz	ppm
CO_2	Laboratory Reference Method	ERMS	1 Hz	%
NOx	Laboratory Reference Method	ERMS	1 Hz	ppm
THC	Laboratory Reference Method	ERMS	1 Hz	
Bhp	Laboratory Reference Method	ERMS	1 Hz	HP
	ECM, if available	ERMS	1 Hz	%

Parameter	Measurement Instrument	Data Collected By	Logging Frequency	Units
Fuel consumption	Laboratory Reference Method MicroMotion Coriolis Flow Meter	ERMS	1 Hz	Liters
	ECM, if available	ERMS	1 Hz	Unknown
Dilution tunnel flow rate	Laboratory Reference Method	ERMS	1 Hz	scfm
Engine intake air flow rate	Laboratory Reference Method	ERMS	1 Hz	
Engine rpm	Laboratory Reference Method	ERMS	1 Hz	rpm
Engine exhaust temperature	Laboratory Reference Method	ERMS	1 Hz	degrees C
Engine Intake Ambient air temperature	Laboratory Reference Method	ERMS	1 Hz	
Ambient relative humidity	Laboratory Reference Method	ERMS	1 Hz	%
Barometric pressure	Laboratory Reference Method	ERMS	1 Hz	mm Hg

3.2.8.11. Laboratory Data Analysis

ERMS staff and candidate technology vendors were responsible for analyzing raw data from their instruments, but were required to provide Southern raw data after each test run and all spreadsheets and calculations for data quality and validation purposes. Data was provided by all participants as total PM (TPM) emissions per test run in the following units:

- grams/second
- grams/gallon
- grams/bhp-hr

To enable the above calculations, Southern provided all vendors with the following data, collected by Environment Canada:

- Engine exhaust temperature (logged at 1 Hz)
- Intake air flow for each test run (logged at 1 Hz)
- Dilution tunnel flow for each test run (logged at 1 Hz)
- Engine horsepower for each test run (logged at 1 Hz)
- ECM fuel consumption (logged at 1 Hz)

Southern then evaluated the performance of the candidate PM measurement technologies using the following data analyses or criteria:

- Comparison of PM measurement technology results (in units of PM mass) to the laboratory reference methods (both 86 and 1065 methods) for steady state, transient, and in-use test runs, at each test condition:
    - the percent difference and 95 percent confidence interval between the mean PM mass emission rate for each candidate technology's test runs and the mean PM mass emission rate for the reference method test runs
- Comparison of the DPF filtration efficiency as measured by the candidate technologies vs. the reference standard
- Comparison of PM Measurement technology results vs. EC/OC data
- Qualitative comparison of real time PM measurement data vs. engine operating parameters.

Southern characterized the candidate technology stability and reliability by analyzing the PM mass drift from test run to test run for each technology, and by logging candidate instrument failures during the test campaign. Southern also logged candidate technology installation, setup, and operating requirements in both lab and field settings in order to characterize field portability.

3.3. FIELD EVALUATION OF TECHNOLOGIES

3.3.1. Objectives

For the field evaluations, the candidate technologies were installed on an on-road diesel box van operated at Environment Canada. Due to space limitations, three to four candidate technologies were installed at a time and testing completed in the same groups as for the laboratory testing. Each candidate technology sampled raw exhaust with its own sampling system, if necessary. Environment Canada's DOES2 (dynamic dilution, on- and off-road, exhaust emissions sampling system), a field portable, 40 CFR 86 compliant, partial flow dilution sampling system served as the field reference method for gravimetric PM emissions sampling and measurement.

Field evaluation procedures and details were based on the Generic In-Use Test Protocol for Non-Road Equipment (generic protocol) (Southern Research Institute, 2007) (http://www.nyserda.org/publications/Generic%20Protocol_Final.pdf) developed by Southern for NYSERDA. The protocol describes overall testing concepts for a consistent in-use testing approach for on- and non-road equipment performing actual work.

The objectives of the field evaluations are to:

- Evaluate the performance of on-board real-time PM measurement technologies on diesel engines when compared to a standard reference method in an on-board, real-world field testing environment
- Evaluate the field installation requirements (power, physical space, etc.) for the PM measurement technologies and the ability to use them in real-world conditions.

3.3.2. Test Groups

Due to physical space limitations and potential impacts of many instruments sampling simultaneously, testing was completed in two groups at two separate times. The test groups were organized as follows.

Table 3-8. In-Use Testing Groups

Instrument	Test Group	In-Use Testing Dates
Artium LII-200	1	08/11/08—08/14/08
TSI DustTrak 8520	1	08/11/08—08/14/08
TSI EAD 3070A	1	08/11/08—08/14/08
TSI EEPS 3090	1	08/11/08—08/14/08
AVL 483 Soot Sensor	2	08/18/08—08/21/08
Dekati DMM-230	2	08/18/08—08/21/08
Dekati ETaPS	2	08/18/08—08/21/08
Control Sistem Micro-PSS	2	08/18/08—08/21/08

3.3.3. Test Vehicle and Engine

In-use evaluations used a 1994 Ford F-350 emergency vehicle with a 7.3 liter International engine. The vehicle was originally equipped with a diesel oxidation catalyst. Specifications for the in-use test vehicle are shown in Table 3-9.

3.3.4. Emission Control Technology

The control technology used for the in-use test engine was also an ECS provided unit. It was a pre-commercial DPF system that consists of a platinum group metals pre-filter catalyst and a cordierite DPF filter with a base metal catalyst coating. It uses a passive regeneration strategy via NO_2 oxidation at low exhaust temperatures and oxygen oxidation at high exhaust temperatures.

3.3.5. Test Fuel

The test fuel used for all field testing was ULSD which met ASTM D975 standards. A single fuel batch was used during each group of tests to eliminate potential impacts of test fuel on engine performance and emissions.

Table 3-9. Specifications for the In-Use Test Vehicle

Make	Ford
Model	F-350
Model Year	1994
Engine Manufacturer	International
Throttle Control	Manual
Injection	Direct Injection
Number of Cylinders	V—8
Displacement	7.3 liter
Compression Ratio	17.5:1
Maximum Power	275 brake horsepower (bhp) @ 2800 revolutions per minute (rpm)
Engine-Out Exhaust Pipe Diameter	3.5”
Current Engine Miles	24,850
PM Emissions Certification Level	N/A
Avg. Engine-Out Emissions w/ ULSD Fuel	
PM grams per mile average in-use value	0.141 g/mi
CO grams per mile average in-use value	0.87 g/mi
NOx grams per mile average in-use value	6.58 g/mi

3.3.6. Duty Cycle

Candidate technologies were evaluated using a simple duty cycle representing operation of the test vehicle in normal work duty. A simple duty cycle is an arbitrary arrangement of simple or composite events of specified duration performed in sequence under controlled conditions. The duty cycle was:

- representative of typical conditions observed for an on road diesel vehicle
- between 15 minutes and one hour to allow for sufficient PM filter loading for gravimetric analysis, and to allow a reasonable number of test runs during a typical day
- repeatable, as determined by the defined cycle criteria.

3.3.6.1. Cycle Criteria

Test campaigns using simple cycles must incorporate methods where each test run accurately reproduces the specified duty cycle. This reduces run-to-run variability and minimizes confidence intervals. Test personnel developed cycle criteria to be applied to each test run. If a test run met its respective cycle criteria, the run was deemed valid. The duty cycle criteria for this test campaign were as follows:

- Ambient air pressure should not vary more than one “Hg for all test runs. This is because a one” Hg air pressure change can cause an approximately 0.3 % change in engine efficiency (Coordinating Research Council , 2007);

- Test run ambient air temperatures must be within ± 10 °F of the mean for all test runs if the mean is < 80 °F, or within ± 5 °F if the mean is ≥ 80 °F
- Elapsed time for each duty cycle or event must be within ± 5.0 % of the mean observed during cycle criteria development
- Mean exhaust temperature over the test run must be within ± 5.0 % of the mean observed during cycle criteria development
- Mean engine rpm over the test run must be within ± 5.0 % of the mean observed during cycle criteria development.

Elapsed time cycle criteria are largely influenced by the driver of the test vehicle and the test vehicle itself. All test runs therefore used the same driver.

To make the in-use testing process reproducible and simulate real-world conditions, the route chosen for evaluation began at the back delivery driveway into the Environment Canada (EVC) facility, followed by a cruise portion on rural roads at highway speeds, stop and go driving through a residential neighborhood, and then a return to the EVC facility. To evaluate repeatability of the selected route, Southern developed a program to automate the collection of event times at designated points throughout the in-use route. Table 3-10 is a description of the in-use test cycle, and Figure 3-6. Outlined Map of 12.055 Mile In-Use Route is an overview of the in-use route. Arrival or stop times were collected at each designated waypoint during test runs, and the runs then evaluated for route consistency (see Table 3-11).

Table 3-10. In-Use Cycle Development

Start Test- 1:00 idle and depart EVC facility left on River Road
Point 1-intersection at Lietrim Road
Point 2-alternate stop after Earl Armstrong Rd if traffic light does not stop vehicle
Point 3-left turn at Rideau Rd
Point 4-left on to Spratt Rd—gravel, paved at beginning of neighborhood
Point 5-left at Limebank–traffic light, alternative stop if light does not stop vehicle
Point 6-left turn at Lietrim Road-very rough surface and lots of potholes
Point 7-right on River Road and head back to EVC—wide open throttle to 80 kmh
Point 8-Arrive at EVC entrance
END -Idle for one minute and **End Test**

Table 3-11. In-Use Route Validation

Elapsed Time at each Checkpoint											
		min	min	min	min	min	min	min	min	min	min
Run #	**start**	**point 1**	**point 2**	**point 3**	**point 4**	**point 5**	**point 6**	**point 7**	**point 8**	**end**	**stop**
1	0	3.33	5.45	7.67	8.83	11.00	14.43	15.67	17.07	19.50	20.50
2	0	3.38	5.58	7.98	9.13	11.28	15.15	16.17	17.48	19.87	20.87
3	0	3.38		7.73	8.88	12.20	15.35	16.72	18.10	20.50	21.50
4	0	3.50	5.73	8.25	9.41	11.63	14.92	16.17	17.55	19.95	20.95
5	0	3.42	5.83	7.93	9.08	11.30	14.70	16.10	17.48	19.93	20.93
	Mean	***3.402***	***5.6475***	***7.912***	***9.066***	***11.482***	***14.91***	***16.166***	***17.536***	***19.95***	***20.95***
	STDEV	***0.063***	***0.167***	***0.230***	***0.231***	***0.459***	***0.363***	***0.373***	***0.368***	***0.358***	***0.358***
	n	***5***	***4***	***5***	***5***	***5***	***5***	***5***	***5***	***5***	***5***
	$T_{0.025,DF}$	***2.776***	***3.182***	***2.776***	***2.776***	***2.776***	***2.776***	***2.776***	***2.776***	***2.776***	***2.776***
	AbsErr	***0.079***	***0.266***	***0.285***	***0.286***	***0.570***	***0.450***	***0.463***	***0.457***	***0.444***	***0.444***
	RelErr,%	***2.314***	***4.706***	***3.603***	***3.160***	***4.966***	***3.019***	***2.867***	***2.606***	***2.226***	***2.120***

The in-use test conditions were selected to provide a broad range of PM emission levels ranging from older off-road equipment levels to levels expected for particulates from 2007 engines and beyond. The in-use cycle selected was 12.055 miles in length and provided various driving conditions. From the start position until point two the vehicle speed was usually maintained at highway speeds. For the duration of the cycle, there were periods of driving through neighborhoods with stop and go patterns, periods of idling, low speeds on dusty and bumpy dirt roads, medium speeds on very bumpy secondary paved roads, and full throttle operation up to 80 km/hr. After the initial shakedown tests with the DOES2 system, it was determined that the selected in-use route produced sufficient PM loading for the PM PEMs evaluation.

3.3.7. Test Procedures

3.3.7.1. Driver Training

The same driver was used for all test periods. In addition, the driver was required to operate the vehicle for several preliminary test runs to ensure test cycle consistency and the ability to meet defined test cycle criteria.

3.3.7.2. Shakedown

The test matrix included operation of the test engine for a brief period prior to documented test runs to allow for PM PEMS instrument shakedowns prior to the start of testing. The shakedown tests allowed for vendors to check instrument general operation and allowed for corrections of sample or dilution flow and other instrument parameters required during normal test setup. For the shakedown run, the test vehicle was operated through a single duty cycle.

Figure 3-6. Outlined Map of 12.055 Mile In-Use Route

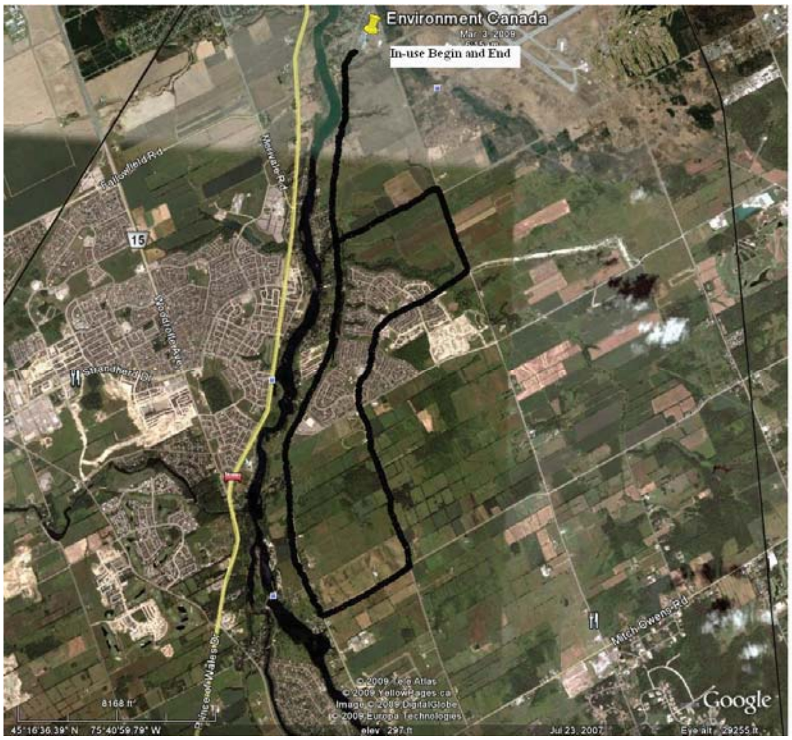


Figure 3-7. Routing of the Exhaust Tube for Installation of PM PEMS Equipment

3.3.7.3. Instrument Installation & Setup

The ERMS staff fabricated and installed an exhaust system that allowed rapid change out of the original muffler with a new DPF and eased the installation of the PM PEMS. The ERMS staff installed a four inch exhaust-tube at the outlet of the original muffler or the DPF, which was routed to the rear of the vehicle where it made a 90 degree bend upward to the top of the vehicle as shown in Figure 3-7. PM PEMs instruments were setup by vendors in the back of the vehicle and their sample probes were routed to the exhaust tube in the rear of the vehicle. Instrument sampling locations were at least 10 diameters downstream of any bends in the exhaust-tube to ensure adequate exhaust mixing. Sampling lines were installed by vendors based on specific requirements for each PM PEMS. Sampling lines consisted primarily of heated sampling lines of five meters or less.

For each group of test instruments, discussions were held with all the participants prior to establishing sampling locations to minimize interferences from sample probes or other instruments on sampling systems or instruments further downstream. Vendor representatives approved their final sampling locations in the exhaust sampling line and proceeded with installation. Environment Canada staff provided assistance with the installation of required sampling ports and fittings on the exhaust line.

Power was supplied to the PM PEMS and the DOES 2 via a generator located on a trailer being pulled by the test vehicle. Any ancillary equipment required by the PEMS was provided and installed by the vendors with assistance from the ERMS staff.

All instrumentation setup and installation requirements were observed and logged by Southern staff. A log sheet of the requirements was completed for each installation and reviewed and approved by each technology vendor to ensure accuracy. Observations of instrument specifications, additional sensors, sampling systems, brackets, hangers, cables, consumables (i.e. compressed air), power consumption, and other requirements were documented. In addition, the estimated physical installation time was monitored and documented. Any changes made to the installation throughout the test program were also documented.

3.3.8. Reference Method

The DOES2 system, in conjunction with ERMS measurement labs, served as the reference method for PM measurement during field evaluations. The DOES2 is a partial flow, portable dilution system that meets the specifications of 40 CFR 86 test procedures. The system is used to collect a sample of the vehicle exhaust while operating in-use, and uses gravimetric filters for PM collection as well as sample bags for gaseous emissions evaluation. The same analyzer bench and weigh bench used in the lab evaluations were used for field evaluations. Exhaust gas flow characterization was made using a laminar flow element (LFE) at the engine air intake. The LFE measures the intake air flow rate and assumes that it is equal to the exhaust gas flow rate. A summary of the instrumentation used in the field reference is provided in Table 3-12.

Table 3-12. In-Use Testing Reference Instruments and Specifications

	Parameter	Sensor Mfg	Model	Logging Frequency	Accuracy	Repeatability
Laboratory Reference Method	CO	Horiba	AIA-210 LE	1 Hz	2% of point or 1% of measure	1% of point or 1% of measure
	CO_2	Horiba	OPE-115			
	NOx	California Analytical Instruments	400-HCLD			
	NO	California Analytical Instruments	400-HCLD			
	THC	California Analytical Instruments	300M-HFID			
	PM filter weight	Sartorius	M5P-000V001	n/a[a]		
Environment Canada DOES2 (Field Reference Method)	Instrumental analyzer concentration	Environment Canada	DOES2 (analyzers same as lab, above)	1 Hz	2.0 % of point	1.0 % of point
	Gravimetric TPM balance			n/a	0.1 %	0.5 μg
	Main flow rate			>1 Hz	1.0 % FS[b]	n/a
	Dilution air flow rate					
	Sample flow rate					
	Differential pressure (if used)					
	Exhaust flow characterization	Environment Canada LFE				
	Gravimetric PM filters	70 mm Emfab TX40HI20-WW		n/a	n/a	n/a
	EC/OC filters	47 mm fired Quartz—Pall Tissuquartz 2500QAT-UP plus 47 mm Teflon membrane		n/a	n/a	n/a

[a] Not applicable (n/a)
[b] Full scale (FS)

In addition to the above information, testing staff also logged the following parameters and associated measurements (units) for usage in data analysis:

- Cycle Time (seconds)
- Engine Intake Air Flow (SCFM)
- Rel. Humidity (%)
- Ambient Pressure [kPa]
- Engine Exhaust Temperature (^{o}C)
- DPF Exhaust Temperature (^{o}C)

3.3.8.1. In-Use Reference Validation

To validate Environment Canada's DOES2 system use as the reference method for in-use testing, correlation with the 40 CFR Part 86 PM emissions testing methods was performed. During the second group of laboratory engine dynamometer testing, the DOES2 system correlation was completed. The DOES2 was operated simultaneously with the other PM PEMS being tested at the time. The following figure displays the comparison of PM test results collected from Environment Canada's DOES2 system and the laboratory Part 86 reference standard method. Environment Canada routinely tests the DOES2 system against laboratory test methods and has modified its engine dynamometer test cell to accommodate the system. The DOES2 was tested in the laboratory prior to each field test campaign. Figure 3-8 displays the results of the comparisons between the Part 86 and the DOES2 gravimetric results at each set of test conditions for the second laboratory test group. Table 3-13 gives the results obtained from the testing. Note that, to obtain sufficient PM sample from the DOES2 for weighing, samples were integrated on a single filter over the three test runs at each condition. Therefore, the DOES2 results are a single point measurement, preventing the statistical analysis of the differences between the reference and DOES2.

Figure 3-8. PM Emissions Comparison (ERMS-Part 86) and (EMRD-DOES2)

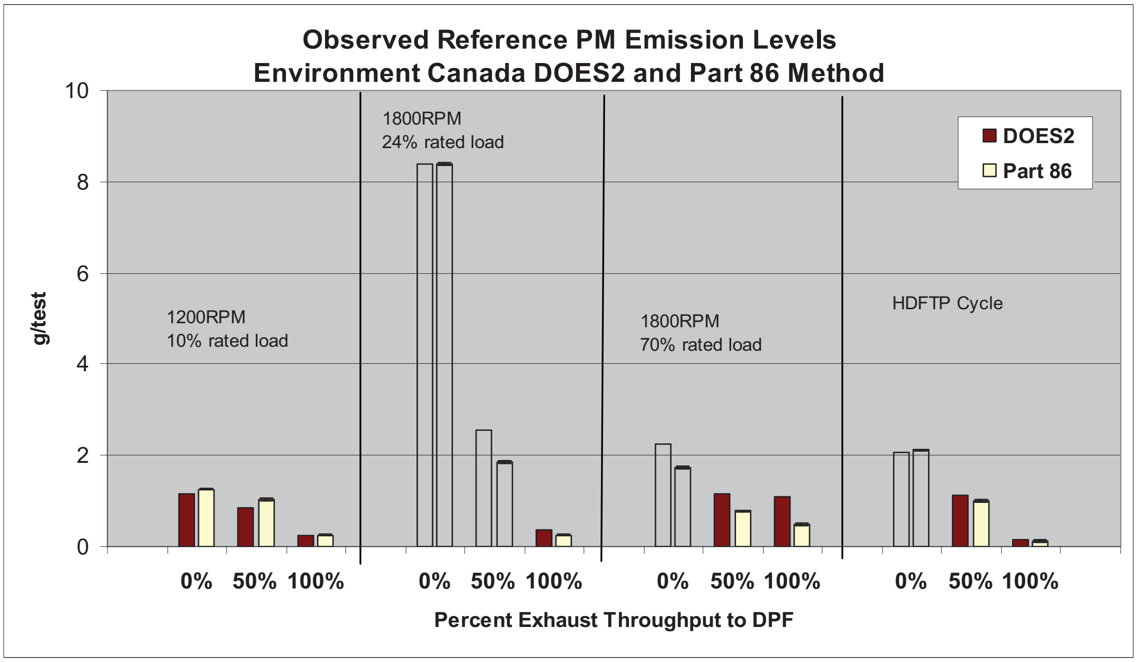


Table 3-13. Comparison of PM Emission Test Results During Laboratory Testing

Engine Mode	Exhaust Condition	DOES2 g/test	PART 86 g/test
1800 RPM @ 10% Engine Power	Engine Out	1.14	1.26
	Intermediate PM	0.84	1.04
	DPF Out	0.25	0.25
1800 RPM @ 24% Engine Power	Engine Out	8.37	8.39
	Intermediate PM	2.54	1.85
	DPF Out	0.36	0.26
1800 RPM @ 70% Engine Power	Engine Out	2.26	1.73
	Intermediate PM	1.16	0.78
	DPF Out	1.10	0.49
HDFTP Cycle	Engine Out	2.06	2.12
	Intermediate PM	1.12	1.00
	DPF Out	0.15	0.12

3.3.9. Test Summary

In-use test runs used the test procedure outlined in Table 3-14.

Table 3-14. Field Evaluation Test Procedures

1	PM measurement technology vendors (or designated personnel) will install their candidate technologies at a designated post-DPF location and secure their equipment and sampling lines to minimize movement during testing. Southern will document installation procedures and setup conditions. The systems will be installed so that they do not interfere with one another's operation.
2	Synchronize all candidate technology clocks to the DOES2 reference method time.
3	Perform post-DPF tests for three test runs over the specified duty cycle. • Begin DOES2 reference method, candidate technology, and ECM logging (if available). • Complete a single duty cycle. • After each test run there will be an approximately 20 minute idle period while ERMS staff change the DOES2 reference method PM filter. • During the 20 minute soak period after each test run, **candidate technology vendors must provide Southern staff with all raw data files for archiving.** • Repeat for next test run
4	ERMS staff will remove the DPF and place the OEM muffler back for engine-out testing.

5	Perform engine-out tests for three test runs over the specified duty cycle. - Begin DOES2 reference method, candidate technology, and ECM logging (if available). - Complete a single duty cycle. - After each test run there will be an approximately 20 minute idle period while ERMS staff change the DOES2 reference method PM filter. - During the 20 minute soak period after each test run, **candidate technology vendors must provide Southern staff with all raw data files for archiving.** - Repeat for next test run.
6	End of test group. PM measurement technology vendors (or designated personnel) will un-install their candidate technologies.
7	Repeat test procedure for the next test group.

3.3.10. Recorded Parameters

Table 3-15 summarizes the parameters that were recorded during all field evaluations.

Table 3-15. Summary of Parameters Recorded in the Field Evaluations

Parameter	Measurement Instrument	Data Collected By	Logging Frequency	Units
PM	DOES2	ERMS	Integrated filter	mg
	Candidate Technologies	Technology Vendors	1 Hz, if available	Varies
EC/OC	NIOSH or similar method	ERMS	Integrated filter	mg/cm^2
CO	DOES2	ERMS	Integrated bagged samples	ppm
CO2	DOES2	ERMS		%
NOx	DOES2	ERMS		ppm
THC	DOES2	ERMS		
Bhp	ECM, if available	ERMS	1 Hz	calculated ft/lbs
Fuel consumption	DOES2 carbon balance	ERMS	Calculated	Liters
Dilution air flow rate	DOES2	ERMS	> 1 Hz	scfm
Engine intake air flow rate	DOES2	ERMS	> 1 Hz	
Engine rpm	DOES2	ERMS	> 1 Hz	rpm
Engine exhaust temperature	DOES2	ERMS	> 1 Hz	degrees C
Intake air temperature	DOES2	ERMS	> 1 Hz	
Ambient air temperature	DOES2	ERMS	Prior to each test run	
Ambient relative humidity	DOES2	ERMS		%
Barometric pressure	DOES2	ERMS		mm/Hg

3.3.10.1. In-Use Data Analysis

ERMS staff and candidate technology vendors were responsible for analyzing raw data from their instruments, and were required to provide Southern raw data after each test run, as well as, all spreadsheets and calculations for data quality and validation purposes. Data was provided by all participants as total PM emissions per test run in the following units:

- grams/second
- grams/gallon
- grams/mi

To enable the above calculations, Southern provided all vendors with the following data, collected by Environment Canada:

- Engine exhaust temperature (logged at 1 Hz)
- Intake air flow for each test run (logged at 1 Hz)
- fuel consumption as measured by the ECM gal/sec

Southern then evaluated the performance of the candidate PM measurement technologies using the following data analyses or criteria:

- Comparison of PM measurement technology results (in units of PM mass) to the in-use reference method (DOES2 PM mass) for the in-use test runs as:
    - the percent difference and 95 percent confidence interval between the mean PM mass emission rate for all candidate technology test runs for each test condition and the mean PM mass emission rate for all reference method test runs for each test condition
- Comparison of the DPF filtration efficiency as measured by the candidate technologies vs. the reference standard
- Comparison of PM Measurement technology results vs. EC/OC data
- Qualitative comparison of real time PM measurement data vs. engine operating parameters
- Candidate technology durability
- Candidate technology installation requirements and field portability.

Southern characterized the candidate technology stability and reliability by analyzing the PM mass drift from test run to test run for each technology, and by logging candidate instrument failures during the test campaign. Southern also logged candidate technology installation, setup, and operating requirements in both lab and field settings in order to characterize field portability.

4.0 DATA QUALITY

This section outlines general data quality requirements for all tests. The major QA/QC procedures to be conducted for this test include:

- Technical system audits
- Audits of data quality
- Independent review

4.1. TECHNICAL SYSTEM AUDITS

Test personnel conducted the technical system audits, calibrations, performance checks, and cross checks listed in Table 4-1. Note that some performance checks occurred before and after each test run, while others were performed in either the field or laboratory as required as part of ERMS standard operating procedures. Southern staff verified that each check was completed as required and that no issues were identified throughout the test program.

Table 4-1. DOES 2 Calibrations and Performance Checks

System or Parameter		Description / Procedure	Frequency	Completed?	Date Completed
DOES2 Field Bench	CO	Gas divider calibration with protocol calibration gases at 11 points evenly spaced throughout span (including zero)	Every 4 weeks	☒	7/9/08
	CO_2			☒	7/9/08
	NOx			☒	7/9/08
	THC			☒	7/9/08
	CO	CO_2 interference check	Monthly	☐	N/A
	CO	Water interference check		☐	N/A
	CO_2	Water interference check		☐	N/A
	NOx	Converter Efficiency Check		☒	7/2/08
	PM gravimetric balance	NIST-traceable calibration	Within 12 months	☒	5/16/08
		Balance calibrated by reference sample / control weights	Daily	☒	As required
Environment Canada DOES2 (Field Reference Method)		Comparison against laboratory CVS system	At purchase; after major modifications	☒	7/10-15/08
		Zero / span analyzers (zero ± 2.0 % of span, span ± 4.0 % of point)	Before and After Each Test Run	☒	Refer to Environment Canada Documentation and field data forms
		Inspect sample lines, filter housings, and sample bags for visible moisture (none is allowed)	Before and After Each Test Run	☒	
		Perform analyzer drift check (± 4.0 % of cal gas point)			N/A

System or Parameter	Description / Procedure	Frequency	Completed?	Date Completed
	THC background check and dilution tunnel blank	Once per test day	☒	Daily During testing 7/22– 7/30, 2008
	PM background check and dilution tunnel blank		☒	
	Dilution tunnel leak check		☒	
	Sample bag leak check (< 0.5 % of normal system flow rate)		☒	
	PM filter face temperature (not to exceed 52 °C	Continuously during sampling	☒	Daily each test
	11 point linearity check of DOES2 main, dilution, and sample flow rates	Within 12 months	☒	6/30, 7/2-3, 7/26/08
TSI SMPS	Laboratory calibration	Within 12 months	☒	6/8-12/08

Table 4-2. HD Test Cell Bench Calibration and Performance Checks

System or Parameter		Description / Procedure	Frequency	Completed?	Date Completed
Laboratory Reference Method	CO	Gas divider calibration with protocol calibration gases at 11 points evenly spaced throughout span (including zero)	Every four weeks	☒	5/20, 6/16, 7/14-2008
	CO_2			☒	5/26, 6/23, 7/21-2008
	NOx			☒	6/7, 6/30, 7/28-2008
	THC			☒	6/9, 7/7, 8/5-2008
	CO	CO_2 interference check	Monthly	☒	6/24/2008
	CO	Water interference check		☒	6/24/2008
	CO_2	Water interference check		☐	N/A
	NOx	Converter Efficiency Check	Weekly	☒	6/9/2008
	PM gravimetric balance	NIST-traceable calibration	Within 12 months	☒	5/16/2008
		Balance calibrated by reference sample / control weights	Daily	☒	As Required

4.2. AUDITS OF DATA QUALITY

The reported results include many contributing measurements from numerous sources, including vendors, ERMS, and Southern. To ensure that data processing was accurate, Southern's analytical staff:

- Manually calculated a proportion of each vendor's reported result from the raw data files, including the applicable engineering conversion(s) and calculation procedures specified by the vendor to convert to the appropriate reporting units
- Manually calculated a portion of the reported results for the comparisons of the vendor results to the reference standards
- Compared the manually-calculated results with the worksheet files and the draft report
- In the event that errors were found, manually calculated a higher proportion of each reported result and resolved any problems.

Original data logger files, signed logbook entries, and signed field data forms will be the source for all Excel worksheets used as analysis tools.

The results of the audits of data quality determined that different vendors performed calculations converting values of PM mass to emission rates (g/bhp-hr, g/gal), in slightly different ways. As a result, to ensure consistency, Southern revised calculations such that each conversion to reporting units was completed the same way by all vendors.

4.3. INDEPENDENT REVIEW

Results of all testing programs were presented to a Project Advisory Group, with preliminary data summaries provided to the group for review. The project advisory group members, if able, provided comments regarding specific data issues, results, analytical procedures, and other items of interest. Southern reviewed these comments and provided written responses to all. PAG comments and responses to comments are on file with NYSERDA.

4.4. DEVIATIONS FROM TEST PLAN

The following issues and deviations from the test plan were noted during testing.

Laboratory—Group 1

- DPF Out—24% Power—June 12, 2008—Test 4: Participants noticed a decrease in PM emissions from the beginning of the test to the end of the test
- Engine Out—10% Power—June 13, 2008—Test 1: PM emission levels were about 25% higher than expected, based on previous test data
- Intermediate PM Loading—70% Power—June 17, 2008—Test 1: intermediate PM load condition was set to 30 ppm, which was less than 50% of the max CO engine out level (87 ppm). Actual bypass level was 35% instead of 50%; Additional cooling was directed into the test cell to keep Venturi below critical temp.

Laboratory—Group 2

- DPF Out—HDFTP-July 24, 2008—Test 1: Engine intercooler hose came off engine—voided and reran test
- DPF Out—HDFTP- July 24, 2008—Test 2: Engine intercooler hose came off engine again—voided test and reran test
- Intermediate PM Loading—24% Load—July 25, 2008—Test 1: Engine Hp output decreased steadily during test from 80 to 68 bhp
- Intermediate PM Loading—24% Load—July 25, 2008—Test 2: Engine Hp increased back to 80.

The following issues and deviations from the test plan were noted during in-use testing:

In-Use Testing—Group 1

- DPF Out—August 12—Shakedown Test—Highway crew painting lines on River Road creating high HC levels, trailer tire blowout
- DPF Out—August 13—Test 1: Artium changed parameters in software and missed test (operator error)
- DPF Out—August 13—Test 2: Artium changed parameters in software and missed test (operator error)
- DPF Out—August 13—Test 4: Faster in-use cycle time observed
- Engine-Out—August 14—Test 1: Difficulties in meeting cycle criteria due to traffic
- Engine-Out—August 14—Test 4: Artium Data validation failed after 900 seconds
- Engine-Out—August 14—Test 6: Interior temperature of vehicle was almost 38 degrees C, which caused some instruments to go beyond their maximum operating temperature of 40 degrees C to 48 degrees C
- Engine-Out—August 14—Test 6—TSI sample pump failure.

In-Use Testing—Group 2

- Engine-Out—August 20—Shakedown Test: New stop sign in neighborhood at Limbank and Leitrium, painting new stop lines forced traffic into one lane;
- Engine-Out—August 20—Test 4: Construction at new stop sign delay for about 45 seconds.

5.0 RESULTS

5.1. REFERENCE METHODS

5.1.1. Laboratory Test Program—Part 1065 and Part 86

The primary reference test method used for evaluation of the PM PEMS in this program was the EPA's 40 CFR Part 1065 method, as this is currently the primary diesel PM emissions regulatory standard in the US. A secondary reference method—40 CFR Part 86—was also used use in laboratory testing to validate the DOES2 system used as a standard in field tests. Both reference test methods were performed at each condition for several reasons:

- At the time of initial program planning, the 1065 test method was not fully implemented, therefore the 86 method was initially selected as the default EPA reference test procedure
- The only feasible field reference method that was currently available and had been well utilized in past test programs was the DOES2, which was compliant with Part 86 test methods. Therefore, to ensure consistency between lab and field performance, Part 86 test methods were included in the lab analyses
- When testing was scheduled, the Part 1065 methods had been finalized and were being implemented. Therefore, to ensure applicability of data obtained from the test program to future PM-PEMS usage, the 1065 methods were incorporated
- The Part 86 method was not developed with the intent of consistently being able to evaluate PM emissions at such low levels observed at DPF-out conditions
- To allow comparison to past EPA engine certification data and previous emission testing done by ERMS on this engine that was performed using Part 86 methods.

The particulate emission levels observed using the reference methods during the laboratory test program are summarized in Table 5-1. This summary table provides the mean emission rate at each operating condition observed in units of g/test. Figure 5-1 provides a summary of the Part 1065 reference method emissions in units of g/bhp-hr.

Table 5-1 also includes the coefficient of variation (CV) for each set of test runs at a specified engine setting or cycle. The CV is an indication of method repeatability. Although often low, especially at higher PM emission levels, it should be noted that in some cases, CVs for the reference methods were higher than anticipated (greater than 5%), and was as high as 117% of the mean. For the very low emission levels observed at DPF out, larger CVs were anticipated due to the large impact a small change has on a very low emission level.

Note that during the Group 2 tests at the 24% rated load at engine out (0% DPF) condition the error bar shows a large difference in the amount of PM reported. When evaluating the results, the first test run reported had an unusually high PM loading when compared to the second and third test. To check the validity, the results were compared from each of the PM PEMS and the same trend was observed for the first test run at this condition. No known reason for the excursion was determined, and, therefore, the data point was included in all analyses.

Also note that Group 2 emissions were often slightly higher than Group 1 emissions (see Figure 5-1). In some cases, the difference was determined to be within statistical error (not significant), but in others a statistically significant difference between the two group's emission levels was noted. Investigations into the differences demonstrated that all methods (86, 1065, and PEMS) showed similar trends. A review of the engine operating parameters and ambient conditions did not identify any single reason for the differences between groups. Also, comparison to historical engine data for the Caterpillar C-11 test engine demonstrates that the observed emissions are within the ranges observed in past testing programs (See Appendix A).

Figure 5-1. 1065 Method Reference PM Emission Level (g/bhp-hr)

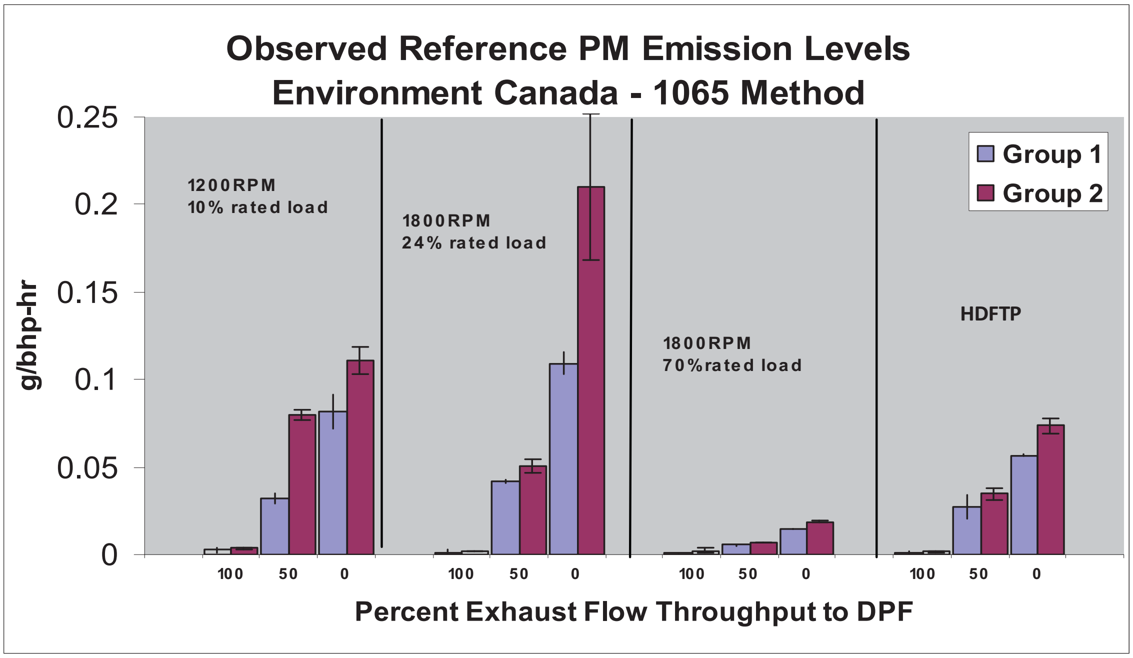


Table 5-1. Laboratory Reference Method Results

Exhaust Condition	Engine Setting / Cycle	Parameter	Group 1		Group 2	
			LAB REFERENCE—1065 Filter	LAB Reference—Part 86 Filter	LAB REFERENCE—1065 Filter	LAB Reference—Part 86 Filter
DPF Out	10% Rated Load, 1200 RPM	Mean Emission Rate (g/test)	0.0197	0.147	0.0265	0.254
		CV	49.4%	16.8%	8.54%	8.61%
		% Difference vs. 1065 Reference		645%		859%
	24% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	0.0306	0.132	0.0591	0.255
		CV	117%	13.7%	6.54%	11.5%
		% Difference vs. 1065 Reference		329%		332%
	70% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	0.0792	0.311	0.184	0.490
		CV	20.1%	46.8%	52.1%	56.9%
		% Difference vs. 1065 Reference		293%		166%
	Heavy Duty FTP (Transient)	Mean Emission Rate (g/test)	0.0209	0.0878	0.0365	0.124
		CV	112%	21.0%	16.%	8.35%
		% Difference vs. 1065 Reference		320%		240%
Intermediate PM Loading	10% Rated Load, 1200 RPM	Mean Emission Rate (g/test)	0.243	0.486	0.621	1.04
		CV	8.82%	3.33%	1.38%	22.1%
		% Difference vs. 1065 Reference		100%		67.0%
	24% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	1.07	1.67	1.25	1.85
		CV	3.63%	2.04%	5.26%	7.12%
		% Difference vs. 1065 Reference		56.0%		47.8%
	70% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	0.435	0.510	0.556	0.778
		CV	7.21%	2.25%	2.99%	5.69%
		% Difference vs. 1065 Reference		17.1%		40.0%
	Heavy Duty FTP (Transient)	Mean Emission Rate (g/test)	0.571	0.727	0.733	1.00
		CV	24.6%	9.79%	8.63%	13.8%
		% Difference vs. 1065 Reference		27.2%		36.7%
Engine Out	10% Rated Load, 1200 RPM	Mean Emission Rate (g/test)	0.721	1.02	0.869	1.26
		CV	22.8%	8.97%	4.12%	5.17%
		% Difference vs. 1065 Reference		41.9%		44.7%
	24% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	2.84	4.00	4.78	7.27
		CV	6.62%	12.7%	1.18%	1.62%
		% Difference vs. 1065 Reference		40.5%		51.9%
	70% Rated Load, Rated Speed (1800 RPM)	Mean Emission Rate (g/test)	1.11	1.32	1.50	1.73
		CV	3.01%	5.68%	3.93%	2.40%
		% Difference vs. 1065 Reference		18.8%		15.2%
	Heavy Duty FTP (Transient)	Mean Emission Rate (g/test)	1.19	1.48	1.57	2.12
		CV	0.68%	1.13%	6.00%	8.40%
		% Difference vs. 1065 Reference		24.6%		35.0%

5.1.1.1. Test Method Comparisons—1065 vs. 86

Because of the differences in the two methods, particularly in terms of dilution tunnel and filter sample temperatures, it was anticipated that differences would be observed between the Part 86 and 1065 results. Nevertheless, the observed differences were larger than anticipated. A comparison of these two methods was not the intent of this project, and there is insufficient data to fully determine the causes of the differences. Some known method differences (filter temperatures, filter media, tunnel temperature), can have significant impacts on particulate matter sampling, but further study would be required to identify exact causes and magnitudes of the differences. This is beyond the scope of this study. The following discussion of the method comparisons is provided for further information and completeness.

Table 5-1 provides a comparison of the two test methods at each operating condition. The observed differences can be associated with known method differences, such as the heating of the entire sampling system in method 1065. In addition, the changes in filter type and filter face velocity can have significant impacts on PM collection on the filter (Coordinating Research Council, Inc., 2006). For the intermediate and engine-out PM emission levels, the difference between the two methods is typically below 50%, often in the 25-35% range. This can be explained, in part, via analysis of the organic carbon fractions of the PM emissions. When using the 1065 methods, the sample line and cabinet heating can prevent the deposition or condensation of semivolatile organic PM on sample filters. As a result, a smaller quantity of organic fraction PM is typically collected on the 1065 method filters. This is demonstrated in Figure 5-2 and Figure 5-3. In these figures, the reference method PM sample filter data was sorted the lowest emissions level to highest. Figure 5-2 shows the gravimetric PM mass data as reported for Group 1 tests using the two methods where Part 86 method results are always greater than Part 1065 results. Figure 5-3 shows the Part 86 PM mass emissions data after the measured percentage of organic carbon was subtracted from the Part 86 PM filter weights.

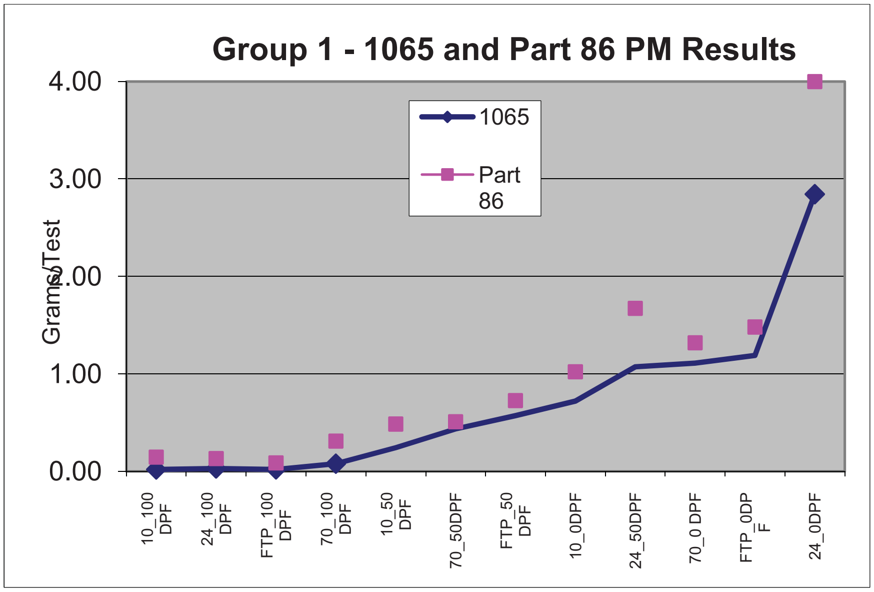


Figure 5-2. Group 1 Reported Gravimetric PM Emission Data

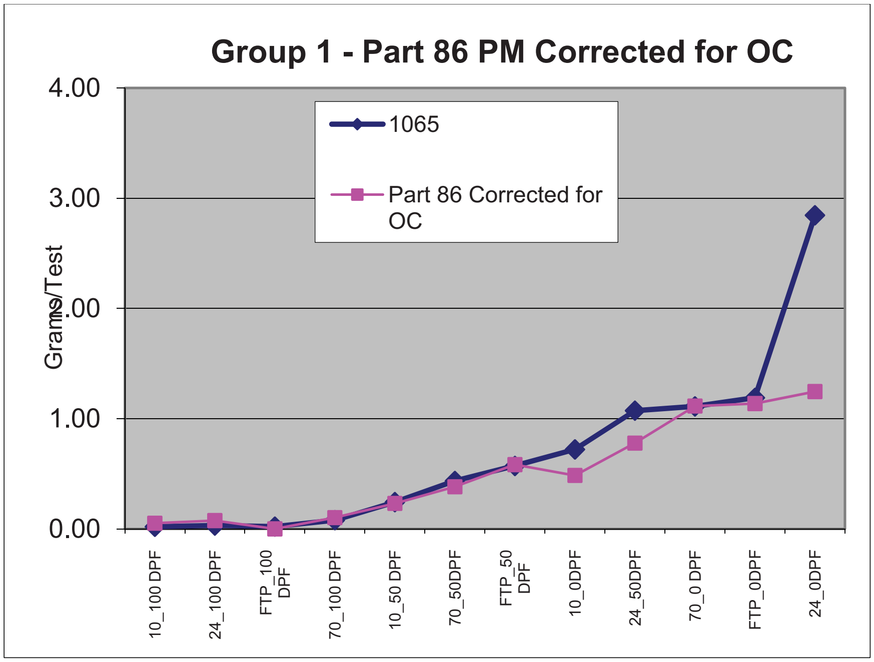


Figure 5-3. Group 1 Gravimetric Data Corrected for Percent Organic Carbon

When organic carbon (OC) measurements are subtracted from Part 86 method mass, there is better agreement between this and Part 1065 results, especially at DPF out and intermediate PM levels. While there are still differences between part 86 and 1065 results when the organic fraction is subtracted from the 86 method results, and there are isolated data points with poor correlation, general trending indicates that the presence and collection of organic carbon likely has the largest impact on the difference between the two test methods. Similar trends were observed for the Group 2 test results. Additional organic carbon data is provided in section 5.1.1.3.

5.1.1.2. Test Result Comparison vs. Engine Certification Data

The observed reference method engine emission levels in units of g/bhp-hr were compared to the EPA engine certification data to verify that the engine was operating in generally expected emission ranges. The certified emission levels for the 2004 model year engine were post- diesel oxidation catalyst (DOC), while the study engine lacked the DOC and represents engine-out. Both certification and this study used the Part 86 laboratory test methodology. Note: CO levels with a DOC are about 50% less than that without a DOC, as expected. Table 5-2 summarizes the engine out emissions in g/bhp-hr as compared to the certification levels. For comparison to the certification data, test results from ERMS are provided using Part 86 methods.

Table 5-2. Comparison of Reference Test Results to EPA Certification Levels

Test		Mass Emission Rate [g/bhp-hr]						
		CO	**CO2**	**NOx**	**HC**	**NO**	**PM (86)**	**TPM (1065)**
Group 1 Mean	Engine Out	3.27	573.7	2.07	0.24	1.58	0.07	0.056
Group 2 Mean	Engine Out	3.94	568.4	1.91	0.21	1.41	0.099	0.074
EPA Certification Level	**(w/DOC)**	**1.6**		**2.3**	**0.1**		**0.09**	
ERMS Historical data (avg.)	(w/DOC)	1.57	570.21	1.97	0.09	2.00	0.07	

5.1.1.3. Laboratory Elemental and Organic Carbon Analyses

In addition to the 1065 and 86 reference test methods for total particulate matter emissions, ERMS also collected PM samples for elemental and organic carbon fraction (EC/OC) analyses. The EC/OC samples were collected using a 40 CFR Part 86 compliant sampling system using 47 mm fired quartz filter (Pall Tissuquartz 2500 QAT-UP). These filters were analyzed using the NIOSH 5040 method for elemental carbon analyses.

Results of EC/OC analyses are shown in Table 5-3 and Table 5-4. The percent EC and percent OC displayed are the mean EC and OC levels observed across the test runs. For the DPF-out test runs, because of the very low levels of PM collected, a single filter was used during all test runs to collect sufficient PM to allow for EC/OC analysis.

Note that at higher engine loads (70% max power and the FTP cycle), the engine-out PM emissions are primarily elemental carbon. At lower loads (10 and 24% max power), significantly higher OC emissions are observed at engine-out. In addition, results show reductions in both EC and OC emissions by the DPF, although the reduction level depends upon the PM constituent concentrations. This is as anticipated, based on the expected reductions in elemental carbon (>90%) when using a wall flow particulate filter and the reductions in organic carbon expected due to the presence of both the catalytic and filtration effects of the catalyzed wall flow DPF.

Table 5-3. Elemental and Organic Carbon Content of PM Emissions—Group 1

Date	**Exhaust Setting (engine load_%DPF)**	**%OC**	**%EC**	**Total PM (Part 86)**	**Total PM (Part 1065)**	**Part 86 Elemental Carbon Emissions**
Group 1 Testing Data				Grams/test	Grams/test	Grams/test
6/11/2008	10_100 DPF	65.03	34.97	0.14705	0.01975	0.05142
6/11/2008	24_100 DPF	42.62	57.38	0.12580	0.00990	0.07546
6/16/2008	70_100 DPF	67.10	32.90	0.31098	0.07918	0.10232
6/11/2008	FTP_100 DPF	bdl	bdl	0.08778	0.02091	N/A
6/12/2008	10_50 DPF	52.45	47.55	0.48589	0.24290	0.23103
6/12/2008	24_50DPF	53.48	46.52	1.67294	1.07277	0.77820
6/17/2008	70_50DPF	24.98	75.02	0.50961	0.43522	0.38230
6/13/2008	FTP_50 DPF	19.79	80.21	0.72682	0.57142	0.58297
6/13/2008	10_0DPF	52.62	47.38	1.02282	0.72103	0.48465
6/16/2008	24_0DPF	68.84	31.16	3.99808	2.84472	1.24560
6/17/2008	70_0 DPF	*15.55*	*84.45*	1.31939	1.11102	1.11418
6/13/2008	FTP_0DPF	23.26	76.74	1.48121	1.18908	1.13671

Table 5-4. Elemental and Organic Carbon Content of PM Emissions—Group 2

Date	**Exhaust Setting**	**%OC**	**%EC**	**Total PM (Part 86)**	Total PM (Part 1065)	**Part 86 Elemental Carbon Emissions**
Group 2 Testing Data				Grams/test	Grams/test	Grams/test
7/23/2008	10_100 DPF	76.00	24.00	0.25437	0.02653	0.06104
7/23/2008	24_100 DPF	67.04	32.96	0.25523	0.05906	0.08412
7/29/2008	70_100 DPF	70.58	29.42	0.49025	0.18445	0.14424
7/24/2008	FTP_100 DPF	31.37	68.63	0.12439	0.03654	0.08537
7/24/2008	10_50 DPF	37.02	62.98	1.03647	0.62058	0.65274
7/25/2008	24_50DPF	46.23	53.77	1.85048	1.25208	0.99507
7/30/2008	70_50DPF	26.42	73.58	0.77816	0.55602	0.57261
7/25/2008	FTP_50 DPF	26.25	73.75	1.00140	0.73258	0.73848
7/28/2008	10_0DPF	47.82	52.18	1.25740	0.86925	0.65612
7/29/2008	24_0DPF	63.80	36.20	8.39364	5.32204	3.03860
7/30/2008	70_0 DPF	18.86	81.14	1.73003	1.50147	1.40375
7/28/2008	FTP_0DPF	44.00	56.00	2.12046	1.57056	1.18741

5.1.2. In-Use Testing Program—DOES2

The primary reference test method used for evaluation of the PM PEMS in the in-use testing program was a 40 CFR Part 86 compliant test method based on gravimetric measurement of PM mass on filters collected by Environment Canada's DOES2 partial flow dilution sampling system. As discussed in Section 3.3.7.1, the method was validated during the laboratory testing program via comparison to the laboratory PM emissions results using the 40 CFR Part

86 laboratory sampling system. Particulate emission levels observed during the in-use testing program are summarized in Figure 5-4, Figure 5-5, and Table 5-5. PM Emissions—DOES2 In-Use Test Reference Note that for the DPF-out levels, the CV was relatively high for all samples.

Figure 5-4. In-Use PM Emission Levels (g/test)

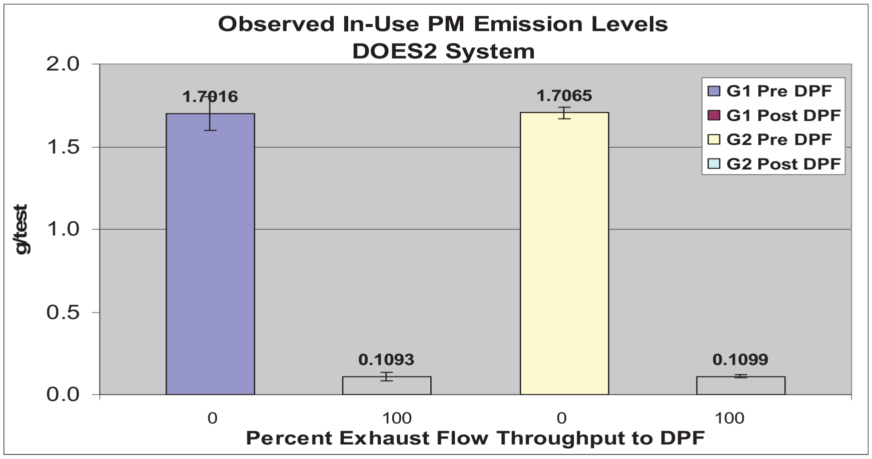


Figure 5-5. PM Emission Level (g/mile)

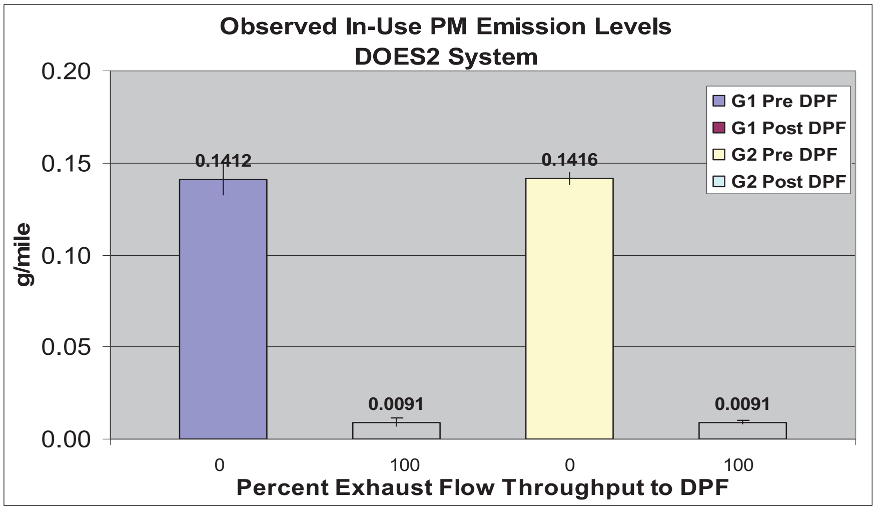


Table 5-5. PM Emissions—DOES2 In-Use Test Reference

Exhaust Condition	Parameter	Group 1 DOES2	Group 2 DOES2
In-Use, DPF Out	Mean Emission Rate (g/test)	0.109	0.110
	CV	18.9%	10.1%
In-Use, Engine Out	Mean Emission Rate (g/test)	1.73	1.71
	CV	4.71%	2.05%
In-Use, DPF Out	Mean Emission Rate (g/mile)	0.0091	0.0091
	CV	22.6%	10.1%
In-Use, Engine Out	Mean Emission Rate (g/mile)	0.143	0.142
	CV	4.71%	2.05%
In-Use, DPF Out	Mean Emission Rate (g/gallon)	0.0770	0.0812
	CV	23.4%	9.84%
In-Use, Engine Out	Mean Emission Rate (g/gallon)	1.25	1.23
	CV	2.41%	1.18%

Because power output measurements were not available during in-use testing via neither direct measurement nor ECM, no comparison of in-use test results to EPA emissions certification levels is possible. For reference, the EPA emissions standards for this engine are provided in Table 5-6. EPA Emission Standards for 1994 On-Highway Diesel Engines

Table 5-6. EPA Emission Standards for 1994 On-Highway Diesel Engines

Pollutant	HC	CO	NOx	PM
Emission Standard (g/bhp-hr)	1.3	15.5	4.0	0.1

5.1.2.1. In-Use Elemental and Organic Carbon Analyses

The EC/OC samples were collected using a 40 CFR Part 86 compliant sampling system using a 47-mm fired quartz filter (Pall Tissuquartz 2500 QAT-UP). These filters were analyzed using the NIOSH 5040 method for elemental carbon analyses.

Results of EC/OC analyses are shown in Table 5-7. The percent EC and percent OC displayed are the results for each individual test run as well as the average for each test group for the engine out condition. Also, as noted in Table 5-7, EC/OC sampling was done for the DPF-out condition as well, with a single filter used to collect a sample over all test runs (four or five in each group). Unfortunately, insufficient sample was present to complete an analysis.

The EC/OC ratios throughout the in-use testing were consistent, with the mean EC/OC ratios for each test group identical.

Table 5-7. In-Use Particulate Elemental and Organic Carbon Fractions

Test Run ID	Date	Exhaust Setting	% OC	% EC
HS 1-5	13-Aug-08	DPF-Out	ND	ND
HS 1	14-Aug-08	Engine-Out	33	67
HS 2	14-Aug-08	Engine-Out	31	69
HS 3	14-Aug-08	Engine-Out	23	77
HS 4	14-Aug-08	Engine-Out	39	61
HS 5	14-Aug-08	Engine-Out	28	72
Average		Engine-Out	31	69
HS 1-4	19-Aug-08	DPF-Out	ND	ND
HS 1	20-Aug-08	Engine-Out	31	69
HS 2	20-Aug-08	Engine-Out	29	71
HS 3	20-Aug-08	Engine-Out	37	63
HS 4	20-Aug-08	Engine-Out	27	73
Average		Engine-Out	31	69

5.2. PM PEMS EVALUATIONS

5.2.1. Artium LII-200

5.2.1.1. Technology Description

The Artium LII-200 uses laser-induced incandescence, an optical technique, for non-intrusive, temporally resolved measurement of soot volume fraction, specific surface area, and primary particle size. A pulsed laser with light pulse duration below 20 nanoseconds is used to rapidly heat the soot particles in diesel exhaust from the local ambient temperature to just below the soot sublimation temperature (<4000 K) to avoid any material losses. Incandescence from the soot particles is detected by photodetectors, and the signals are recorded for subsequent analyses. Complex analysis, involving the laser light energy absorption by the soot particles and the subsequent cooling process, is used to calculate the soot volume fraction and primary particle size.

The Artium LII 200 consists of a self-contained optics enclosure that includes the laser and all components needed for operating the instrument. The optical system consists of a computer-controlled automated laser beam energy detection and adjustment system that maintains the laser light fluence through the sampling volume at optimum conditions. The incandescence signal is collected at 90 degrees to the transmitted beam. The incandescence signal is detected by a pair of detectors that use light filters centered at wavelengths of approximately 400 nm and 780 nm.

Besides measuring the soot volume fraction, the LII signal decay characteristics are also processed to infer the primary particle size and specific surface area. Artium's Integrated Management Software (AIMS) controls all aspects of the instrument setup and operation.

A summary of the LII-200 system's specifications is provided in Appendix B. The LII-200 measures soot (elemental carbon) only, is effective for particle sizes from 10-100 nm, concentrations ranging from 1 μg/m^3 to 1 g/m^3, and is capable of sampling at a 20Hz rate. The LII-200 system evaluated sampled raw exhaust through a standard 3/8" sampling probe connected to a heated sample line which is routed to the analyzer. A low pressure air supply is also required and supplied via a small pump. The LII-200 provides PM concentrations in mg/m3 as well as a soot volume fraction.

Figure 5-6. Artium LII-200

5.2.1.2. Installation & Setup Requirements

The LII-200 required approximately two hours for setup and installation. The installation consisted of:

- welding a 3/8" port to the exhaust line
- installation of the Artium sample probe into the sample port and connection of the heated line
- connection of the sampling system to a compressed air source, in this case a small vacuum pump provided by Artium
- connection of the sample line to the analyzer
- connection of all systems to electrical power (120VAC-5A)
- startup and warmup of the analyzer and heated line
- initial operational checks and setup.

The in-use testing setup was similar to the lab setup. The complete Artium LII-200 system is large by comparison to some other PEMS units tested here, which made it more difficult to use in the in-use test program. Artium indicates that a more compact version of the system with slightly different capabilities is in development.

In addition, it should be noted that, as with many instruments in this test program, although a PM emissions concentration may be provided, an emission rate relies on knowledge of the exhaust flow rate. Artium does not supply an exhaust flow measurement system with the LII-200. Therefore, exhaust flow data from the ERMS LFE was required to calculate emission rates in units of g/test, g/min, g/gal, or g/bhp-hr.

5.2.1.3. Data Processing

The LII-200 provides second-by-second (or faster) PM soot concentration data in mg/m^3. To convert this to a PM mass emission rate for comparison to the lab and in-use references, the exhaust flow rate was provided to all vendors to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. These data are then converted, in a uniform calculation for all vendors validated by Southern, into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the Artium data required no further processing.

During review of the data, however, it was noted that there was a major discrepancy between the Artium PM emission rates and the reference data. The discrepancy appeared to be consistent across all data and all operating conditions. After further review, Artium completed additional testing of the unit that was used during this test program as compared to other test units, and found a consistent offset.

According to Artium: "*The LII is designated as "self-calibrating", with calibration based upon knowledge of particulate surface temperature, determined by optical pyrometry. This approach avoids the necessity of calibrating the instrument with a soot particulates source of a known concentration. However, there remain some uncertainties associated with this calibration procedure. Primarily, in the published literature, values of the soot index of refraction affecting particulate absorptivity and emissivity are not highly certain. There are other uncertainties associated with nanosecond heating of nanoscale aggregates of particles. Thus, we are sometimes obliged to revert to calibrating or evaluating our calibration through comparisons to measurements obtained using gravimetric techniques. After tests at Environment Canada in the NYSERDA PM-PEMS program, we recognized that the instrument we were using had a faulty calibration parameter set which was well outside of the typical uncertainties. This wasn't detected until after the tests were complete. In our efforts to track down and resolve the problem, we conducted tests at NRC Canada where we detected this difference. We then conducted an additional set of tests over a full range of soot conditions from a diesel engine at Environment Canada to verify the absolute value of this calibration error or difference. We also made measurements in an inverted flame soot source and with comparison of these results to gravimetric; the results confirmed our calibration error. Therefore, we have deemed it necessary to apply a calibration factor determined under these evaluations to the test results that were conducted under the NYSERDA program at Environment Canada. The factor for direct correlation with gravimetric is 7.5. However, this also includes the volatiles and OC that we do not measure. For EC measurements by gravimetric, we estimate the factor is 6.0, assuming an average 20% volatile fraction on the filters. We believe that this adjustment to our results* *is valid based on the fact that we have detected a calibration difference for that particular instrument. As a result of these experiments, we have refined our procedures and believe that we have eliminated the possibility of making such errors in the future."*

As stated above, as a result of this further evaluation, Artium developed a correction factor for the data obtained using the test unit provided during this NYSERDA testing program. Artium revised its entire data set to reflect the offset. To ensure transparency, all testing results for the Artium system are presented here—both the original results and the results with the correction factor applied.

5.2.1.4. Reference Comparison—Lab

The summary of the corrected Artium LII-200 results is provided in Table 5-8. Uncorrected results are provided in Table 5-9. Difference Between Artium Non-Corrected PM Measurement and Gravimetric Reference Methods These tables provide the LII-200 results, original and corrected, the reference standard results (via part 1065 methods), the difference between the two data sets, and the determination of the statistical significance of the difference based on a t-test analysis. Figure 5-7, Figure 5-8, and Figure 5-9 also present the results.

Table 5-8. Difference between Artium PM Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	Artium LII-200 Difference vs. Reference (1065)	Artium LII-200 Difference vs. Reference (86)	Artium LII-200 Difference vs. Reference (86 EC)
DPF OUT			
10% Load, 1200 RPM	53.3%	95.1%	79.7%
24% Load, 1800 RPM	5.84%	78.2%	33.9%
70% Load, 1800 RPM	77.9%	91.7%	71.8%
HDFTP	-72.7%	49.3%	26.1%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	-46.1%	12.6%	-38.9%
24% Load, 1800 RPM	-6.16%	28.2%	-33.6%
70% Load, 1800 RPM	-83.4%	-31.1%	-78.1%
HDFTP	-177%	-103%	-175%
ENGINE OUT			
10% Load, 1200 RPM	-23.5%	14.6%	-63.6%
24% Load, 1800 RPM	32.6%	55.6%	-22.5%
70% Load, 1800 RPM	-91.2%	-65.9%	104%
HDFTP	-186%	-112%	-278%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

Table 5-9. Difference Between Artium Non-Corrected PM Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	Artium LII-200 Difference vs. Reference (1065)	Artium LII-200 Difference vs. Reference (86)	Artium LII-200 Difference vs. Reference (86 EC)
DPF OUT			
10% Load, 1200 RPM	93.77%	99.35%	97.29%
24% Load, 1800 RPM	87.44%	97.09%	91.19%
70% Load, 1800 RPM	97.06%	98.89%	96.23%
HDFTP	79.97%	93.24%	90.14%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	80.53%	88.34%	81.49%
24% Load, 1800 RPM	85.85%	90.42%	82.19%
70% Load, 1800 RPM	75.54%	82.52%	76.25%
HDFTP	63.01%	72.94%	63.31%
ENGINE OUT			
10% Load, 1200 RPM	83.53%	88.62%	78.18%
24% Load, 1800 RPM	91.02%	94.09%	83.67%
70% Load, 1800 RPM	74.51%	77.88%	72.74%
HDFTP	61.91%	71.79%	49.63%
N/A indicates data is not available Shading indicates a statistically significant difference (reference vs. technology)			

The Artium LII-200 did not correlate well with the reference standards in most cases, providing a statistically significant difference between the LII results and references at nearly every operating condition. It should be noted that at DPF-out conditions, the percentage differences may be large due to the very low levels of PM observed that are near the detection limits of the reference methods. Small differences in measurements can result in large percentage differences in this range. The faulty calibration of the Artium system used in this test is the likely cause for a significant portion of this error, although without further evaluation or repeat testing, it is difficult to determine any causes for differences between the Artium system and the references.

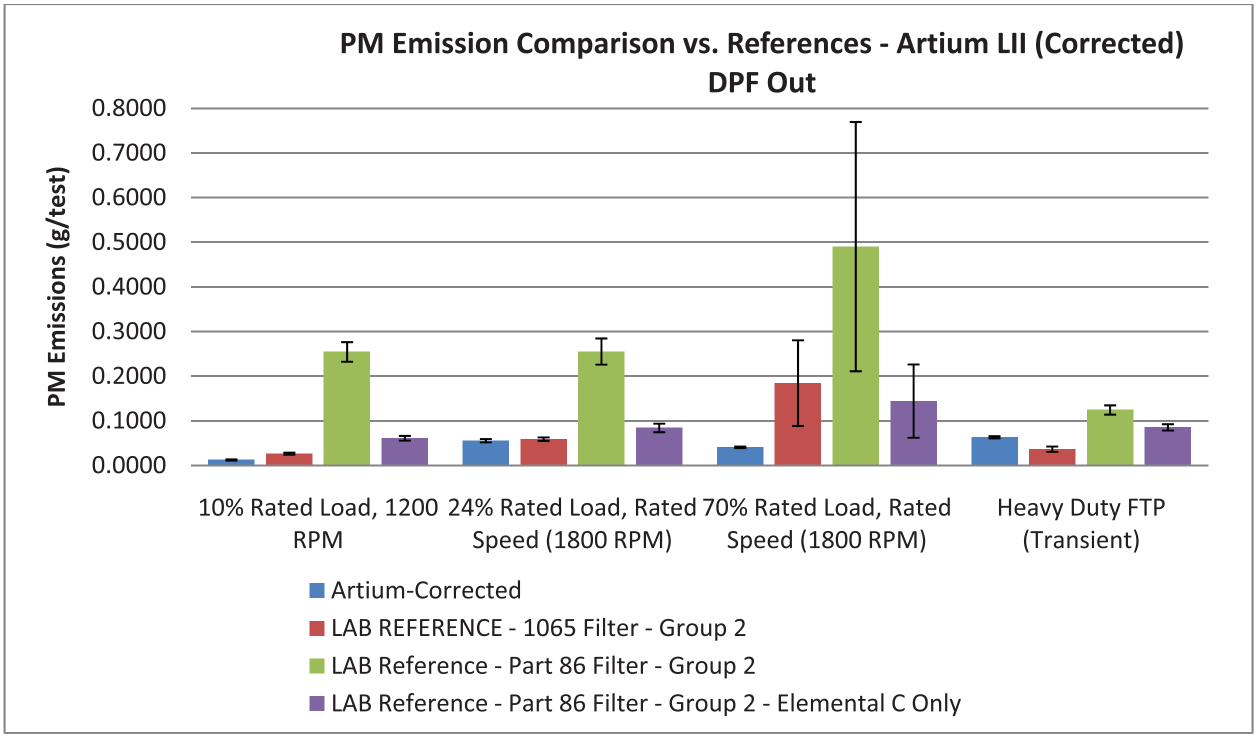


Figure 5-7. Artium LII-200 and Gravimetric Reference PM Emissions—DPF-Out

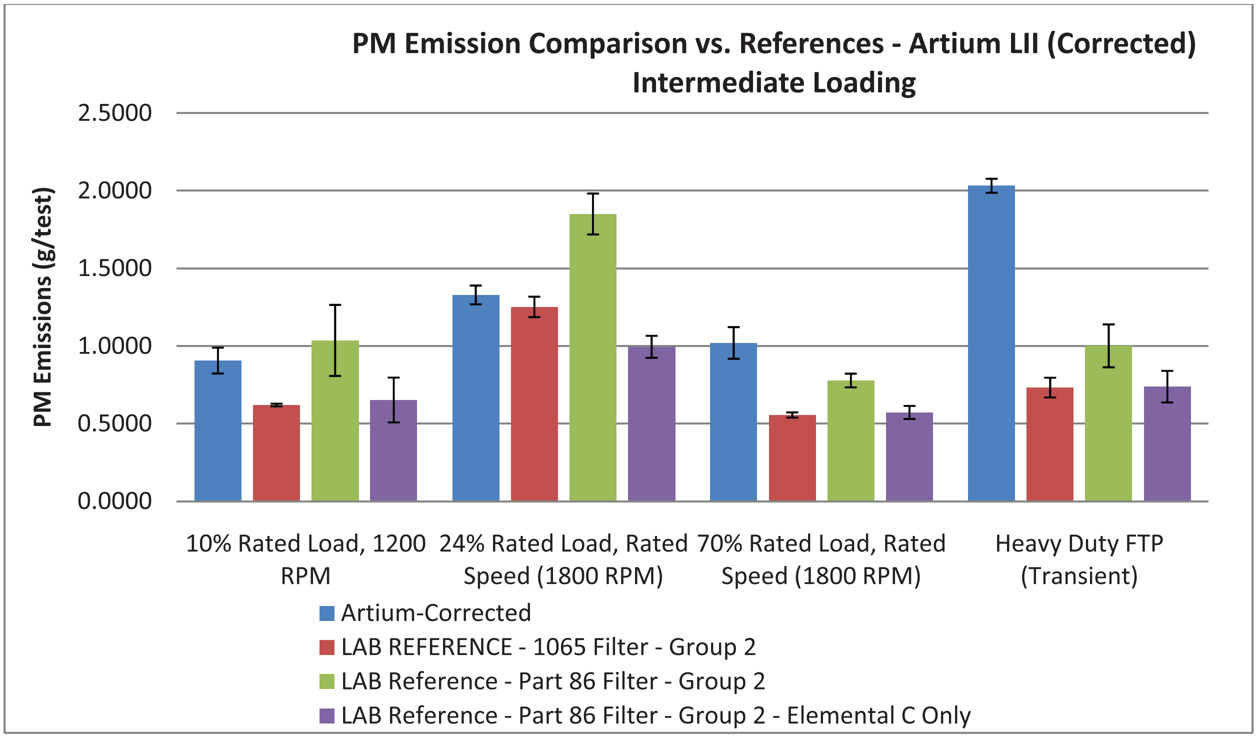


Figure 5-8. Artium LII-200 and Gravimetric Reference PM emissions—Intermediate PM

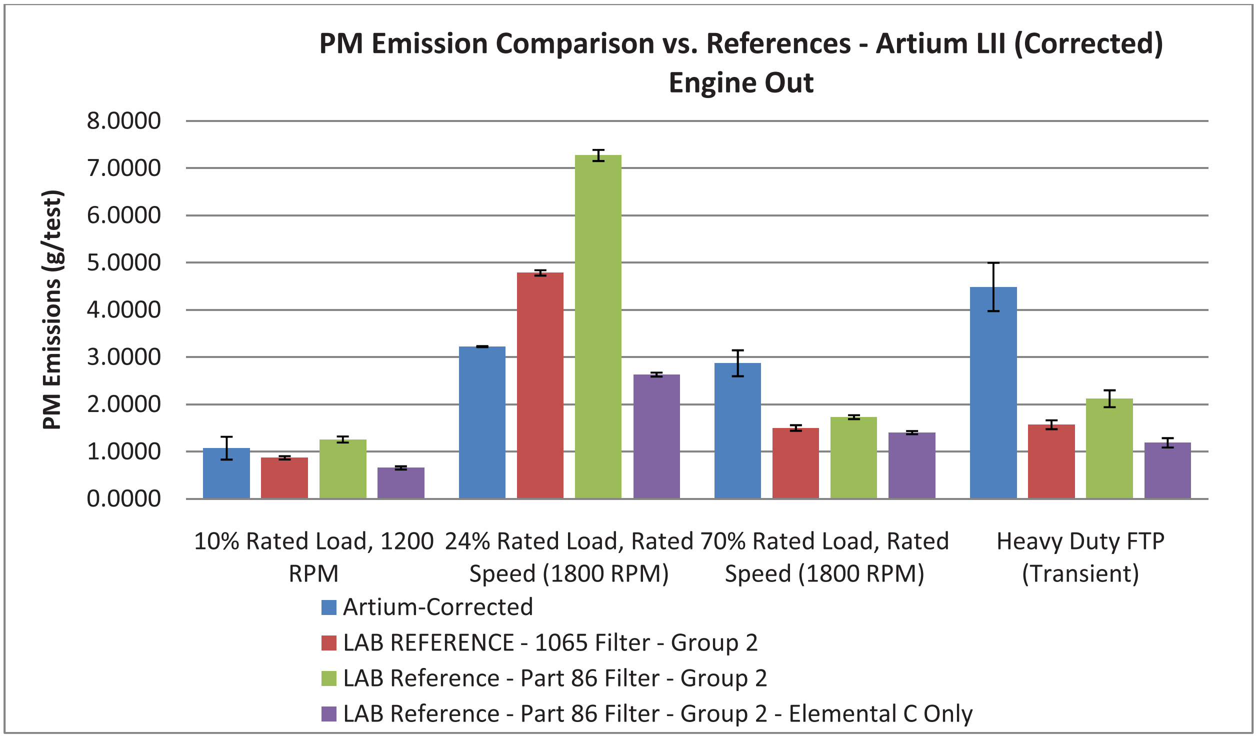


Figure 5-9. Artium LII-200 and Gravimetric Reference PM emissions—Engine Out

5.2.1.4.1. Repeatability

The test-to-test repeatability of each PM-PEMS can be evaluated by observing the coefficient of variation (CV) for each group of test runs at a specific operating condition or test cycle. The CV for the LII-200 at each test condition is summarized in the table below, along with the CV for the reference methods for comparison.

At the DPF-out, very low levels of PM emissions, and especially low elemental carbon (soot) emissions, the LII-200 proved to provide excellent reproducibility, with most CVs equivalent to or well below to CV of the 1065 reference method. At other operating conditions, CVs were variable, ranging from well below reference method CVs to somewhat higher than references. Overall, the Artium LII-200 appears to provide sufficient repeatability, especially at low elemental carbon emission levels, when compared with reference methods.

Table 5-10. Coefficient of Variation for Artium LII-200

Engine Setting	**CV—LAB REFERENCE 1065 Filter Group 2**	**CV—LAB Reference Part 86 Filter Group 2**	**CV—Artium LII-200**
DPF-Out			
10% Rated Load, 1200 RPM	0.0854	0.0861	0.117
24% Rated Load, Rated Speed (1800 RPM)	0.0654	0.115	0.0672
70% Rated Load, Rated Speed (1800 RPM)	0.521	0.570	0.0412
Heavy Duty FTP (Transient)	0.163	0.0835	0.0385
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0138	0.221	0.0917
24% Rated Load, Rated Speed (1800 RPM)	0.0526	0.0712	0.0455
70% Rated Load, Rated Speed (1800 RPM)	0.0299	0.0569	0.100
Heavy Duty FTP (Transient)	0.0863	0.138	0.0222
Engine -Out			
10% Rated Load, 1200 RPM	0.0412	0.0517	0.225
24% Rated Load, Rated Speed (1800 RPM)	0.0118	0.0162	0.0034
70% Rated Load, Rated Speed (1800 RPM)	0.0393	0.0240	0.0955
Heavy Duty FTP (Transient)	0.0600	0.0840	0.114

5.2.1.4.2. Control Device Efficiency

In addition to evaluation of emissions, PM-PEMS may be used for evaluation of the impacts of an emission control device or novel emission reduction technology, where a direct measurement of the emissions level is not the primary target, but, rather, a difference between two emission levels is targeted. To evaluate the suitability of the Artium LII-200 in this application, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference and Artium DPF-out and engine-out data from each set of test runs.

Table 5-11. Comparison of Control Device Evaluation Results for Artium LII-200

Engine Condition	Parameter	Reference—1065	Artium-Corrected	Reference—86	Artium-Corrected	Reference 86 EC	Artium-Corrected
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	96.9%	98.8%	79.8%	98.8%	0.907	0.989
	% Difference vs. Reference		-1.96%		-23.9%		-8.98%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.8%	98.3%	96.5%	98.3%	0.968	0.983
	% Difference vs. Reference		0.50%		-1.85%		-1.52%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	87.7%	98.6%	71.7%	98.6%	0.897	0.986
	% Difference vs. Reference		-12.39%		-37.56%		-9.87%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	97.7%	98.6%	94.1%	98.6%	0.928	0.986
	% Difference vs. Reference		-0.94%		-4.74%		-6.23%

In all cases except for one, the Artium LII-200 predicted the control device efficiency within 2% of the 1065 reference measurement. At the 70% power output level, calculated efficiencies differed by more than 12% from the reference standards.

5.2.1.5. Comparison vs. References—In-Use

Comparisons of the Artium data (corrected) vs. the DOES2 reference are provided in the table below. The differences versus reference standards in both exhaust configurations (DPF and engine out) are greater than 75% and are statistically significant. Because of the method design, the part 86 in-use reference will typically provide results that are higher than an analytical technique focused primarily on soot measurement, such as the LII. The larger difference vs. the reference observed at DPF-out conditions is not surprising. Still, at engine-out conditions, the large difference vs. reference and the CV that is significantly higher than the reference indicate a poor correlation with the gravimetric reference.

Table 5-12. Artium LII-200 In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	Artium	REFERENCE—DOES2 Part 86 Filter—EC Only
DPF OUT				
In-Use	Mean Emission Rate (g/test)	0.109	0.0225	0.109
	CV	0.189	0.0583	0.189
	% Difference vs. Reference		79.4%	79.4%
	Statistically Significant Difference?	YES		YES
Engine Out				
In-Use	Mean Emission Rate (g/test)	1.73	3.18	1.19
	CV	0.0471	0.152	0.0685
	% Difference vs. Reference		-83.9%	-167%
	Statistically Significant Difference?	YES		YES

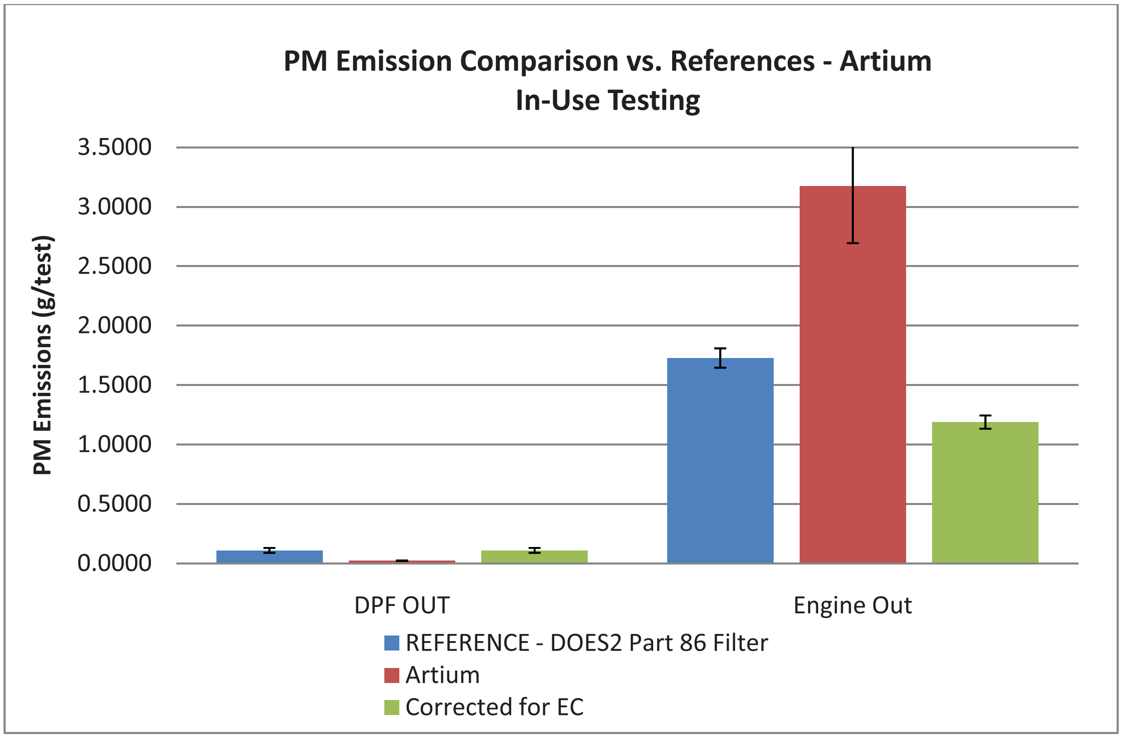


Figure 5-10. In-Use PM Emissions—Artium

When comparing control device efficiency calculations using reference standard data and Artium data, there is a 6% difference between the two methods. A large portion of this difference results from the significantly higher DPF-out emission rate observed with the reference method.

Table 5-13. In-Use Control Device Efficiency Determination—Artium LII-200

Engine Condition	Parameter	REFERENCE—DOES2 Part 86 Filter	Artium LII-200 Corrected	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.7	99.3	90.8
	% Difference vs. Reference		-6.00%	-9.3%

5.2.1.6. Reliability and Operability

The Artium system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. There were some minor software glitches that were observed during testing, including:

- an issue with time alignment of data in raw data files which had to be addressed by manual file manipulation
- problems with exporting data files or loss of original files either due to system or operator errors.

5.2.2. AVL 483 Micro Soot Sensor

5.2.2.1. Technology Description

The AVL 483 Micro Soot Sensor is a system for continuous measurement of soot concentration in the diluted exhaust from internal combustion engines. The device is sensitive for soot without interference from other components. The soot concentration is determined directly from the primary measurement quantity. The AVL 483 Micro Soot Sensor works on the photo acoustic principle. The photo-acoustic cell design allows a detection limit typically of about 5 µg/m³. With the additional "Conditioning Unit", engine-out measurements upstream from a Diesel Particulate Filter (DPF) are also possible. The conditioning unit provides controlled dilution of exhaust samples at an adjustable dilution ratio ranging from 2-20.

A summary of the AVL 483 Micro Soot Sensor is provided in Appendix B. The unit is capable of measuring soot mass concentration in a range from 0-50 mg/m^3. The detection limit is typically 5 µg/m^3. The Soot Sensor unit is shown in Figure 5-11.

Figure 5-11. AVL 483 Micro Soot Sensor

5.2.2.2. Installation & Setup Requirements

The AVL 483 Micro Soot Sensor required less than one hour to install and setup. The system used an 8 mm OD custom sample probe that is connected to a 2m heated sampling line routed to the sample conditioning unit (diluter). ERMS staff installed a sampling port on the exhaust transfer tube that allowed the insertion of the AVL sample probe. The sample conditioning unit required a connection to clean (filtered) shop air to supply dilution air. The system's software is well integrated and included a built-in startup diagnostic procedure for sensitivity loss and calibration check. Instrument warm-up of approximately 20 minutes was required, with an additional 15 minutes for the startup diagnostic check.

Overall, the installation and setup was straightforward, with very few problems encountered during installation or instrument setup. For the laboratory test program, the dilution ratio was varied depending upon the PM emission level. For DPF-out emissions, a dilution ratio of two was used; for intermediate PM levels, a dilution ratio of three was used, and for engine out measurements, a ratio of five was used.

5.2.2.3. Data Processing

The AVL 483 Micro Soot Sensor provided second-by-second PM soot concentration reported in units of mg/m^3. To convert this to a PM mass emission rate for comparison to the lab and in-use references, the exhaust flow rate was provided by ERMS to determine the total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. These data are then converted by AVL (and validated by Southern), into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the AVL data required no further processing.

5.2.2.4. Reference Comparison—Lab

The summary of the AVL lab testing results as compared to the reference standard is provided in Table 5-14. The AVL results compared best with the 1065 reference results. For the HDFTP cycle, results were within 33% or less at all operating conditions. In addition, the AVL 483 compares well with the elemental carbon reference mass emissions and higher PM loads, both the engine out and intermediate levels with emission levels within approximately 20% of reference for most cases. Considering that the AVL instrument provides a measurement of soot only and that, based on the 86 method EC/OC sampling results, the OC constitutes anywhere from approximately 14% to 75% of the PM mass, depending on operating condition, the comparison vs. the 1065 reference could improve if only the elemental carbon fraction of the PM was evaluated. Figure 5-12, Figure 5-13, and Figure 5-14 provide emission comparisons in g/test.

Figure 5-12. AVL 483 Micro Soot Sensor and Gravimetric Reference PM Emissions—DPF Out

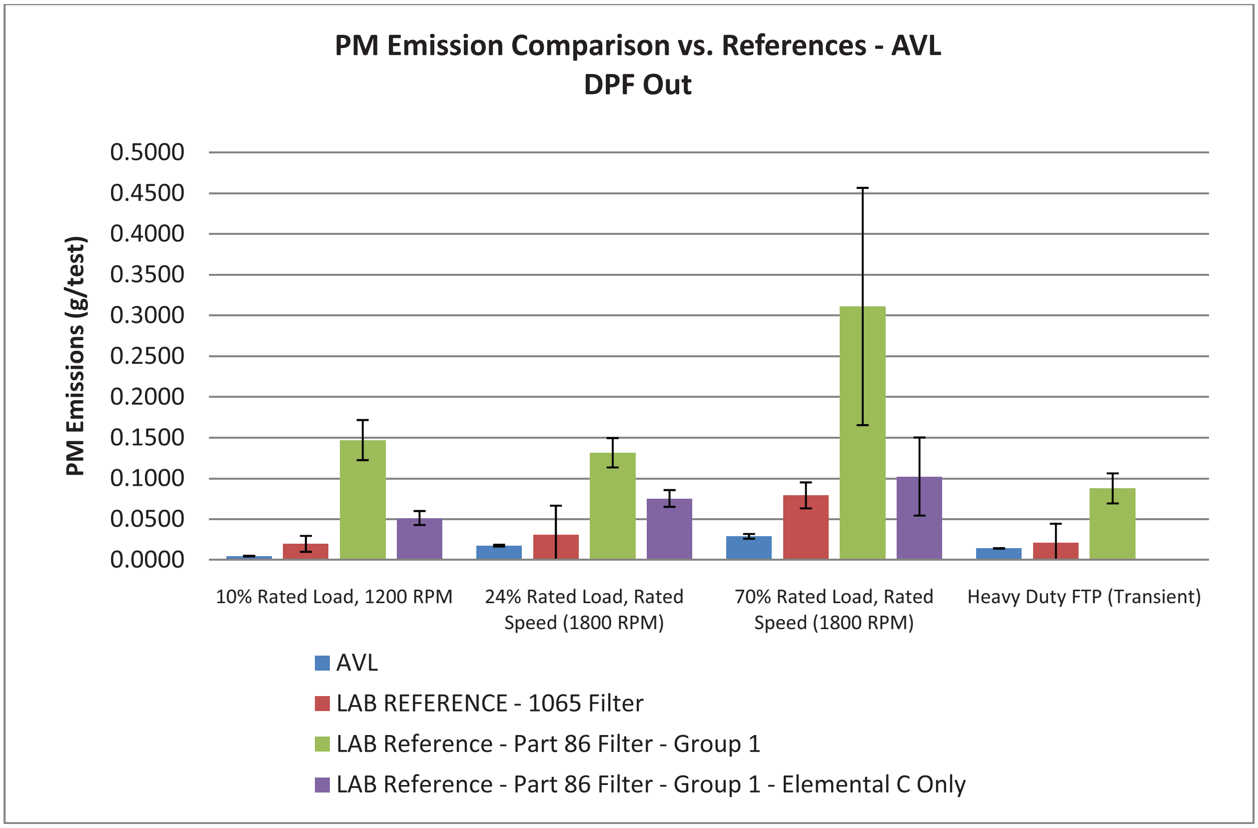


Figure 5-13. AVL 483 Micro Soot Sensor and Gravimetric Reference PM Emissions—Intermediate PM Loads

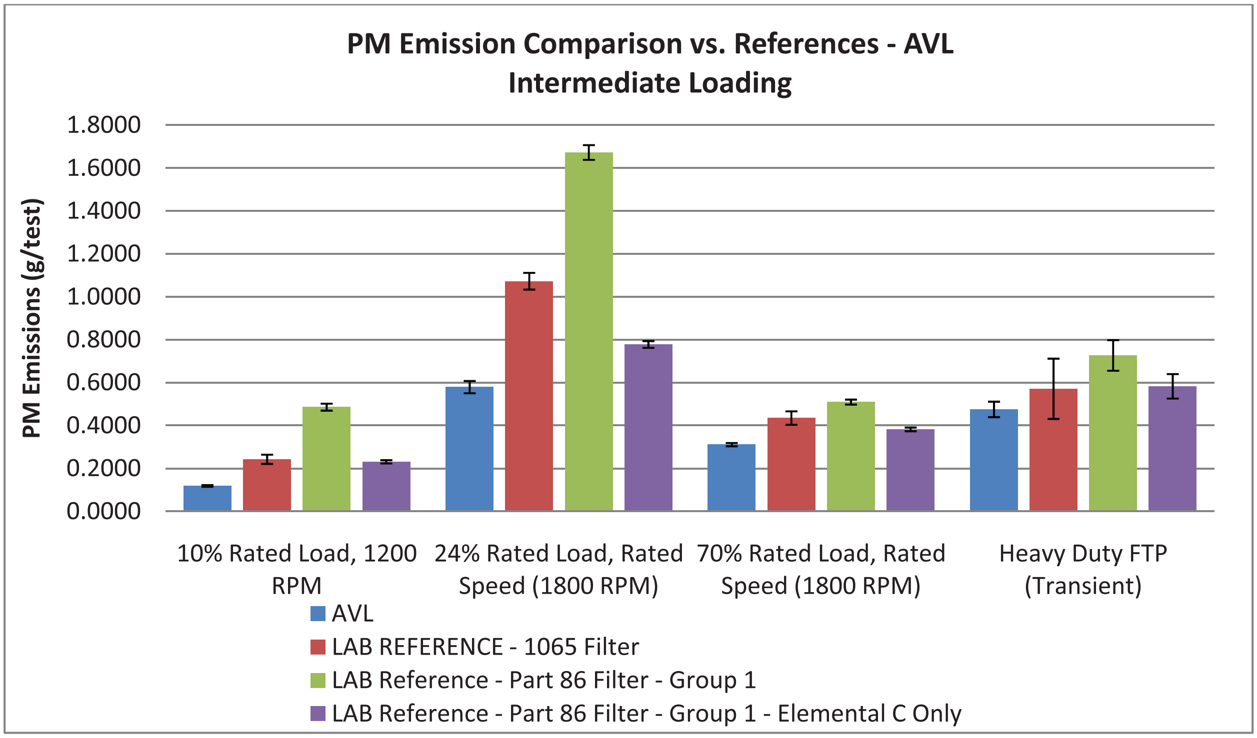


Figure 5-14. AVL 483 Micro Soot Sensor and Gravimetric Reference PM Emissions—Engine Out

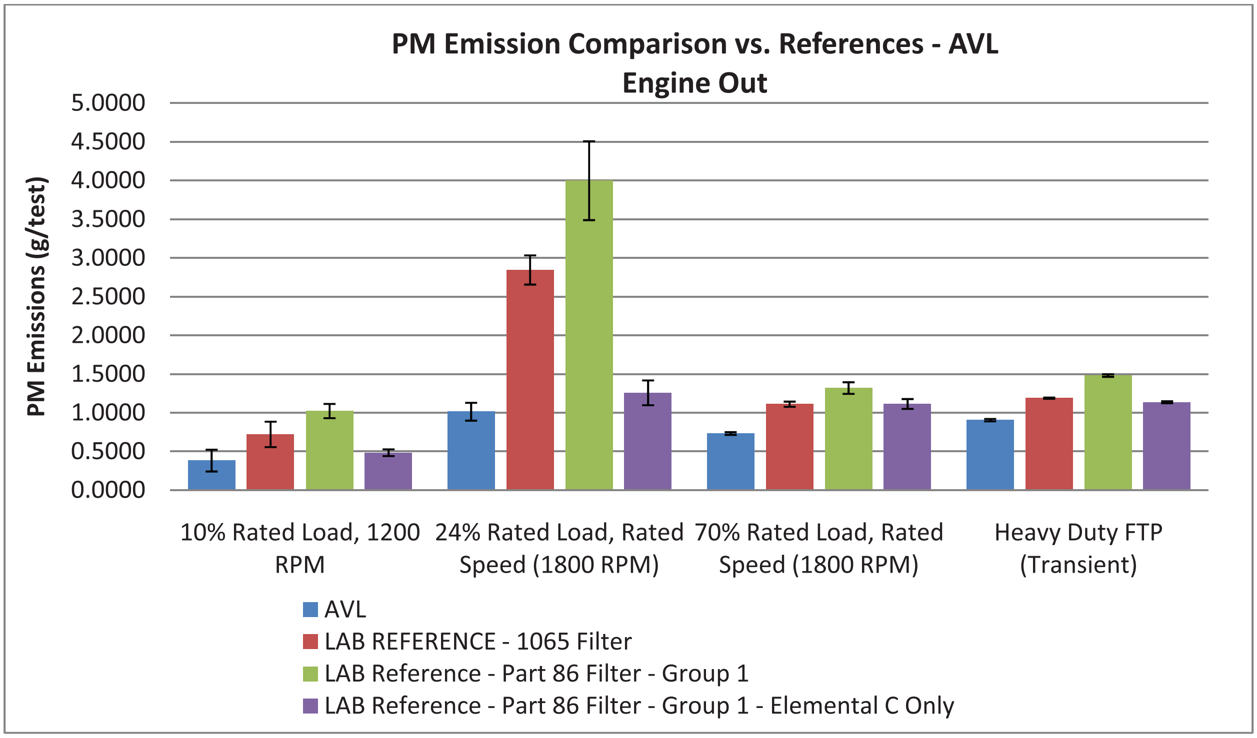


Table 5-14. Comparison of AVL 483 Results vs. Reference Standards

Engine Setting / Cycle	AVL 483 Difference vs. Reference (1065)	AVL 483 Difference vs. Reference (86)	AVL 483 Difference vs. Reference (86 EC)
DPF OUT			
10% Load, 1200 RPM	76.1%	96.8%	90.8%
24% Load, 1800 RPM	42.7%	86.7%	76.7%
70% Load, 1800 RPM	63.5%	90.7%	71.7%
HDFTP	32.5%	83.9%	N/A
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	51.2%	75.6%	48.7%
24% Load, 1800 RPM	46.0%	65.4%	25.6%
70% Load, 1800 RPM	28.5%	38.9%	18.6%
HDFTP	16.8%	34.6%	18.5%
ENGINE OUT			
10% Load, 1200 RPM	47.0%	62.6%	21.1%
24% Load, 1800 RPM	64.4%	74.7%	19.4%
70% Load, 1800 RPM	34.1%	44.5%	34.2%
HDFTP	23.9%	38.9%	20.4%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

5.2.2.4.1. Repeatability

The CV for the AVL 483 at each test condition is summarized in the table below, along with the CV for the reference methods for comparison. The AVL 483 CV was consistently below the reference standard CV in all but four instances. Even in those instances, the CV for the AVL system was very low, indicating excellent repeatability of measurement by the system.

Table 5-15. Comparison of CV for AVL 483 PM-PEMS and Laboratory Reference Methods

Engine Setting	CV—LAB REFERENCE—1065 Filter—Group 2	CV—LAB Reference—Part 86 Filter—Group 2	CV—AVL
DPF-Out			
10% Rated Load, 1200 RPM	0.494	0.168	0.0964
24% Rated Load, Rated Speed (1800 RPM)	1.173	0.137	0.0658
70% Rated Load, Rated Speed (1800 RPM)	0.201	0.468	0.101
Heavy Duty FTP (Transient)	1.12	0.210	0.0097
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0882	0.0333	0.0341
24% Rated Load, Rated Speed (1800 RPM)	0.0363	0.0204	0.0493
70% Rated Load, Rated Speed (1800 RPM)	0.0721	0.0225	0.0243
Heavy Duty FTP (Transient)	0.246	0.0979	0.0761
Engine -Out			
10% Rated Load, 1200 RPM	0.228	0.0897	0.367
24% Rated Load, Rated Speed (1800 RPM)	0.0662	0.127	0.114
70% Rated Load, Rated Speed (1800 RPM)	0.0301	0.0568	0.024
Heavy Duty FTP (Transient)	0.0068	0.0113	0.0172

5.2.2.4.2. Control Device Efficiency

In addition to evaluation of emissions, PM-PEMS may be used to evaluate the impacts of an emission control device or novel emission reduction technology, where a direct measurement of the emissions level is not the primary target, but, rather, a difference between two emission levels is targeted. To evaluate the suitability of the AVL 483 system in this application, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference method and AVL DPF-out and engine-out data from each set of test runs. As shown, the data from the AVL system provides control device efficiency values that are within less than 3.4% of the 1065 reference standard, and, in two cases, less than 1%. The 1065 reference is the primary standard used for comparison here due to the limited ability of the 86 reference method to measure DPF-out PM emission levels.

Table 5-16. Comparison of Control Device Evaluation Results for AVL 483 Micro Soot Sensor

Engine Condition	Parameter	Reference—1065	AVL	Reference—86	AVL	Reference—86 EC	AVL
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	97.3%	98.8%	85.6%	98.8%	89.4%	98.8%
	% Difference vs. Reference		-1.5%		-15.4%		-10.5%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.9%	98.3%	96.7%	98.3%	94.0%	98.3%
	% Difference vs. Reference		0.7%		-1.6%		-4.5%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	92.9%	96.1%	76.4%	96.1%	90.8%	96.1%
	% Difference vs. Reference		-3.4%		-25.7%		-5.8%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	98.2%	98.4%	94.1%	98.4%	N/A	98.4%
	% Difference vs. Reference		-0.2%		-4.6%		N/A

5.2.2.5. Comparison vs. References—In-Use

Comparisons of the AVL in-use PM emissions data vs. the DOES2 reference are provided in the table below. The differences between the AVL measurements and the reference standard results are approximately 90% at DPF-out. This difference is large, primarily because of the method differences. The part 86 in-use reference will typically provide results that are higher than an analytical technique focused primarily on soot measurement, such as the AVL. Therefore, the larger difference observed at DPF-out conditions is not surprising or to be taken as a deficiency. The engine-out PM emissions were within 44% of the reference standard. Again, as the AVL provides a soot-only measurement, this difference is not unreasonable, and is similar to the difference between the AVL measurements compared to the Part 86 reference method in the laboratory evaluation, which was 38%. Also note that the CV for the AVL measurements in the in-use evaluation was higher than those for the references.

Table 5-17. AVL 483 In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	REFERENCE—DOES2 Part 86 Filter—EC Only	AVL
DPF OUT	Mean Emission Rate (g/test)	0.110	0.110	0.0102
	CV	0.101	0.101	0.137
	% Difference vs. Reference		90.7%	90.7%
	Statistically Significant Difference?		YES	YES
Engine Out	Mean Emission Rate (g/test)	1.71	1.18	0.960
	CV	0.0205	0.0205	0.0427
	% Difference vs. Reference		18.8%	43.8%
	Statistically Significant Difference?		YES	YES

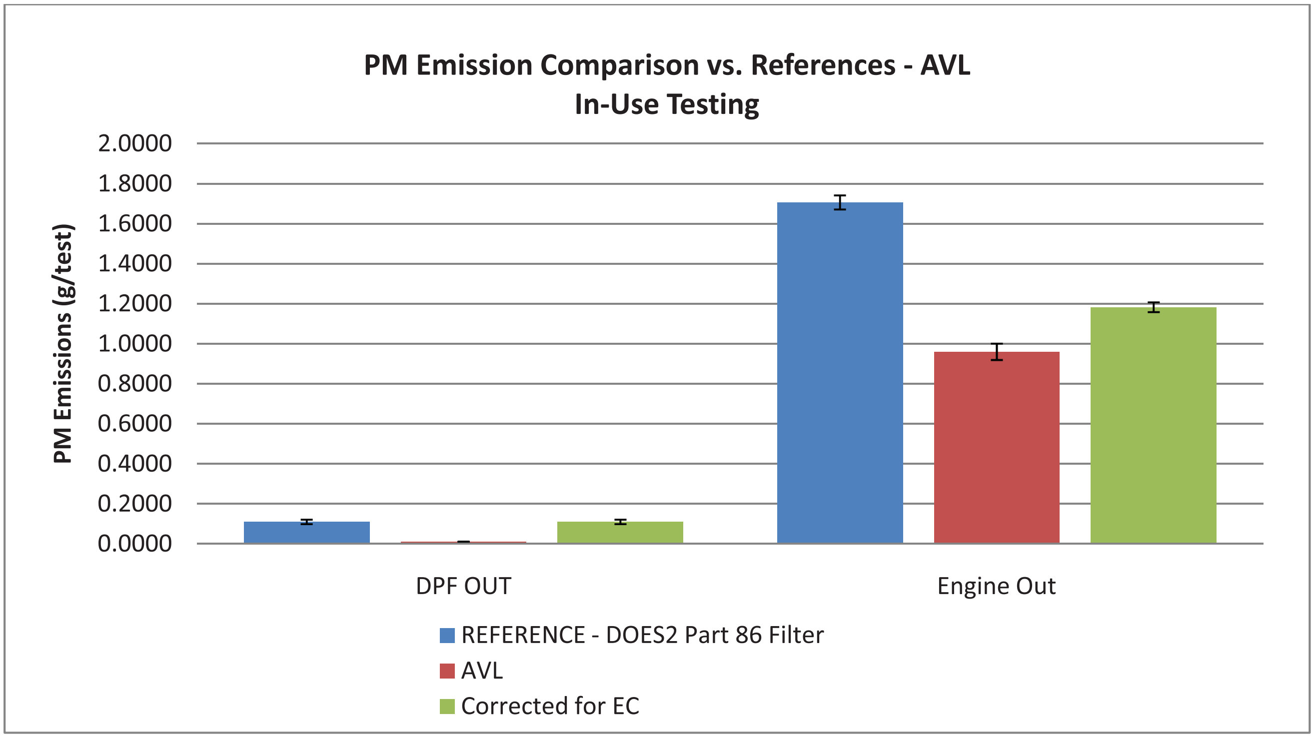


Figure 5-15. In-Use PM Emissions—AVL

The in-use efficiency of the DPF using the AVL unit was about 6% less than that using the DOES2, Part 86 compliant system. A large portion of this difference results from the significantly higher DPF out emission rate observed with the reference method compared to that observed by the AVL system as discussed earlier in this section.

Table 5-18. In-Use Control Device Efficiency Determination—AVL 483

Engine Condition	Parameter	Reference—DOES2-86	AVL 483	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.6%	98.9%	90.7%
	% Difference vs. Reference		-5.75%	-9.1%

5.2.2.6. Reliability and Operability

The AVL system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. The observed installation and operation of the system was straightforward and the analyzer, sampling system and software systems seemed well integrated.

After a week of testing, AVL technicians changed filters and cleaned the windows in the analyzer. They stated this was not necessary, but did it anyway to inspect system components and ensure optimal operation of the system. No other issues arose during any of the testing with the AVL system.

5.2.3. Dekati DMM-230A

5.2.3.1. Technology Description

The Dekati Mass Monitor (DMM), is a real-time instrument for diesel and gasoline vehicle PM (Particulate Matter) emission measurements. It can be used either with a tailpipe sampling system or existing CVS tunnel. The DMM provides second-by-second PM mass emissions as well as particle size and number. The DMM lower detection limit is 1 $\mu g/m^3$, with a mass concentration range of approximately 1-5000 $\mu g/m^3$. The DMM is applicable to particles in the size range from 0-1200 nm.

The operating principle is based on particle charging, particle density measurement, particle size classification using inertial impaction, and electrical detection of charged particles. The device consists of a corona charger complete with on-line particle density measurement, and an inertial 6-stage impactor with electrical detection. A diffusion charger is used to give a precisely known charge to particles, and an integrated mobility analyzer provides information on particle electrical mobility. Combining the particle mobility size information from the charger and aerodynamic size from the impactor enables calculation of the effective density of the particles required for conversion from measured current values to particle mass concentration.

A summary of the Dekati DMM-230 specifications is provided in Appendix B. The DMM is shown in Figure 5-16. Dekati DMM-230.

Figure 5-16. Dekati DMM-230

5.2.3.2. Installation & Setup Requirements

The Dekati DMM required about one hour to install and setup, including a 20-30 minute warm-up period for the dilution system and the DMM. The system used an 8mm sample port on the exhaust pipe connected to a heated sample line routed to the diluter. The diluter consisted of two of Dekati's DI-1000 ejector diluters in series to obtain a dilution ratio of 32 for most sampling periods. The dilution system required a connection to clean (filtered) shop air to supply dilution air. The system's software is well integrated with the analyzer and dilution system.

Overall, the installation and setup was straightforward, with very few problems encountered during installation or instrument setup.

5.2.3.3. Data Processing

The Dekati DMM-230 provided second-by-second PM mass concentration reported in units of mg/m^3. To convert this to a PM mass emission rate for comparison to the lab and in-use references, the exhaust flow rate was provided by ERMS to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. This data was then converted by Dekati (and validated by Southern), into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the Dekati data required no further processing. In addition, the Dekati unit provides particle size and number information on a real time basis for further analysis of PM characteristics.

5.2.3.4. Reference Comparison—Lab

The summary of the Dekati testing results as compared to the reference standard is provided in Table 5-19. The Dekati DMM results compared favorably with the 1065 reference results, with no statistical difference observed between the methods in eight of twelve operating conditions. This is partially a result of the variability of the reference methods, but does reflect a good mass correlation between the Dekati DMM and 1065 methods, especially at intermediate PM load and engine out conditions. Figure 5-17, Figure 5-18, and Figure 5-19 provide emission comparisons in g/test.

Figure 5-17. Dekati DMM and Gravimetric Reference PM Emissions—DPF Out

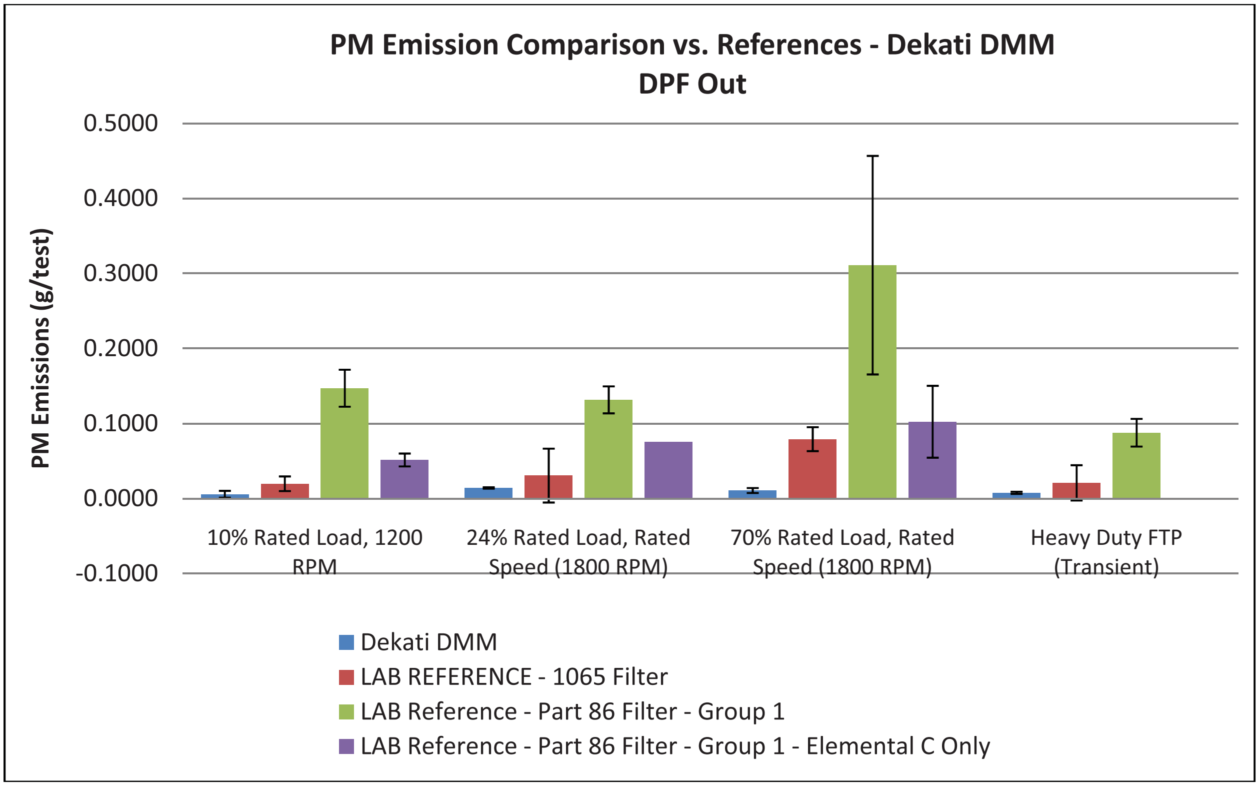


Figure 5-18. Dekati DMM and Gravimetric Reference PM Emissions—Intermediate PM Loads

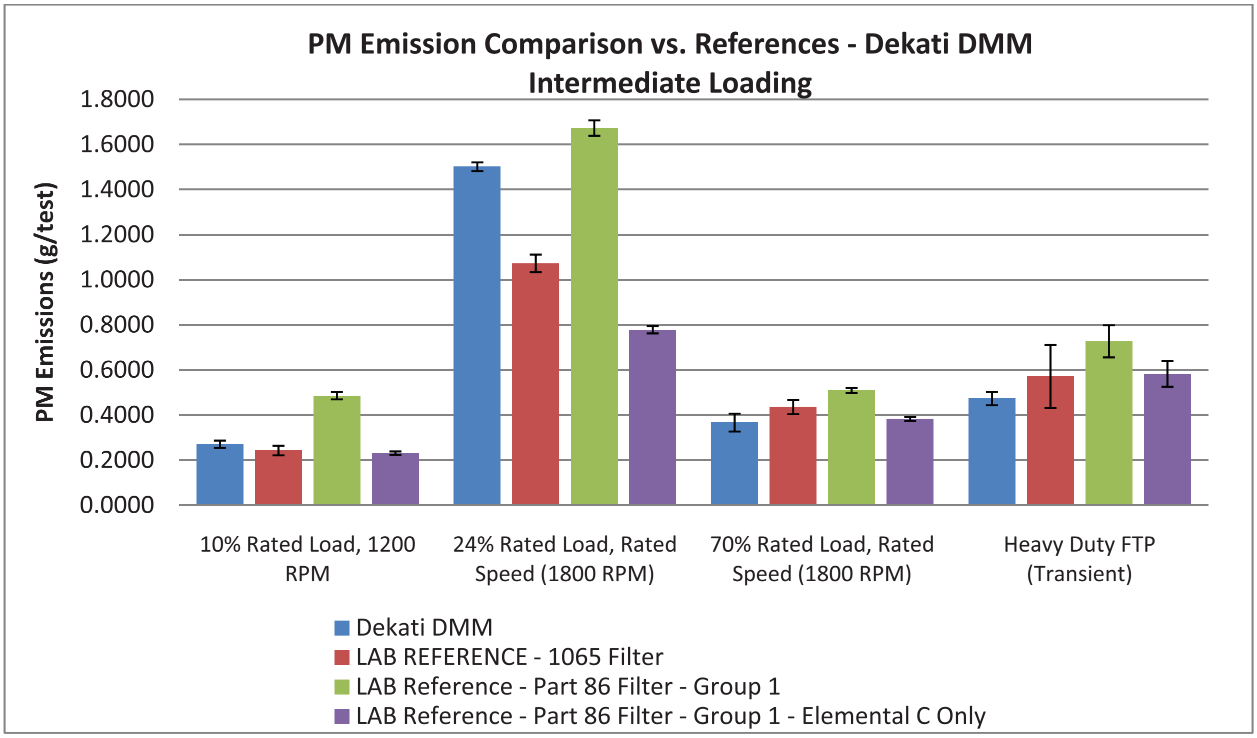


Figure 5-19. **Dekati DMM and Gravimetric Reference PM Emissions—Engine Out**

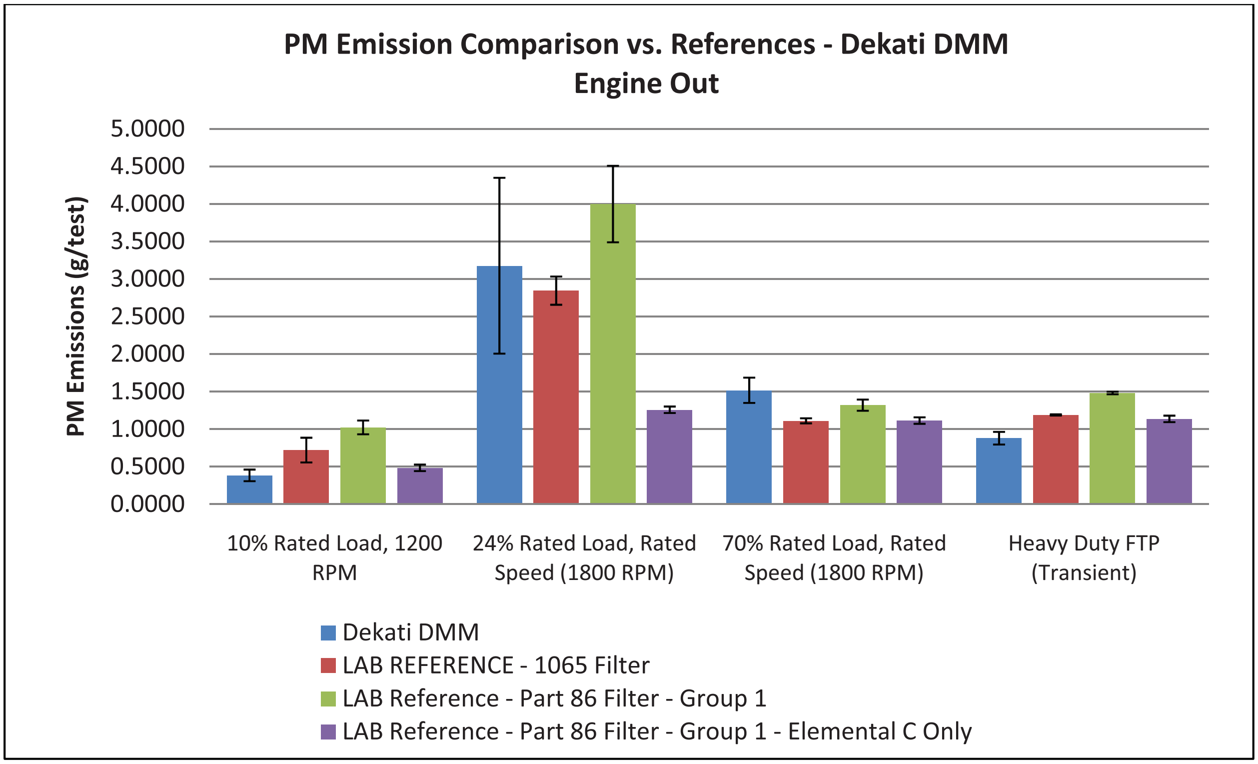


Table 5-19. Comparison of Dekati DMM Results vs. Reference Standards

Engine Setting / Cycle	Dekati DMM Difference vs. Reference (1065)	Dekati DMM Difference vs. Reference (86)	Dekati DMM Difference vs. Reference (86 EC)
DPF OUT			
10% Load, 1200 RPM	70.8%	96.1%	88.8%
24% Load, 1800 RPM	53.9%	89.3%	81.3%
70% Load, 1800 RPM	86.4%	96.6%	89.5%
HDFTP	63.3%	91.2%	N/A
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	-11.4%	44.3%	-17.1%
24% Load, 1800 RPM	-40.0%	10.3%	-92.9%
70% Load, 1800 RPM	15.7%	28.0%	4.01%
HDFTP	17.2%	34.9%	18.8%
ENGINE OUT			
10% Load, 1200 RPM	46.7%	62.4%	20.7%
24% Load, 1800 RPM	-11.7%	20.6%	-152%
70% Load, 1800 RPM	-36.6%	-15.0%	-36.2%
HDFTP	26.0%	40.6%	22.6%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

5.2.3.4.1. Repeatability

The CV for the Dekati DMM at each test condition is summarized in the table below, along with the CV for the reference methods for comparison. The Dekati DMM CV was consistently below or on par with the reference standard CV for DPF out and intermediate loads. Yet, at engine-out conditions, the CV was typically higher that either reference method.

Table 5-20. Comparison of CV for Dekati DMM PM-PEMS and Laboratory Reference Methods

Engine Setting	CV—LAB REFERENCE—1065 Filter—Group 2	CV—LAB Reference—Part 86 Filter—Group 2	CV—Dekati DMM
DPF-Out			
10% Rated Load, 1200 RPM	0.494	0.168	0.780
24% Rated Load, Rated Speed (1800 RPM)	1.17	0.137	0.0666
70% Rated Load, Rated Speed (1800 RPM)	0.201	0.468	0.306
Heavy Duty FTP (Transient)	1.12	0.210	0.189
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0882	0.0333	0.0606
24% Rated Load, Rated Speed (1800 RPM)	0.0363	0.0204	0.0128
70% Rated Load, Rated Speed (1800 RPM)	0.0721	0.0225	0.108
Heavy Duty FTP (Transient)	0.246	0.0979	0.0632
Engine –Out			
10% Rated Load, 1200 RPM	0.228	0.0897	0.201
24% Rated Load, Rated Speed (1800 RPM)	0.0662	0.127	0.369
70% Rated Load, Rated Speed (1800 RPM)	0.0301	0.0568	0.111
Heavy Duty FTP (Transient)	0.0068	0.0113	0.0957

5.2.3.4.2. Control Device Efficiency

To evaluate the suitability of the Dekati DMM in determination of control device performance, a relative measurement, as opposed to an absolute, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference method and Dekati DMM DPF-out and engine-out data from each set of test runs. As shown, the data from the Dekati system provides control device efficiency values that are within less than 1.3% of the 1065 reference standard for three of the operating conditions. The 1065 reference is the primary standard used for comparison here due to the limited ability of the 86 reference to measure DPF-out PM emission levels.

Table 5-21. Comparison of Control Device Evaluation Results for Dekati DMM-230A

Engine Condition	Parameter	Reference—1065	Dekati DMM	Reference—86	Dekati DMM	Reference—86 EC	Dekati DMM
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	97.3%	98.5%	85.6%	98.5%	89.4%	98.5%
	% Difference vs. Reference		-1.3%		-15.0%		-10.2%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.9%	99.6%	96.7%	99.6%	94.0%	99.6%
	% Difference vs. Reference		-0.6%		-2.9%		-5.9%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	92.9%	99.3%	76.4%	99.3%	90.8%	99.3%
	% Difference vs. Reference		-6.9%		-29.9%		-9.3%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	98.2%	99.1%	94.1%	99.1%	N/A	99.1%
	% Difference vs. Reference		-0.9%		-5.4%		N/A

5.2.3.5. Comparison vs. References—In-Use

Comparisons of the Dekati DMM in-use PM emissions data vs. the DOES2 reference are provided in the table below. The differences between the Dekati DMM measurements and the reference standard results are approximately 90% at DPF-out. Nevertheless, the larger differences observed at DPF-out conditions is not surprising due to the difficulties encountered in measuring DPF-out level PM emissions with the part 86 method. The Dekati DMM measurements of engine-out PM emissions were within 55% of the reference standard. This is consistent with the differences observed between the Dekati DMM and 86 reference method laboratory tests.

Table 5-22. Dekati DMM In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	Dekati DMM	REFERENCE—DOES2 Part 86 Filter—EC Only
DPF OUT	Mean Emission Rate (g/test)	0.110	0.0021	0.110
	CV	0.1013	0.416	0.101
	% Difference vs. Reference		98.1%	98.1%
	Statistically Significant Difference?		YES	YES
Engine Out	Mean Emission Rate (g/test)	1.71	0.773	1.18
	CV	0.0205	0.177	0.0205
	% Difference vs. Reference		54.7%	34.7%
	Statistically Significant Difference?		YES	YES

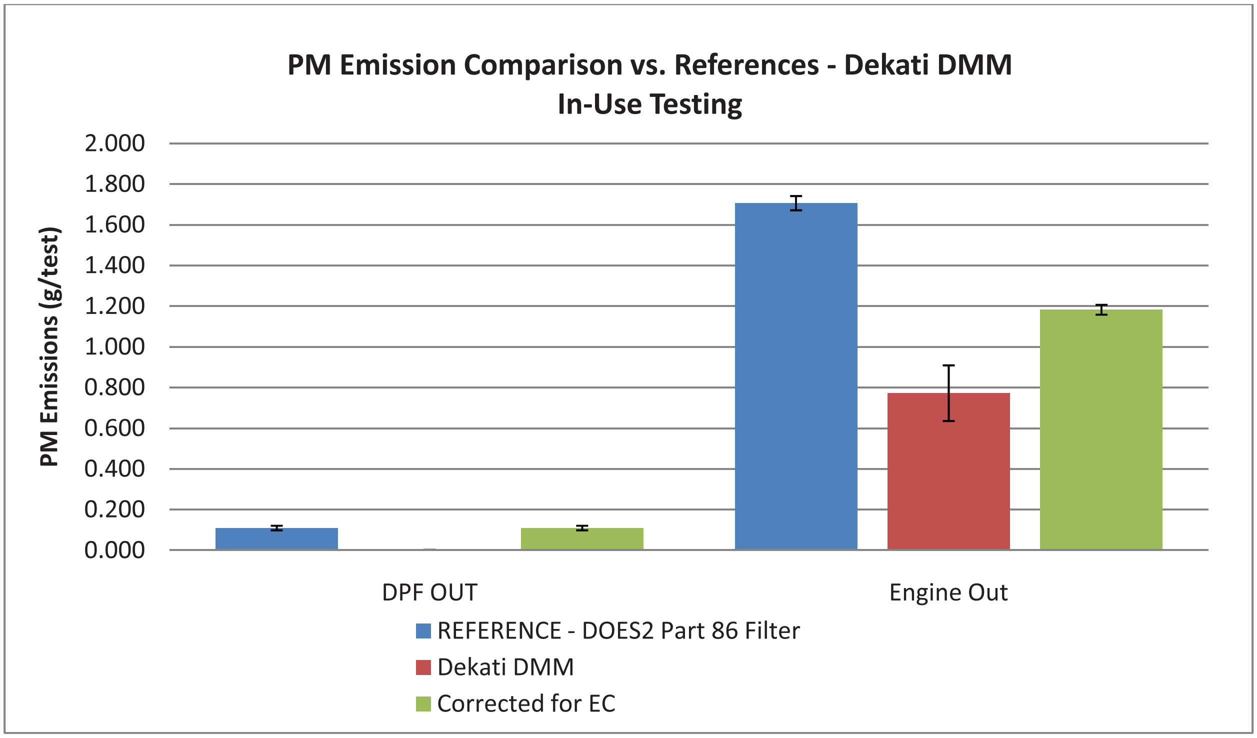


Figure 5-20. In-Use PM Emissions—Dekati DMM

When comparing control device efficiency calculations using reference standard data and Dekati DMM data for the in-use testing, there is an approximately 6% difference between the two methods. A large portion of this difference results from the significantly higher DPF out emission rate observed with the reference method.

Table 5-23. In-Use Control Device Efficiency Determination—Dekati DMM

Engine Condition	Parameter	Reference—DOES2-86	Dekati DMM	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.6%	99.7%	90.7%
	% Difference vs. Reference		-6.6%	-10.0%

5.2.3.6. Reliability and Operability

The Dekati DMM system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. The observed installation and operation of the system was straightforward and the analyzer, sampling system and software systems seemed well integrated.

5.2.4. Dekati ETaPS

5.2.4.1. Technology Description

The Dekati Electrical Tailpipe Particulate Sensor (ETaPS), is a real-time instrument for diesel and gasoline vehicle PM emission measurements. It is installed directly into the vehicle tailpipe, and therefore it does not need a dilution systems usually required for PM measurements. The ETaPS detects the amount of particles flowing through the sensor head. Its low power consumption and lack of dilution equipment makes it a feasible device for on-board tests as well as for I/M (inspection and maintenance) type of measurements.

ETaPS operation is based on the principle of particle charging and electrical detection. When exhaust flow passes through the inner charging chamber, a known amount of charge is attached to all solid and volatile particles. The charge carried by particles leaving the outer charging cage is then measured with an electrometer. This signal is proportional to the amount of particles emitted by the engine.

A summary of the Dekati ETaPS specifications is provided in Appendix B. The ETaPS is shown in Figure 5-21.

Figure 5-21. **Dekati ETaPS**

5.2.4.2. Installation & Setup Requirements

The Dekati ETaPS required less than 30 minutes to install and setup, because of the lack of a sampling system and direct attachment at the end of the exhaust tailpipe. Additional time was needed for setup and calibration checks. The ETaPS was clamped on exhaust tube to attach to the engine exhaust. The ETaPS required a source of filtered air for system cooling and cleaning. The ETaPS used an on-board controller and datalogger, but can be connected to a standard PC for data access.

5.2.4.3. Data Processing

The Dekati ETaPS provides a second-by-second voltage signal output that corresponds directly to a PM Mass concentration. To obtain a PM mass concentration from the voltage value, however, the ETaPS must be correlated with an instrument measuring PM mass concentration on the engine being evaluated. A general correlation factor may also be used based on multiple data sources maintained by Dekati. In this case, Dekati ran the ETaPS during the same period when the DMM-230 was being run for all test cases. The DMM-230 provided a direct PM mass emission concentration measurement that Dekati used to develop a linear correlation between ETaPS voltage and PM mass concentration. Using the derived correlation equation, Dekati was able to convert all ETaPS outputs to a PM mass concentration reported in units of mg/m^3.

To convert this derived PM mass to a PM mass emission rate for comparison to the lab and in-use references, the exhaust flow rate was provided by ERMS to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. This data was then converted by Dekati (and validated by Southern), into the reporting units of g/test, g/gal, and g/bhp-hr.

5.2.4.4. Reference Comparison—Lab

The summary of the Dekati testing results as compared to the reference standard is provided in Table 5-24. The Dekati ETaPS results compared most favorably with the 1065 reference results, particularly at the intermediate and engine out emission levels. Overall, the ETaPS agreed with the 1065 reference results seven out of the 12 trials. In some cases, however, there was a major excursion observed at the 70% power engine operating condition, where the ETaPS results were over 200% different from the reference standards. It is not known why this significant difference occurred at this condition. This condition provided some of the lowest emission rates observed in ERMS of g/bhp-hr and also had the highest engine out elemental carbon content at 84%. It also had the highest exhaust flow rate and exhaust and test cell temperature. Figure 5-22, Figure 5-23, and Figure 5-24 provide emission comparisons in g/test.

Table 5-24. Comparison of Dekati ETaPS Results vs. Reference Standards

Engine Setting / Cycle	Dekati ETaPS Difference vs. Reference (1065)	Dekati ETaPS Difference vs. Reference (86)	Dekati ETaPS Difference vs. Reference (86 EC)
DPF-OUT			
10% Load, 1200 RPM	-63.2%	78.1%	37.3%
24% Load, 1800 RPM	-0.07%	76.7%	59.4%
70% Load, 1800 RPM	-78.2%	54.6%	-37.9%
HDFTP	-283%	8.82%	N/A
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	6.93%	53.5%	2.15%
24% Load, 1800 RPM	-22.7%	21.3%	-69.1%
70% Load, 1800 RPM	-199%	-155%	-240%
HDFTP	-5.86%	16.8%	-3.76%
ENGINE-OUT			
10% Load, 1200 RPM	-0.42%	29.2%	-49.4%
24% Load, 1800 RPM	-13.4%	19.3%	-156%
70% Load, 1800 RPM	-280%	-220%	-279%
HDFTP	-16.5%	6.49%	-21.9%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

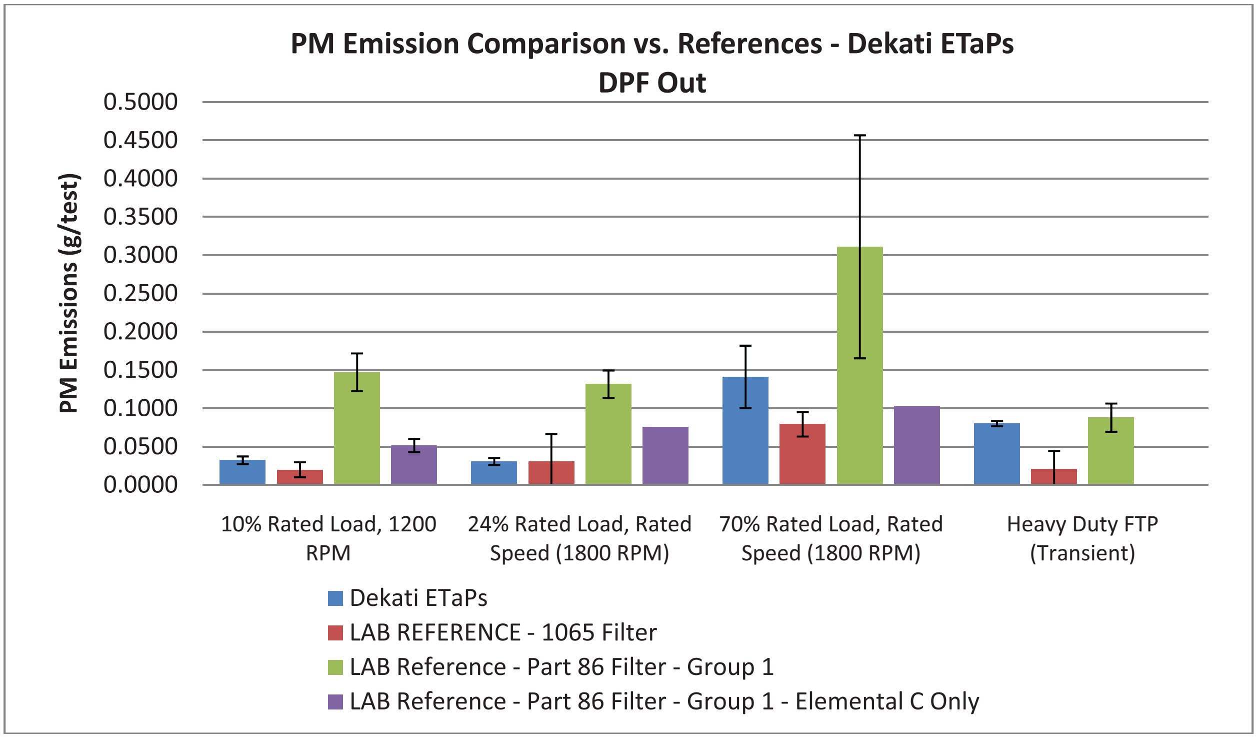


Figure 5-22. Dekati ETaPS and Gravimetric Reference PM Emissions—DPF-Out

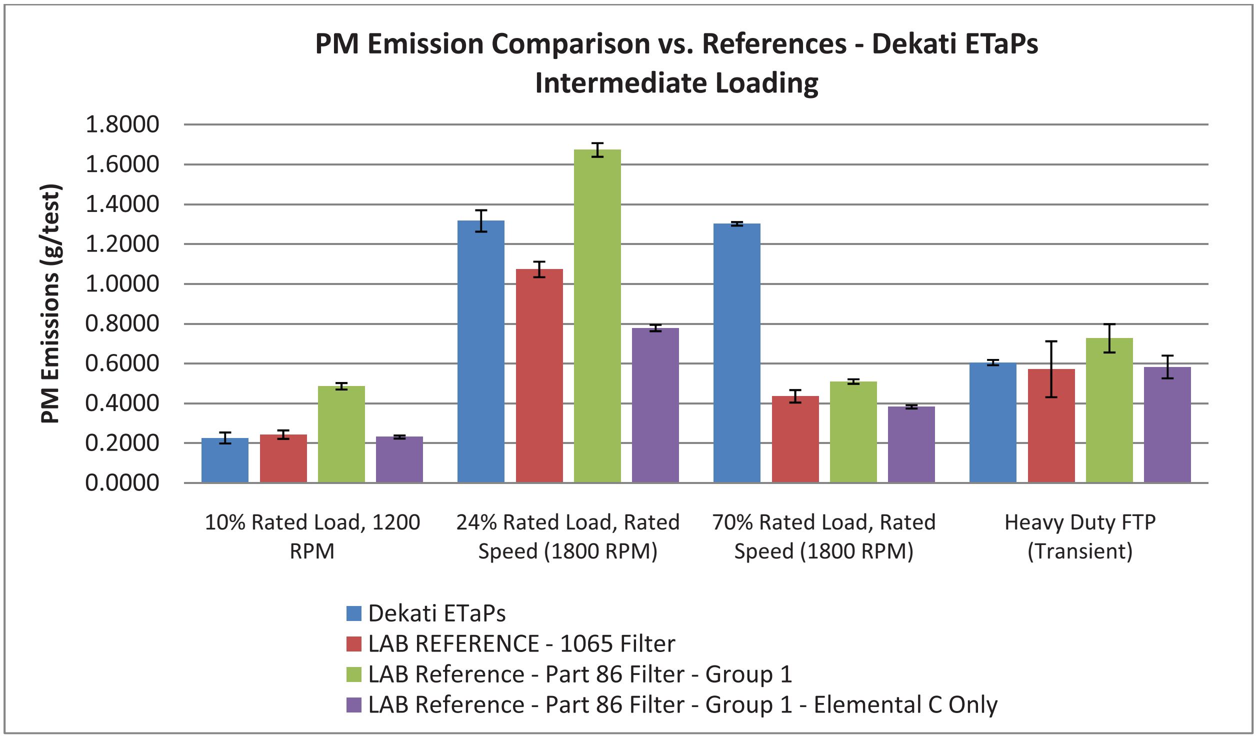


Figure 5-23. Dekati ETaPS and Gravimetric Reference PM Emissions—Intermediate PM Loads

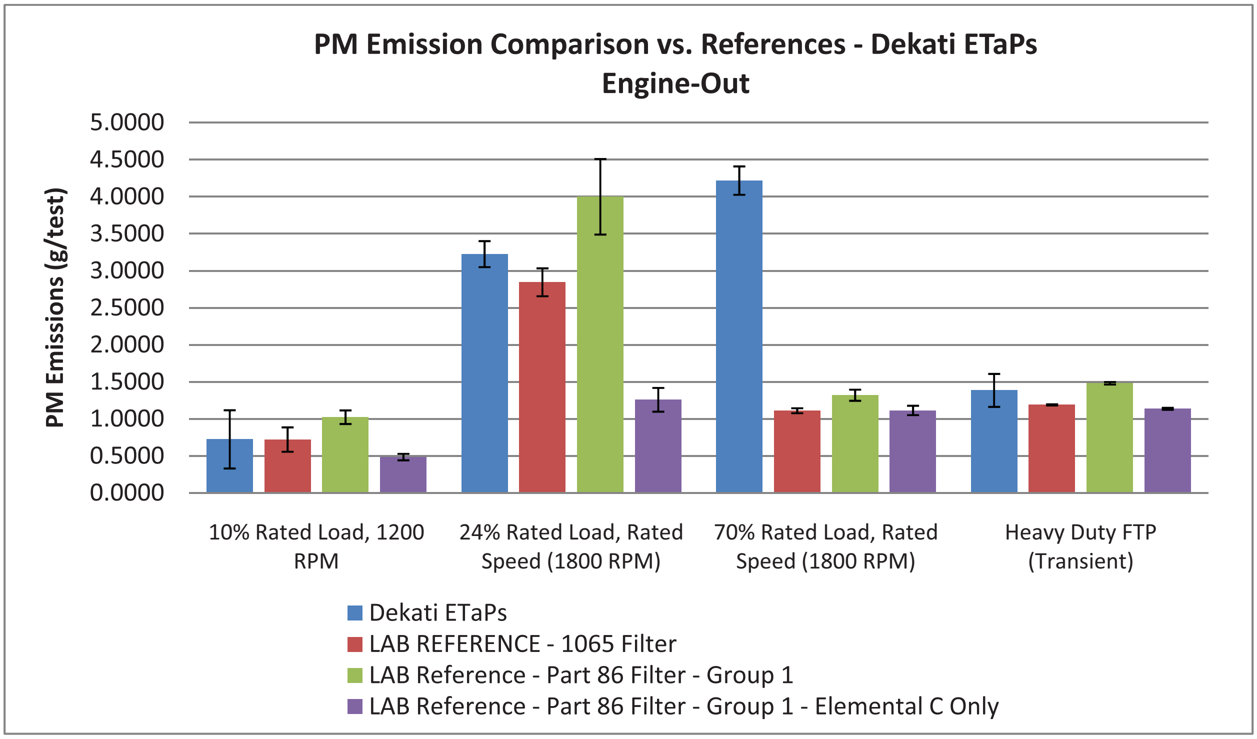


Figure 5-24. Dekati ETaPS and Gravimetric Reference PM Emissions—Engine-Out

5.2.4.4.1. Repeatability

The CV for the Dekati ETaPS at each test condition is summarized in the table below, along with the CV for the reference methods for comparison. The Dekati ETaPS CV was typically lower than the reference standard CV for all loads except engine-out, where the FTP cycle resulted in significantly higher CV than the reference. This indicates excellent reproducibility of measurement across nearly all conditions.

Table 5-25. Comparison of CV for Dekati ETaPS PM-PEMS and Laboratory Reference Methods

Engine Setting	CV—LAB REFERENCE—1065 Filter—Group 2	CV—LAB Reference—Part 86 Filter—Group 2	CV—Dekati ETaPS
DPF-Out			
10% Rated Load, 1200 RPM	0.49	0.17	0.15
24% Rated Load, Rated Speed (1800 RPM)	1.17	0.14	0.148
70% Rated Load, Rated Speed (1800 RPM)	0.20	0.47	0.29
Heavy Duty FTP (Transient)	1.12	0.21	0.044
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.09	0.03	0.12
24% Rated Load, Rated Speed (1800 RPM)	0.04	0.02	0.041
70% Rated Load, Rated Speed (1800 RPM)	0.07	0.02	0.0069
Heavy Duty FTP (Transient)	0.25	0.10	0.022
Engine –Out			
10% Rated Load, 1200 RPM	0.23	0.09	0.54
24% Rated Load, Rated Speed (1800 RPM)	0.07	0.13	0.054
70% Rated Load, Rated Speed (1800 RPM)	0.03	0.06	0.045
Heavy Duty FTP (Transient)	0.01	0.01	0.16

5.2.4.4.2. Control Device Efficiency

To evaluate the suitability of the Dekati ETaPS in determination of control device performance, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference method and Dekati ETaPS DPF-out and engine-out data from each set of test runs. The data from the Dekati ETaPS provides control device efficiency values that are within less than 4% of the 1065 reference standard or better.

Table 5-26. Comparison of Control Device Evaluation Results for Dekati ETaPS

Engine Condition	Parameter	Reference—1065	ETaPS	Reference—86	ETaPS	Reference—86 EC	ETaPS
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	97.3%	95.5%	85.6%	95.5%	89.4%	95.5%
	% Difference vs. Reference		1.8%		-11.6%		-6.9%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.9%	99.0%	96.7%	99.0%	94.0%	99.0%
	% Difference vs. Reference		-0.1%		-2.4%		-5.4%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	92.9%	96.7%	76.4%	96.7%	90.8%	96.7%
	% Difference vs. Reference		-4.1%		-26.5%		-6.4%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	98.2%	94.2%	94.1%	94.2%	N/A	94.2%
	% Difference vs. Reference		4.1%		-0.2%		N/A

5.2.4.5. Comparison vs. References—In-Use

Comparisons of the Dekati ETaPS in-use PM emissions data vs. the DOES2 reference are provided in the table below. The difference between ETaPS and the reference standards are above 90% at DPF-out is similar to the difference between the 1065 and 86 laboratory results. Based on the laboratory results, the larger difference observed at DPF-out conditions was anticipated due to the reference method used during in-use testing. The ETaPS engine out PM emission measurements were within 55% of the reference standard. This is consistent with the differences observed between the Dekati DMM and 86 reference in laboratory tests.

Table 5-27. Dekati ETaPS In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	Dekati ETaPS	REFERENCE—DOES2 Part 86 Filter—EC Only
DPF OUT	Mean Emission Rate (g/test)	0.110	0.0020	0.110
	CV	0.101	0.0732	0.101
	% Difference vs. Reference		98.1%	98.1%
	Statistically Significant Difference?		YES	YES
Engine Out	Mean Emission Rate (g/test)	1.71	0.763	1.18
	CV	0.0205	0.106	0.0205
	% Difference vs. Reference		55.3%	35.5%
	Statistically Significant Difference?		YES	YES

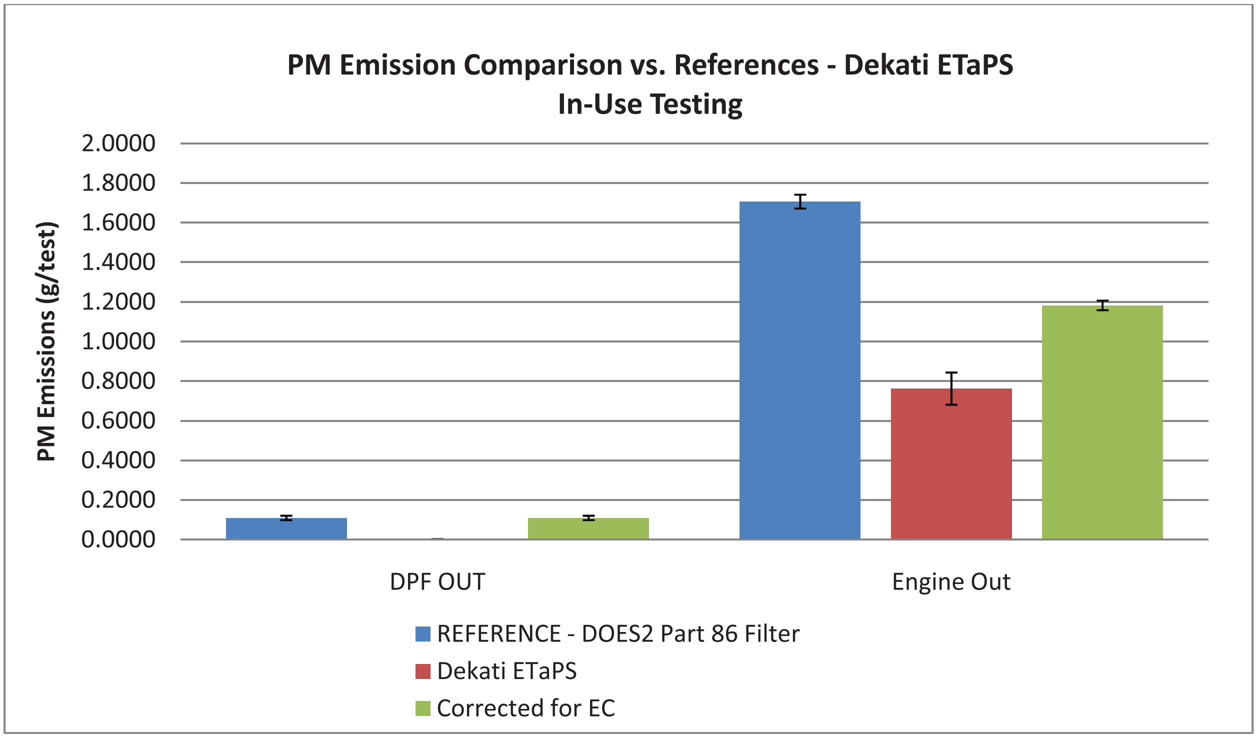


Figure 5-25. In-Use PM Emissions—Dekati ETaPS

When comparing control device efficiency calculations using reference standard data and Dekati DMM data for the in-use testing, there is an approximately 6% difference between the two methods. A large portion of this difference results from the significantly higher DPF-out emission rate observed with the reference method.

Table 5-28. In-Use Control Device Efficiency Determination—Dekati ETaPS

Engine Condition	Parameter	Reference—DOES2-86	ETaPS	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.6%	99.7%	90.7%
	% Difference vs. Reference		-6.6%	-9.90%

5.2.4.6. Reliability and Operability

The Dekati ETaPS system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. There were a few minor issues that arose that required attention during the testing program, including:

- Requirement to determine approximate emissions range during tests and select high or low range on the ETaPS. In a couple of cases, ranges were changed on subsequent tests due to over-ranging.

- In one test, and operator error led to improper cooling for the ETaPS, which was detected and fixed for later test runs.

5.2.5. CONTROL SISTEM MICRO-PSS

5.2.5.1. Technology Description

The Control Sistem Micro-PSS is a partial flow dilution tunnel with associated flow controllers and sampling system. The Micro-PSS provides 40CFR 86 and ISO 16183 compliant sampling system for particulate sample collection via a gravimetric filter method. The Micro-PSS can be used for sample collection over steady state and transient cycles on a wide variety of engine types and sizes. Its size and low power requirements allow it to be used in on-board, real-world testing programs. The Control Sistem unit tested here did not provide any real-time measurement capability for PM emissions, nor did it provide exhaust flow measurement capability to allow for conversion of PM mass concentrations to PM mass emission rates. In addition, the system required the input of an exhaust flow volume for control of the partial flow dilution sampling system. This required that the flow signal from the ERMS LFE be routed to the Control Sistem controller prior to testing.

A summary of the Micro-PSS system's specifications is provided in Appendix B. The Micro PSS is shown below.

Figure 5-26. Control Sistem Micro-PSS

5.2.5.2. Installation & Setup Requirements

The Micro PSS required approximately one hour for the primary setup and installation. The installation consisted of:

- Directly welding the sample probe to the exhaust transfer tubing
- Installation of the heated sampling line
- connection of the sample line to the Micro-PSS
- connection of all systems to electrical power (24V)
- provision of 0-5v signal from LFE differential pressure transducer and thermocouple to control dilution air flow rate and brief reprogramming of system based on flow signal information
- startup and warmup of the system
- initial operational checks and setup.

The in-use testing setup was similar to the lab setup. The inability of the Micro-PSS system to obtain its own exhaust flow and temperature signal was a significant issue, and would prevent its utilization in on-board emissions tests unless a signal was coming from other instrumentation such as a gaseous PEMS. Control Sistem indicated that they were developing additional equipment for this purpose to allow for standalone implementation of their system. As a result of this issue, significant time was spent identifying which signals from the LFE would be appropriate and wiring the system to provide the real-time signal from the LFE to the Micro-PSS controller.

It should be noted that, as with many instruments in this test program, although a total PM mass for a specified test cycle may be provided, an emission rate relies on knowledge of the exhaust flow rate. As discussed above, Control Sistem had to use ERMS data to both control its dilution system and calculate emission rates in units of g/test, g/min, g/gal, or g/bhp-hr.

5.2.5.3. Comparison vs. Reference—Lab

5.2.5.3.1. Data Processing

The Micro-PSS provides an integrated PM sample, collected on a filter and measured gravimetrically. Therefore, a total PM mass for each test cycle is determined (g/test). This data was then converted, in a uniform calculation for all vendors validated by Southern, into the reporting units of g/gal, and g/bhp-hr. Beyond this conversion, the Micro-PSS data required no further processing.

5.2.5.3.2. Reference Comparison

The summary of the Micro-PSS results is provided in Table 5-29. As expected, the Micro-PSS compares most favorably with the Part 86 reference methods. Since it is based on this type of sampling system, and is very similar to the DOES2, this correlation is expected. In addition, based on the sampling system conditions and method, the very large differences between the 1065 reference results and the Micro-PSS at DPF-out conditions was anticipated and are consistent with the differences between the 86 and 1065 methods observed. Figure 5-27, Figure 5-28, and Figure 5-29 also present the results.

Table 5-29. Difference Between Control Sistem Micro-PSS Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	Micro-PSS Difference vs. Reference (1065)	Micro-PSS Difference vs. Reference (86)	Micro-PSS Difference vs. Reference (86 EC)
DPF-OUT			
10% Load, 1200 RPM	-287%	59.6%	-68.2%
24% Load, 1800 RPM	-290%	9.78%	174%
70% Load, 1800 RPM	-496%	-124%	-663%
HDFTP	-271%	-9.12%	-59.0%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	-2.64%	38.5%	2.41%
24% Load, 1800 RPM	-10.8%	25.1%	39.4%
70% Load, 1800 RPM	-90.4%	-36.1%	-84.9%
HDFTP	-0.02%	26.8%	0.78%
ENGINE-OUT			
10% Load, 1200 RPM	11.4%	38.7%	-17.4%
24% Load, 1800 RPM	34.5%	56.9%	-19.1%
70% Load, 1800 RPM	-19.9%	-4.08%	-28.3%
HDFTP	7.51%	31.5%	-22.3%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

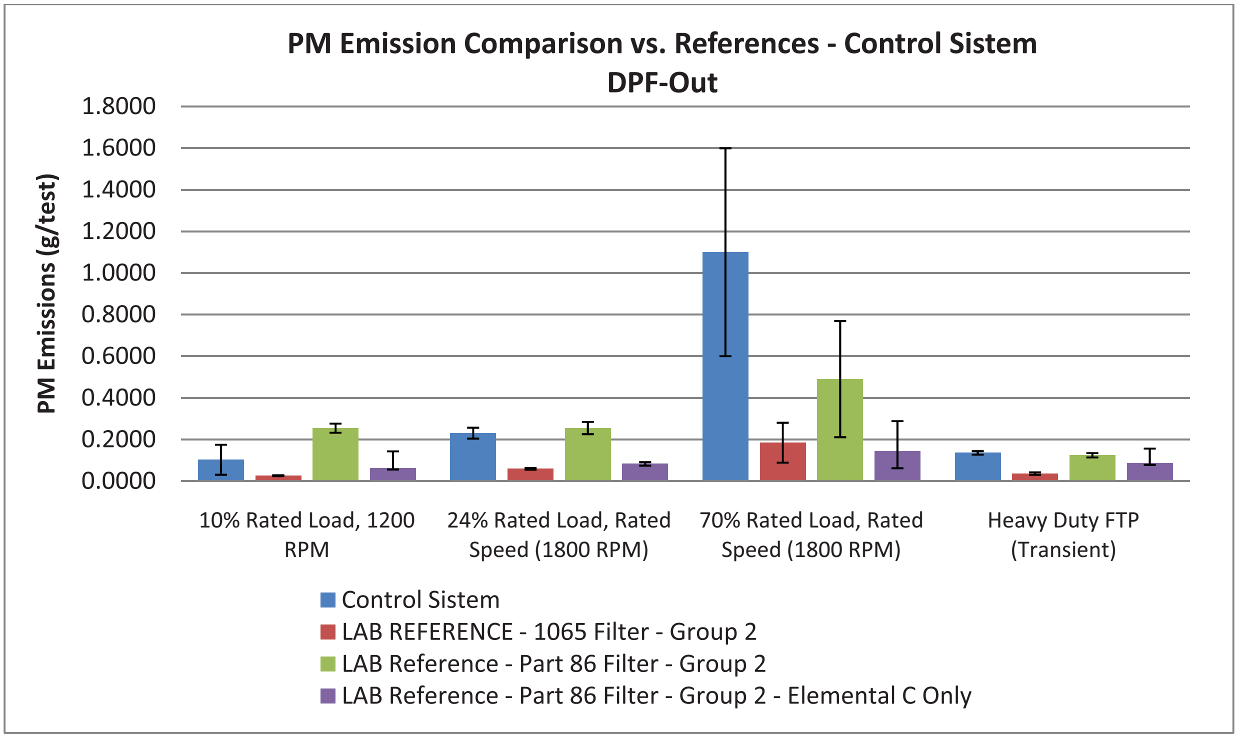


Figure 5-27. Micro-PSS and Gravimetric Reference PM Emissions—DPF-Out

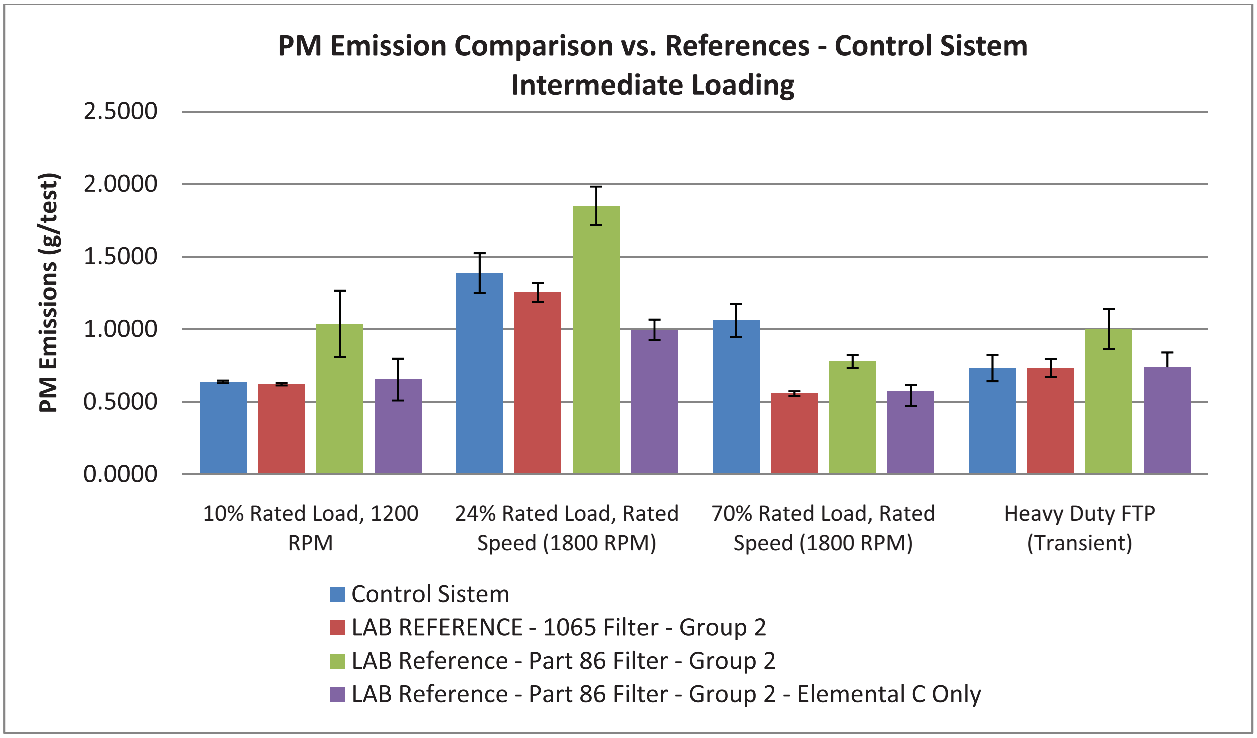


Figure 5-28. Micro-PSS and Gravimetric Reference PM emissions—Intermediate PM

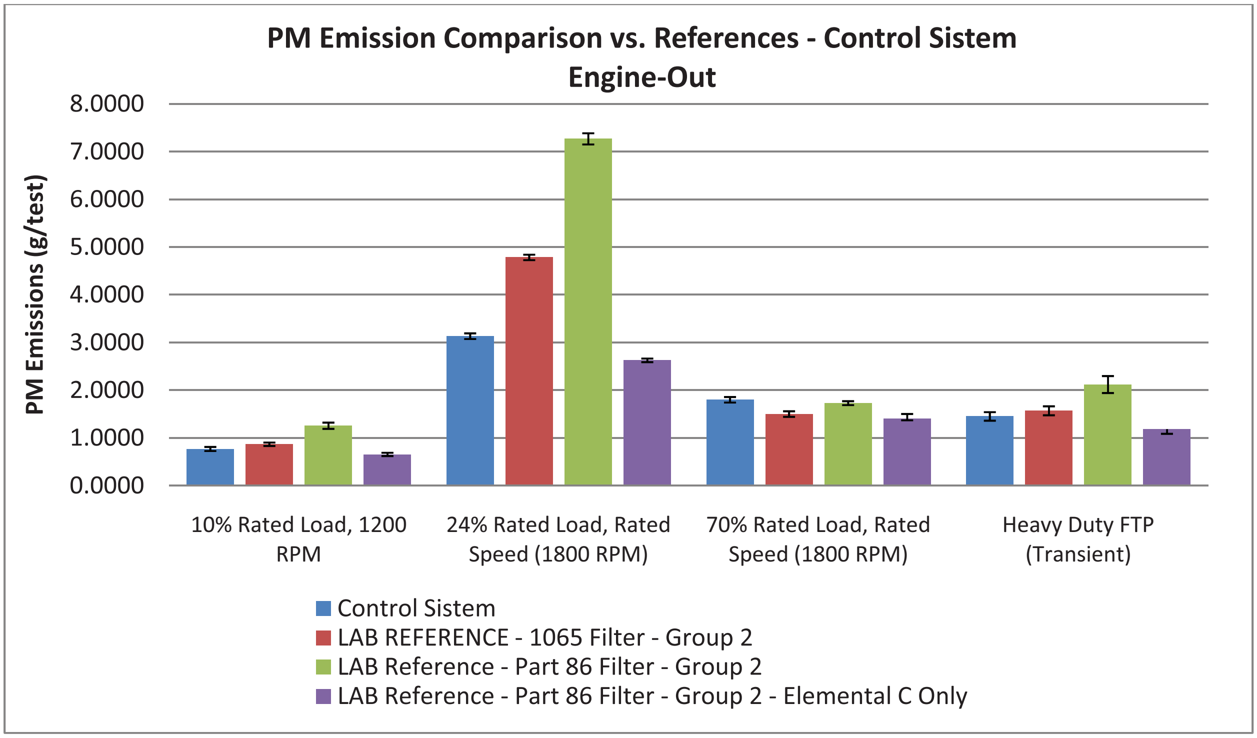


Figure 5-29. Micro-PSS and Gravimetric Reference PM emissions—Engine-Out

5.2.5.3.3. <u>Repeatability</u>

The CV for the Micro-PSS at each test condition is summarized in the table below, along with the CV for the reference methods for comparison. The Micro-PSS system provided very similar repeatability to the Part 86 reference method throughout all conditions. Because the system is based on the Part 86 method, this could be expected.

Table 5-30. Coefficient of Variation for Control Sistem Micro-PSS

Engine Setting	CV—LAB REFERENCE 1065 Filter Group 2	CV—LAB Reference Part 86 Filter Group 2	CV— Micro-PSS
DPF-Out			
10% Rated Load, 1200 RPM	0.0854	0.0861	0.702
24% Rated Load, Rated Speed (1800 RPM)	0.0654	0.115	0.114
70% Rated Load, Rated Speed (1800 RPM)	0.521	0.569	0.454
Heavy Duty FTP (Transient)	0.163	0.0835	0.0635
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0138	0.221	0.0144
24% Rated Load, Rated Speed (1800 RPM)	0.0526	0.0712	0.0982
70% Rated Load, Rated Speed (1800 RPM)	0.0299	0.0569	0.107
Heavy Duty FTP (Transient)	0.0863	0.138	0.124
Engine -Out			
10% Rated Load, 1200 RPM	0.0412	0.0517	0.0552
24% Rated Load, Rated Speed (1800 RPM)	0.0118	0.0162	0.0191
70% Rated Load, Rated Speed (1800 RPM)	0.0393	0.0240	0.0323
Heavy Duty FTP (Transient)	0.0600	0.0840	0.0620

5.2.5.3.4. Control Device Efficiency

To evaluate the suitability of the Micro-PSS for measurement of control device efficiency, calculations were completed using both reference and Micro-PSS DPF-out and engine-out data from each set of test runs. The control device efficiency based on the Part 86 reference method, as would be expected. Nevertheless, the differences were greater than 3% in all cases. This difference is larger than that for many of the PEMS tested. The inability of the Micro-PSS to be used to measure DPF-out levels consistent with other methods such as 1065 likely limits its applicability to these types of measurements.

Table 5-31. Comparison of Control Device Evaluation Results for Micro-PSS

Engine Condition	Parameter	Reference—1065	Control Sistem	Reference—86	Control Sistem	Reference—86 EC	Control Sistem
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	96.9%	86.7%	79.8%	86.7%	90.7%	86.7%
	% Difference vs. Reference		10.6%		-8.7%		4.4%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.8%	92.7%	96.5%	92.7%	96.8%	92.7%
	% Difference vs. Reference		6.2%		4.0%		4.3%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	87.7%	38.9%	71.7%	38.9%	89.7%	38.9%
	% Difference vs. Reference		55.6%		45.7%		56.6%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	97.7%	90.7%	94.1%	90.7%	92.8%	90.7%
	% Difference vs. Reference		7.2%		3.7%		2.3%

5.2.5.4. Comparison vs. References—In-Use

Comparisons of the Micro-PSS data vs. the DOES2 reference are provided in the table below. The differences compared to reference standards in both exhaust configurations (DPF and engine out) are 6% or less and are not statistically significant. Since the operating principle is the same as seen in the DOES2 in-use reference method, users can expect similar performance between the two systems. And, as shown, the correlation between the two is excellent. The CV at the DPF-out level is noticeably lower than the reference for the Micro-PSS.

Table 5-32. TSI DRX 8533 In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	Micro-PSS	Reference Elemental Carbon
DPF-OUT				
	Mean Emission Rate (g/test)	0.110	0.103	0.110
	CV	0.101	0.0479	0.101
	% Difference vs. Reference		5.89%	5.89%
	Statistically Significant Difference?		No	No
Engine-Out				
	Mean Emission Rate (g/test)	1.71	1.64	1.17
	CV	0.0205	0.027	0.0205
	% Difference vs. Reference		3.75%	-39.9%
	Statistically Significant Difference?		No	Yes

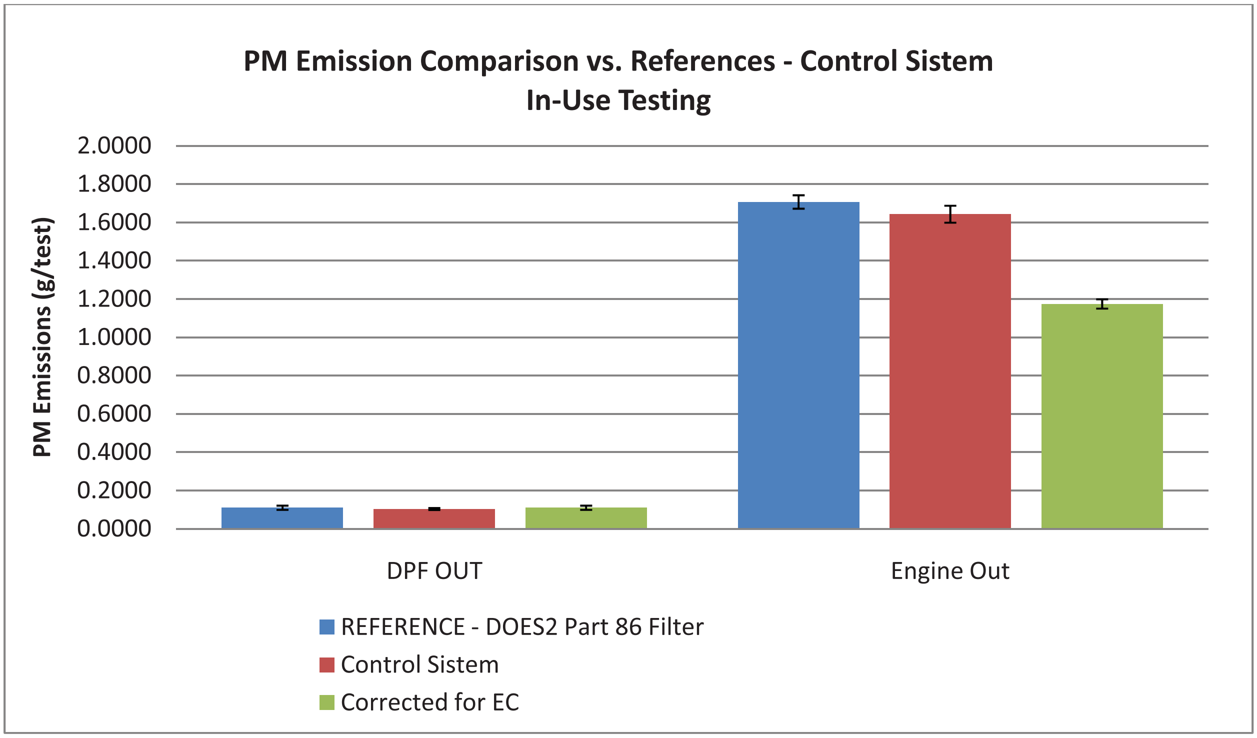


Figure 5-30. Micro-PSS PM Emissions compared to In-use Reference Method

Similarly, when comparing control device efficiency calculations using reference standard data and Micro-PSS data, there is <1% difference between the two methods.

Table 5-33. In-Use Control Device Efficiency Determination—Micro-PSS

Engine Condition	Parameter	REFERENCE—DOES2 Part 86 Filter	Micro-PSS	
In-Use	DPF Control Efficiency (%)	93.6%	93.7%	90.6%
	% Difference vs. Reference		-0.2%	-3.4%

5.2.5.5. Reliability and Operability

The Control Sistem Micro-PSS operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. The system was relatively simple to operate. Still, it did require regular input adjustments based on the LFE data and cell operating temperatures, since the system did not have an integrated exhaust flow rate or temperature data source. In addition, the dilution factor was adjusted in one instance (DPF-out, 10% power) to allow for collection of more particulate via application of a lower dilution factor.

5.2.6. TSI DUSTTRAK 8533 DRX

5.2.6.1. Technology Description

The DustTrak model 8533 is an advanced version of the TSI DustTrak Aerosol Monitor known as the DRX model. The DRX can measure size fractions of the sampled aerosol in addition to making a mass based photometric measurement. The DRX employs a method to simultaneously measure size segregated mass fraction concentrations (PM1, PM2.5, Respirable/PM4, PM10/Thoracic, and TPM) over a wide concentration range (0.001–150 mg/m3) in real time. This method combines a photometric measurement to cover the mass concentration range and a single particle detection measurement to be able to size discriminate the sampled aerosol.

Aerosol is drawn in to the sensing chamber in a continuous stream using a diaphragm pump. Part of the aerosol stream is split ahead of the sensing chamber and passed through a HEPA filter and injected back in to the chamber flowing around the inlet nozzle as sheath flow. The remaining flow passes through the inlet entering the sensing chamber and is illuminated by laser light. First, the light emitted from the laser diode passes through a collimating lens and then through a cylindrical lens to create a thin sheet of light. A gold coated spherical mirror captures a significant fraction of the light scattered by the particles and focuses it on to a photodetector.

The optics inside the DUSTTRAK DRX Aerosol Monitor are kept clean by surrounding the aerosol stream with a sheath of clean filtered air. This sheath air confines the aerosol to a narrow stream and prevents particles from circulating around the optics chamber and depositing on the optics and also increases the response time of the instrument.

The DUSTTRAK DRX Model 8533 is a desktop instrument with components housed in a case that weighs 2.5 kg including two batteries and a built in sample pump. For high particle concentration applications, TSI offers the Model 379020 Rotating Disk Thermodiluter with a conditioned air supply that has a variable dilution range from 15:1 to 3000:1 and selectable heated dilution temperatures up to 150°C. The thermodiluter has a sample probe that’s separate from the control unit and the DRX analyzer. This allows the dilution of the sample at the point of measurement to minimize and preserve size distribution and concentration.

A summary of the DRX system’s specifications is provided in Appendix B. The DRX effective particle size measurement range is 0.1um to 15um, with an aerosol concentration measurement range from 0.001 to 150 mg/m3, and a sampling rate of 1Hz. The DRX system evaluated sampled raw exhaust via the thermodiluter and sampling probe through a heated sample line that was routed to the DRX analyzer. A low pressure air supply was also required and supplied via a small pump. The DRX sampled dilution rate was set to 154:1 with a total of 2.76 liters per minute of sample flow into the instrument.

Figure 5-31. TSI DRX 8533

5.2.6.2. Installation & Setup Requirements

The DRX required approximately 1/2 hour for setup and installation. The installation consisted of:

- adapting a 1/4” sampling port to the 8mm sampling line to the DRX
- installation of the DRX sample probe and connection of the thermodiluter and heated line
- connection of the sampling system to a compressed air source, in this case a small pump was provided by TSI
- connection of the sample line to the analyzer
- connection of all systems to electrical power (115 to 240VAC- or self contained battery)
- startup and warmup of the analyzer 5 minutes; heated line about 1 hour
- initial operational checks and setup.

The in-use testing setup was similar to the lab setup. The DRX system was simple to install and setup in both the lab and field. In addition, it should be noted that, as with many instruments in this test program, although a PM emissions concentration may be provided, an emission rate relies on knowledge of the exhaust flow rate. TSI does not supply an exhaust flow measurement system with the DRX. Therefore, exhaust flow data from the ERMS LFE was required to calculate emission rates in units of g/test, g/min, g/gal, or g/bhp-hr.

5.2.6.3. Comparison vs. Reference—Lab

5.2.6.3.1. Data Processing

The DRX provides second-by-second PM concentration data in mg/m^3. To convert mg/m^3 into mass, TSI developed a conversion factor during previous testing programs. For direct PM mass emission rate comparison to the lab and in-use references, the exhaust flow rate was provided to all vendors to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. This data was then converted, in a uniform calculation for all vendors validated by Southern, into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the TSI DRX data required no further processing.

5.2.6.3.2. Reference Comparison

The summary of the DRX 8533 results is provided in Table 5-34. This table provides the DRX results, the reference standard results (via part 1065 methods), the difference between the two data sets, and the determination of the statistical significance of the difference based on a t-test analysis. Figure 5-32, Figure 5-33, and Figure 5-34 also present the results in graphical form.

Table 5-34. Difference Between TSI DRX PM Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	TSI DRX 8533 Difference vs. Reference (1065)	TSI DRX 8533 Difference vs. Reference (86)	TSI DRX 8533 Difference vs. Reference (86 EC)
DPF-OUT			
10% Load, 1200 RPM	-201%	68.7%	30.7%
24% Load, 1800 RPM	-237%	21.9%	136.8%
70% Load, 1800 RPM	37.4%	48.3%	-75.7%
HDFTP	-290%	-14.6%	-66.9%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	50.3%	70.3%	52.8%
24% Load, 1800 RPM	66.4%	77.3%	57.7%
70% Load, 1800 RPM	42.1%	58.3%	43.8%
HDFTP	38.2%	54.8%	38.7%
ENGINE-OUT			
10% Load, 1200 RPM	62.6%	74.2%	50.5%
24% Load, 1800 RPM	80.0%	86.8%	63.6%
70% Load, 1800 RPM	50.5%	57.0%	47.0%
HDFTP	46.7%	60.5%	29.4%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

The TSI DRX 8533 did not correlate well with the reference standards in most cases, providing a statistically significant difference between the results and references at nearly every operating condition. It should be noted that at DPF-out conditions, the percentage differences may be large due to the very low levels of PM observed that are near the detection limits of the reference methods. Small differences in measurements can result in large percentage differences in this range. In addition, it should be noted that the thermodiluter was operated at 150°C, eliminating organic fraction PM, resulting in measurement of primarily elemental carbon. At both engine-out and intermediate loads, the DRX system measured PM emissions lower than the references, which may be an effect of the thermodiluter's impacts on PM in the sampled exhaust stream.

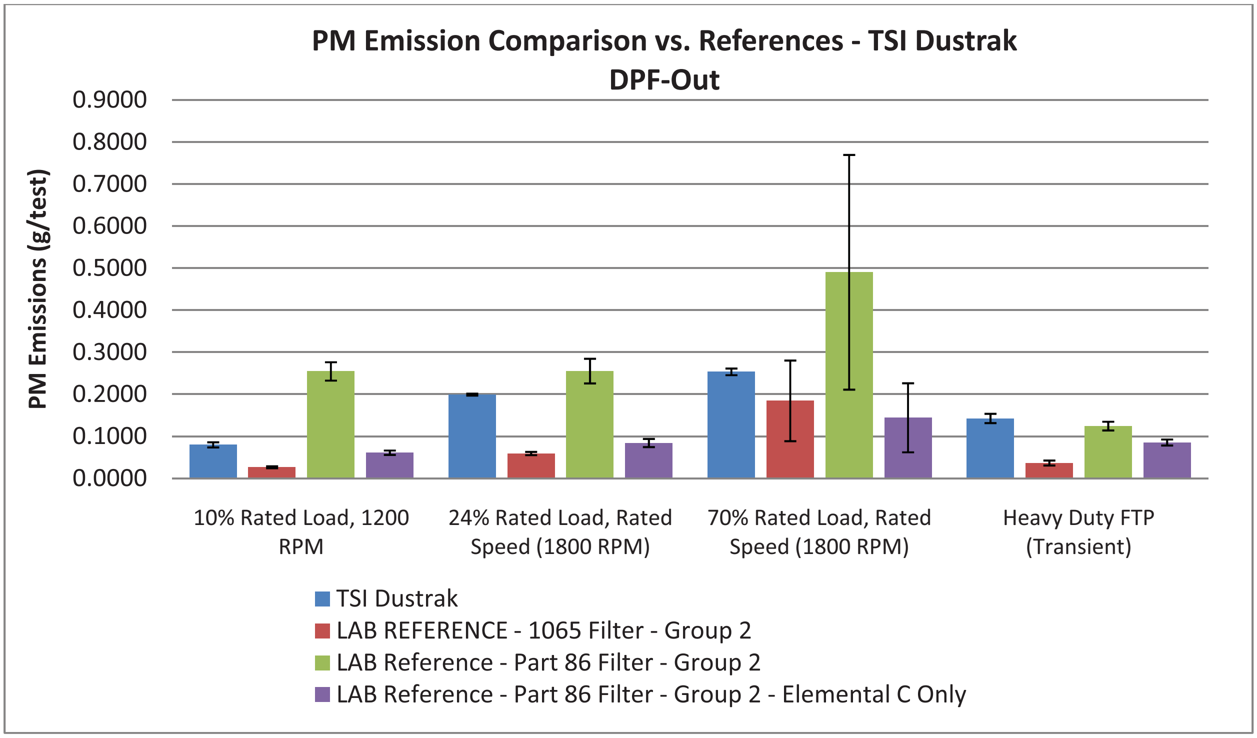


Figure 5-32. TSI DRX 8533 and Gravimetric Reference PM Emissions—DPF-Out

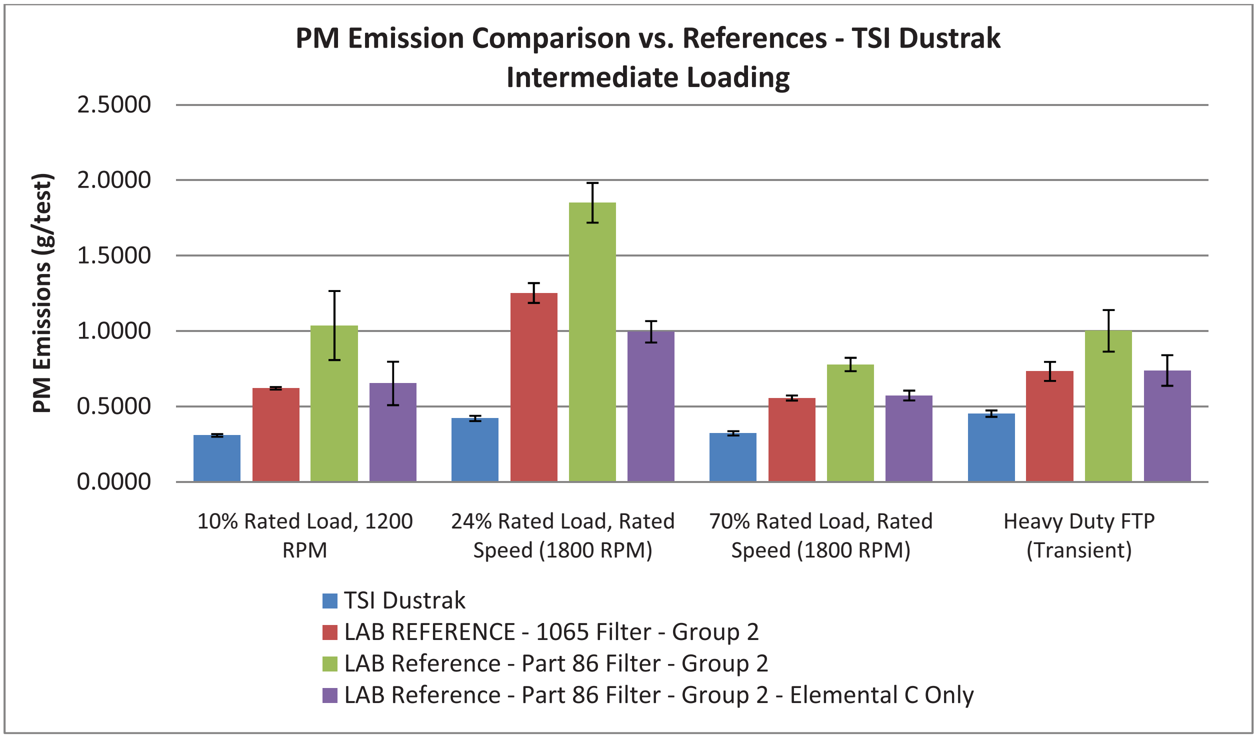


Figure 5-33. TSI DRX 8533 and Gravimetric Reference PM Emissions—Intermediate PM

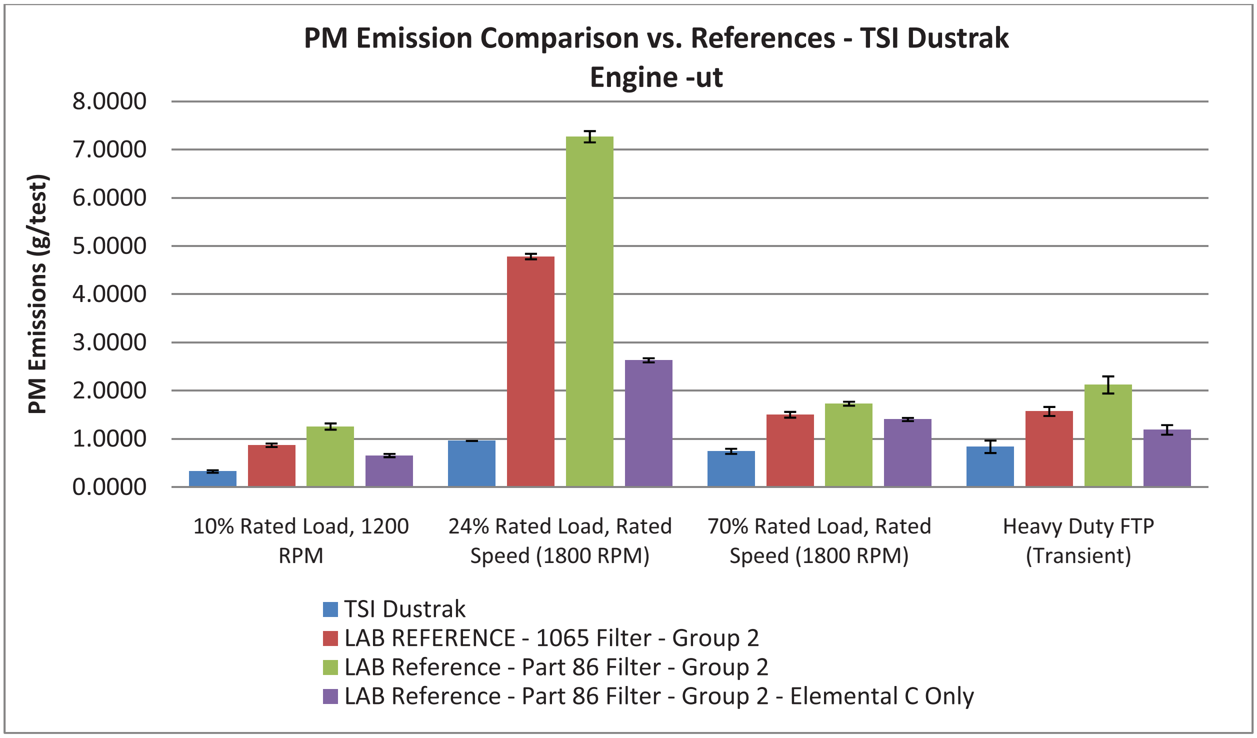


Figure 5-34. TSI DRX 8533 and Gravimetric Reference PM Emissions—Engine-Out

5.2.6.3.3. Repeatability

The test-to-test repeatability of each PM-PEMS can be evaluated by observing the coefficient of variation (CV) for each group of test runs at a specific operating condition or test cycle. The CV for the DRX 8533 at each test condition is summarized in the table below, along with the CV for the reference methods for comparison.

At the DPF-out condition, with very low levels of PM emissions, and especially low elemental carbon (soot) emissions, the DRX proved to provide excellent reproducibility, with most CVs equivalent to or well below to CV of the 1065 reference method. At other operating conditions, CVs were variable, ranging from well below reference method CVs to somewhat higher than references. In all, the DRX appears to provide sufficient repeatability, especially at low elemental carbon emission levels, when compared with reference methods.

Table 5-35. Coefficient of Variation for TSI DRC 8533

Engine Setting	CV—LAB REFERENCE 1065 Filter Group 2	CV—LAB Reference Part 86 Filter Group 2	CV—TSI DRX 8533
DPF-Out			
10% Rated Load, 1200 RPM	0.0854	0.0861	0.0772
24% Rated Load, Rated Speed (1800 RPM)	0.0654	0.115	0.0113
70% Rated Load, Rated Speed (1800 RPM)	0.521	0.569	0.0309
Heavy Duty FTP (Transient)	0.162	0.0835	0.0773
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0138	0.221	0.0296
24% Rated Load, Rated Speed (1800 RPM)	0.0526	0.0712	0.0416
70% Rated Load, Rated Speed (1800 RPM)	0.0299	0.0569	0.0446
Heavy Duty FTP (Transient)	0.0863	0.138	0.0471
Engine -Out			
10% Rated Load, 1200 RPM	0.0412	0.0517	0.0799
24% Rated Load, Rated Speed (1800 RPM)	0.0118	0.0162	0.0007
70% Rated Load, Rated Speed (1800 RPM)	0.0393	0.0240	0.0713
Heavy Duty FTP (Transient)	0.0600	0.0840	0.154

5.2.6.3.4. Control Device Efficiency

In addition to evaluation of emissions, PM-PEMS may be used for evaluation of the impacts of an emission control device or novel emission reduction technology, where a direct measurement of the emissions level is not the primary target, but, rather, a difference between two emission levels is targeted. To evaluate the suitability of the TSI DRX in this application, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference and TSI DRX DPF-out and engine-out data from each set of test runs. In all cases, the DRX data resulted in a control device efficiency that was significantly lower than the reference method calculations. This is a result of the lower PM emissions measured by the DRX at engine out conditions, due in part to the use of the thermodiluter, and the higher emissions measured at DPF-out.

Table 5-36. Comparison of Control Device Evaluation Results for TSI DRX 8533

Engine Condition	Parameter	Calculated Control Device PM Removal Efficiency					
		Reference—1065	DRX 8533	Reference—86	DRX 8533	Reference—86 EC	DRX 8533
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	96.9%	75.5%	79.8%	75.5%	90.7%	75.5%
	% Difference vs. Reference		22.2%		5.4%		16.8%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.8%	79.2%	96.5%	79.2%	96.8%	79.2%
	% Difference vs. Reference		19.8%		17.9%		18.2%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	87.7%	65.9%	71.7%	65.9%	89.7%	65.9%
	% Difference vs. Reference		24.9%		8.0%		26.5%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	97.7%	83.0%	94.1%	83.0%	92.8%	83.0%
	% Difference vs. Reference		15.0%		11.8%		10.6%

5.2.6.4. Comparison vs. References—In-Use

Comparisons of the TSI DRX data vs. the DOES2 reference are provided in the table below. The differences versus reference standards in both exhaust configurations (DPF and engine-out) is less than 20% at DPF-out, and is not statistically significant. This is a good correlation with the reference method. At engine-out, however, the differences are greater than 40% and are statistically significant, a somewhat poor correlation. Large differences between the TSI DRX and the DOES2 may be primarily related to method differences, since the sampling system used for the DRX essentially removed a large portion of the organic PM fraction as a result of the high operating temperature.

Table 5-37. TSI DRX 8533 In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE— DOES2 Part 86 Filter	TSI DRX	Reference Elemental Carbon
DPF-OUT				
	Mean Emission Rate (g/test)	0.109	0.0905	0.109
	CV	0.189	0.0399	0.189
	% Difference vs. Reference		17.2%	17.2%
	Statistically Significant Difference?		NO	NO
Engine-Out				
	Mean Emission Rate (g/test)	1.73	0.680	1.19
	CV	0.0471	0.0574	0.0471
	% Difference vs. Reference		60.7%	42.8%
	Statistically Significant Difference?		YES	YES

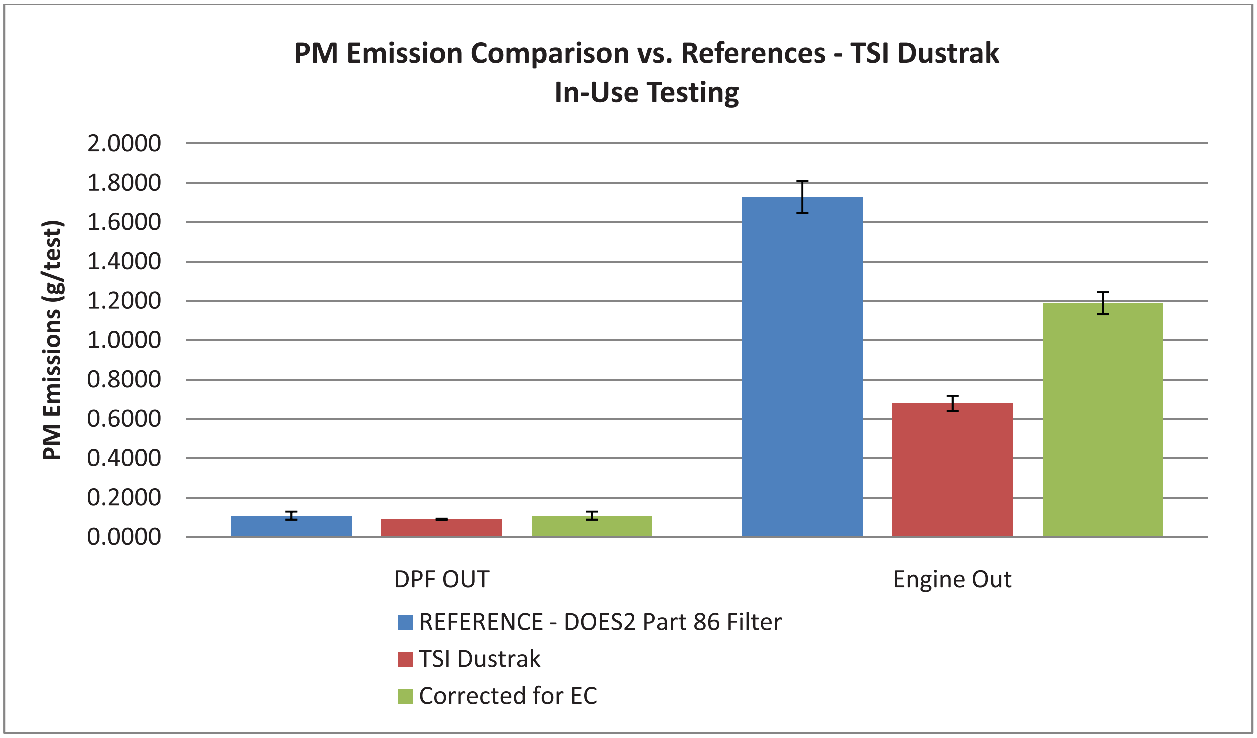


Figure 5-35. TSI DRX 8533 PM Emissions compared to In-use Reference Method

When comparing control device efficiency calculations using reference standard data and TSI DRX data, there is a 7.46% difference between the two methods. This difference results from the significantly lower engine-out emission rate observed with the Dustrak DRX as compared to the reference method. When compared to elemental carbon reductions only, the Dustrak DRX fared much better, with a 4.5% difference between the reference and DRX values—a result of the use of the thermodiluter and removal of the organic carbon fraction in the sampling system.

Table 5-38. In-Use Control Device Efficiency Determination—TSI DRX 8533

Engine Condition	Parameter	REFERENCE—DOES2 Part 86 Filter	TSI DRX	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.7%	86.7%	90.8%
	% Difference vs. Reference		7.5%	4.5%

5.2.6.5. Reliability and Operability

The TSI DRX 8533 system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. During one test day, a software problem was encountered and the DRX had to be re-programmed, which did not require a major effort. In addition, the unit was removed and calibration checked once, with no changes required.

5.2.7. TSI Electrical Aerosol Detector (EAD 3070A)

5.2.7.1. Technology Description

The EAD 3070A provides a measure of particle concentration as a function of time based on aerosol diameter concentration. The measurement principle is based on diffusion charging of particles followed by detection of the aerosol via an electrometer. According to TSI, in the measurement process, a particulate laden sample stream (aerosol) enters the instrument at 2.5 liters per minute. The flow is split, with one liter per minute passing through a filter and ionizer, and the remaining 1.5 liters per minute making up the aerosol flow. The flows reunite in a mixing chamber where particles in the aerosol flow mix with the ions carried by the filtered clean air. This “counter-flow diffusion charging” brings the aerosol particles into a defined charge state. The separation of the particles from direct interaction with the corona needle, and/or the strong field near it, reduces particle losses and makes the charging process more efficient and reproducible. The charged aerosol then passes through an ion trap to remove excess ions and moves on to a highly sensitive aerosol electrometer for charge measurement. The diffusion charger produces a linear relationship between particle diameter and the number of elementary units of charge acquired for particles in the range from 10 nanometers to one micrometer. The overall EAD response that includes internal particle losses follows a nearly linear power law, with the net electrometer current being proportional to the 1.133 power of the particle diameter.

TSI EAD components are housed in a single cabinet that weighs 6.7 kg. For high particle concentration applications, TSI offers the Model 379020 Rotating Disk Thermodiluter with a conditioned air supply that has a variable dilution range from 15:1 to 3000:1 and selectable heated dilution temperatures up to 150°C. The thermodiluter has a sample probe that is separate from the control unit and the EAD. This allows the dilution of the sample at the point of measurement to minimize and preserve size distribution and concentration.

A summary of the EAD 3070A system's specifications is provided in Appendix B. The EAD measures particle diameter concentrations from 0.01 to 2500 mm/cm^3, is effective for size range from 10 nm to >1 µm, and is capable of sampling at a rate of 3.75 times per second. The EAD system evaluated sampled raw exhaust with the thermodiluter and sampling probe through a heated sample line, which was then routed to the EAD analyzer. A low pressure air supply was also required and supplied via a small pump that supplied conditioned air for the sample dilution at a rate of 154:1. The EAD's sample flow rate was set to 2.5 liters a minute.

Figure 5-36. TSI EAD 3070A

5.2.7.2. Installation & Setup Requirements

The EAD required about ½ hour for setup and installation. The installation consisted of:

- installation of the EAD sample probe and connection of the thermodiluter and heated line
- connection of the sampling system to a compressed air source, in this case a small pump was provided by TSI
- setup the dilution flow of 154:1
- connection of the sample line to the analyzer
- connection of all systems to electrical power (100 to 203 VAC)
- startup and warmup of the analyzer and heated line about 1 hour
- initial operational checks and setup.

The in-use testing setup was similar to the lab setup. The EAD system is a compact system that is very manageable and relatively simple to set up and install. In addition, it should be noted that, as with many instruments in this test program, although a PM emissions concentration may be provided, an emission rate relies on knowledge of the exhaust flow rate. TSI does not supply an exhaust flow measurement system with the EAD. Therefore, exhaust flow data from the ERMS LFE was required to calculate emission rates in units of g/test, g/min, g/gal, or g/bhp-hr.

5.2.7.3. Comparison vs. Reference—Lab

5.2.7.3.1. Data Processing

The EAD provides second-by-second (or faster) PM concentration data in mm/cm^3. To convert mm/cm^3 into mass, TSI has developed a conversion factor based on previous testing programs. For direct PM mass emission rate comparison to the lab and in-use references the exhaust flow rate was provided to all vendors to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. This data was then converted, in a uniform calculation for all vendors, validated by Southern, into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the TSI EAD data required no further processing.

5.2.7.3.2. Reference Comparison

The summary of the corrected EAD 3070A results is provided in Table 5-39. This table provides the EAD results, the reference standard results (via part 1065 methods), the difference between the two data sets, and the determination of the statistical significance of the difference based on a t-test analysis. Figure 5-37, Figure 5-38, and Figure 5-39 also present the results.

Table 5-39. Difference Between TSI EAD PM Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	TSI EAD 3070A Difference vs. Reference (1065)	TSI EAD 3070A Difference vs. Reference (86)	TSI EAD 3070A Difference vs. Reference (86 EC)
DPF-OUT			
10% Load, 1200 RPM	-105%	78.7%	11.0%
24% Load, 1800 RPM	-130%	46.7%	-61.8%
70% Load, 1800 RPM	5.13%	60.5%	-34.4%
HDFTP	-104%	40.1%	12.8%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	55.2%	73.2%	62.4%
24% Load, 1800 RPM	60.4%	76.3%	34.0%
70% Load, 1800 RPM	25.4%	46.7%	27.6%

HDFTP	64.9%	74.3%	65.2%
ENGINE-OUT			
10% Load, 1200 RPM	64.0%	75.1%	52.3%
24% Load, 1800 RPM	70.9%	80.9%	47.1%
70% Load, 1800 RPM	42.6%	50.2%	38.6%
HDFTP	71.7%	79.0%	62.5%
N/A indicates data is not available Shading indicates a statistically significant difference (reference vs. technology)			

The TSI EAD 3070A did not correlate well with the reference standards in most cases, providing a statistically significant difference between the EAD results and references at nearly every operating condition. It should be noted that at DPF-out conditions, the percentage differences may be large due to the very low levels of PM observed that are near the detection limits of the reference methods. Small differences in measurements can result in large percent differences in this range. The most favorable comparisons were vs. the elemental carbon references, which is logical, due to the utilization of the thermodiluter operating at 150°C, resulting in the measurement of primarily soot only by the EAD.

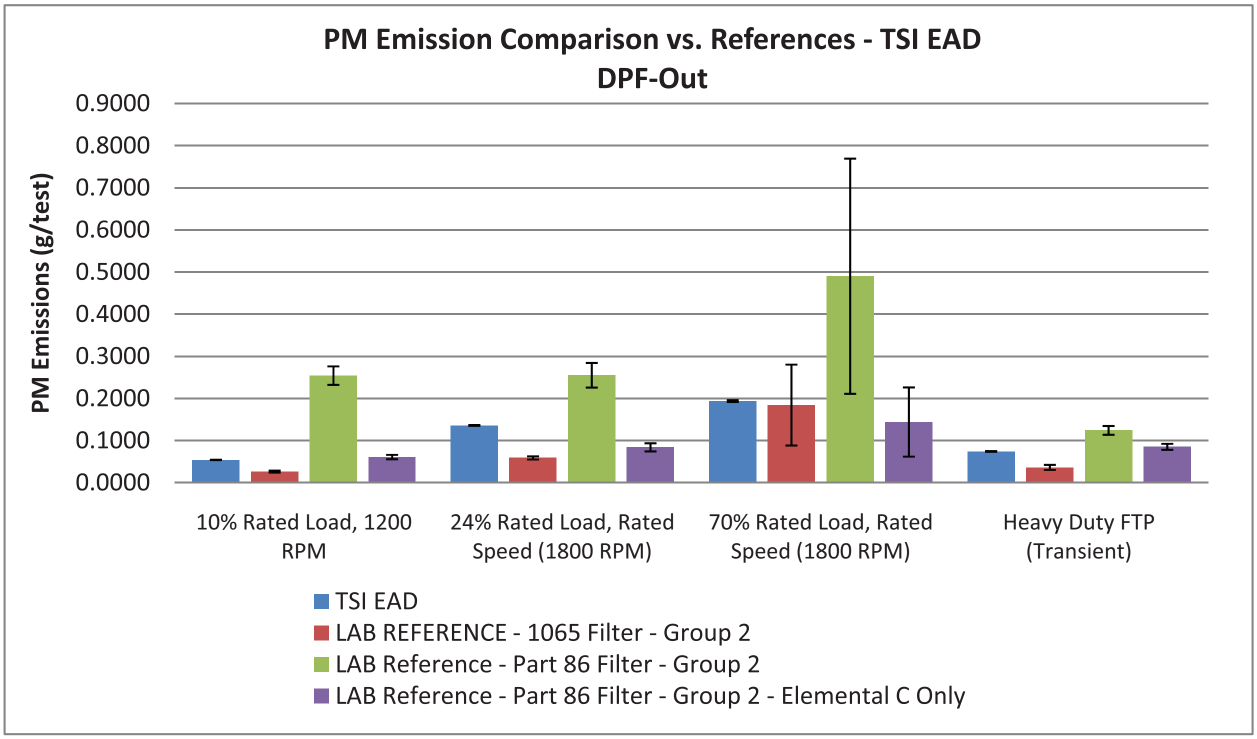


Figure 5-37. TSI EAD 3070A and Gravimetric Reference PM Emissions—DPF-Out

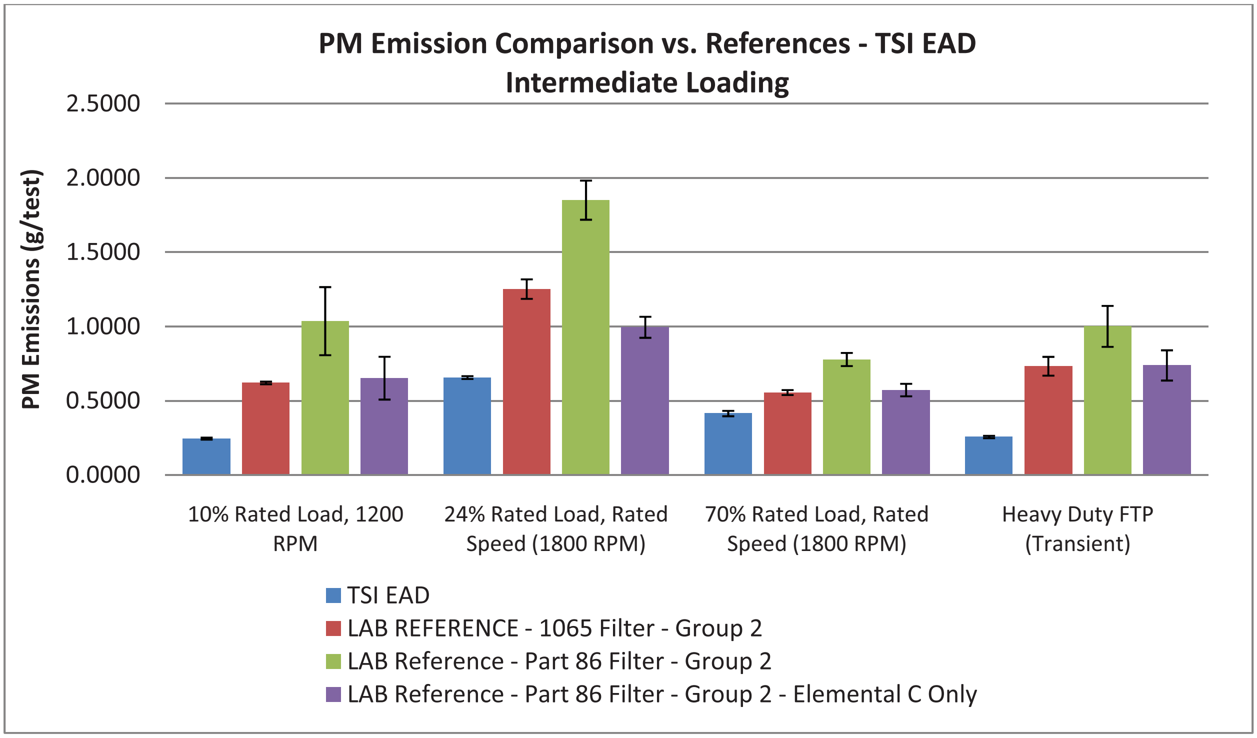


Figure 5-38. TSI EAD 3070A and Gravimetric Reference PM emissions—Intermediate PM

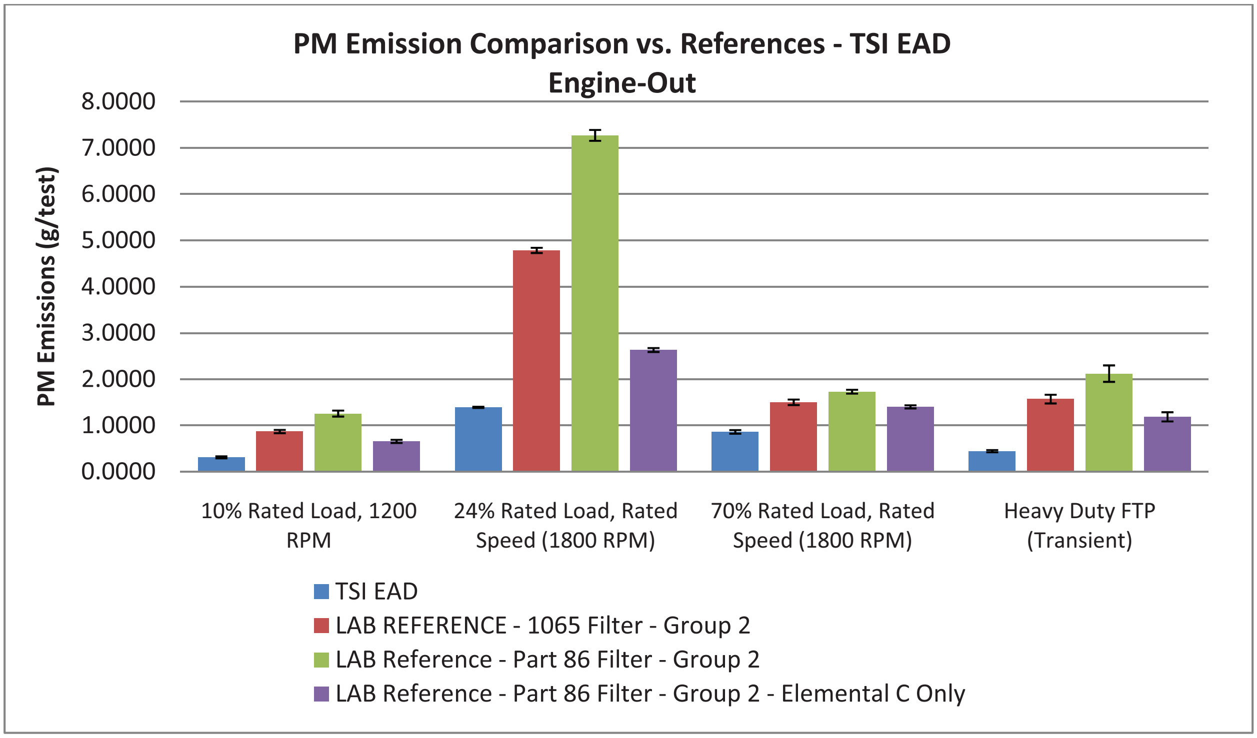


Figure 5-39. TSI EAD 3070A and Gravimetric Reference PM emissions—Engine-Out

5.2.7.3.3. Repeatability

The test-to-test repeatability of each PM-PEMS can be evaluated by observing the coefficient of variation (CV) for each group of test runs at a specific operating condition or test cycle. The CV for the EAD 3070A at each test condition is summarized in the table below, along with the CV for the reference methods for comparison.

At the DPF-out condition, with very low levels of PM emissions, the EAD proved to provide excellent reproducibility, with most CVs equivalent to or well below the CV of the 1065 reference method. At other operating conditions and higher elemental and organic levels, CVs were more variable, ranging from well below reference method CVs to slightly higher than references. In all, the EAD appears to provide sufficient repeatability, especially at low elemental carbon emission levels, when compared with reference methods.

Table 5-40. Coefficient of Variation for TSI EEPS 3090

Engine Setting	CV—LAB REFERENCE 1065 Filter Group 2	CV—LAB Reference Part 86 Filter Group 2	CV—TSI EAD 3070A
DPF-Out			
10% Rated Load, 1200 RPM	0.0854	0.0861	0.0077
24% Rated Load, Rated Speed (1800 RPM)	0.0654	0.115	0.0082
70% Rated Load, Rated Speed (1800 RPM)	0.521	0.569	0.0118
Heavy Duty FTP (Transient)	0.163	0.0835	0.0107
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0138	0.221	0.0282
24% Rated Load, Rated Speed (1800 RPM)	0.0526	0.0712	0.0149
70% Rated Load, Rated Speed (1800 RPM)	0.0299	0.0569	0.0439
Heavy Duty FTP (Transient)	0.0863	0.138	0.0307
Engine -Out			
10% Rated Load, 1200 RPM	0.0412	0.0517	0.0673
24% Rated Load, Rated Speed (1800 RPM)	0.0118	0.0162	0.0102
70% Rated Load, Rated Speed (1800 RPM)	0.0393	0.0240	0.0448
Heavy Duty FTP (Transient)	0.0600	0.0840	0.0525

5.2.7.3.4. Control Device Efficiency

In addition to evaluation of emissions, PM-PEMS may be used for evaluation of the impacts of an emission control device or novel emission reduction technology, where a direct measurement of the emissions level is not the primary target, but rather, a difference between two emission levels is targeted. To evaluate the suitability of the TSI EAD in this application, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference and TSI EAD DPF-out and engine-out data from each set of test runs. In all tests, the EAD predicted the control device efficiency to <15% of the reference measurement. Any differences observed are likely a result of the utilization of the thermodiluter and its impact on the measured PM stream.

Table 5-41. Comparison of Control Device Evaluation Results for TSI EAD 3070A

Engine Condition	Parameter	Reference—1065	EAD 3070A	Reference—86	EAD 3070A	Reference Elemental Carbon	EAD 3070A
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	96.9%	82.7%	79.8%	82.7%	90.7%	82.7%
	% Difference vs. Reference		14.7%		-3.6%		8.9%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.8%	90.2%	96.5%	90.2%	96.8%	90.2%
	% Difference vs. Reference		8.6%		6.5%		6.8%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	87.7%	77.5%	71.7%	77.5%	89.7%	77.5%
	% Difference vs. Reference		11.6%		-8.2%		13.6%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	97.7%	83.3%	94.1%	83.3%	92.8%	83.3%
	% Difference vs. Reference		14.8%		11.5%		10.3%

5.2.7.4. Comparison vs. References—In-Use

Comparisons of the TSI EAD data vs. the DOES2 reference are provided in the table below. The difference between the in-use EAD measurements and the part 86-based DOES2 reference standard for DPF out exhaust configuration is shown to be 37.3%, and is not statistically significant. In the engine-out configuration, the difference versus reference standard is over 66%, which is statistically significant. The utilization of the thermodiluter with the EAD, and associated removal of the majority of the organic carbon PM fraction, has a significant impact on the comparison vs. the 86 reference. When compared to the elemental carbon reference only, the difference between the EAD and reference is reduced to 43%. Although this is an improvement, it is still a somewhat poor correlation with the reference.

Table 5-42. TSI EAD 3070A In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	TSI EAD 3070A	Reference Elemental Carbon
DPF-OUT				
	Mean Emission Rate (g/test)	0.109	0.0685	0.109
	CV	0.189	0.293	0.189
	% Difference vs. Reference		37.3%	37.3%
	Statistically Significant Difference?		NO	NO
Engine-Out				
	Mean Emission Rate (g/test)	1.73	0.582	1.19
	CV	0.0471	0.0480	0.0471
	% Difference vs. Reference		66.3%	51.1%
	Statistically Significant Difference?		YES	YES

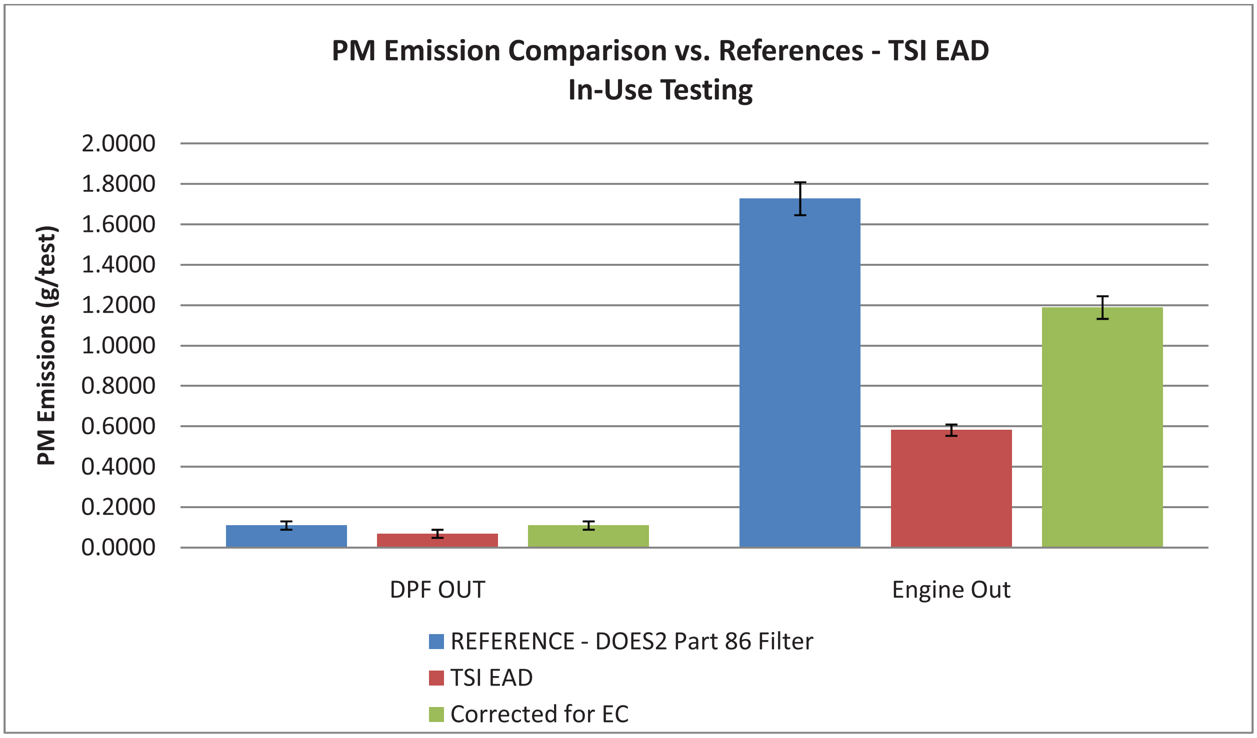


Figure 5-40. TSI EAD 3070A PM Emissions compared to In-use Reference Method

When comparing control device efficiency calculations using reference standard data and TSI EAD data, there is a 5.8% difference between the two methods. A large portion of this difference results from the significantly lower engine-out emission rate observed with the TSI EAD, possibly resulting from use of the thermodiluter at high temperature. When compared to elemental carbon results, the comparison is much better, with a less than 3% difference.

Table 5-43. In-Use Control Device Efficiency Determination—TSI EAD 3070A

Engine Condition	Parameter	REFERENCE—DOES2 Part 86 Filter	TSI EAD 3070A	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.7%	88.2%	90.8%
	% Difference vs. Reference		5.8%	2.8%

5.2.7.5. Reliability and Operability

The TSI EAD system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed.

5.2.8. TSI Engine Exhaust Particle Sizer (EEPS 3090)

5.2.8.1. Technology Description

According to TSI, the EEPS 3090 spectrometer is a fast-response, high-resolution instrument that is designed to measure very low particle number concentrations in diluted exhaust. The EEPS spectrometer was designed for continuous measurement of transient test cycles with a fast resolution time of up to 10 times per second. The EEPS incorporates electrometers to provide the ability to measure particle concentrations across a very broad range greater than four orders of magnitude. The EEPS spectrometer can measure concentrations as low as 200 particles/cm^3 (corresponding to <1 μg/m^3). Additionally, it operates at ambient pressure to eliminate concern about evaporating volatile and semivolatile particles. The software provided with the EEPs system combines data collection and analysis in a single program for ease of use, so there is no need for external processing in spreadsheets.

EEPS components are housed in a single cabinet that weighs 32 kg. For high particle concentration applications, TSI offers the Model 379020 Rotating Disk Thermodiluter with a conditioned air supply that has a variable dilution range from 15:1 to 3000:1 and selectable heated dilution temperatures up to 150°C. The thermodiluter has a sample probe that is separate from the control unit and the EEPS spectrometer. This allows the dilution of the sample at the point of measurement to minimize and preserve size distribution and concentration.

The EEPS draws a continuous sample of the exhaust flow into the inlet. The particles are positively charged to a predictable level using a corona charger, introduced to the measurement region near the center of a high-voltage electrode column, and transported down the column surrounded by HEPA-filtered sheath air. A positive voltage is applied to the electrode, creating an electric field that repels the positively charged particles outward according to their electrical mobility. Charged particles strike the respective electrometers and transfer their charge. A particle with higher electrical mobility strikes an electrometer near the top; whereas a particle with lower electrical mobility strikes an electrometer lower in the stack. This multiple detector arrangement using highly sensitive electrometers allows for simultaneous concentration measurements of multiple particle sizes.

A summary of the EEPS 3090 system's specifications is provided in Appendix B. The EEPS measure particles down to < 1μg/ m^3, is effective for particle sizes from 5.6 to 560 nanometers, and is capable of sampling at a 10Hz rate. The EEPS system evaluated sampled raw exhaust with the thermodiluter and sampling probe through a heated sample line that was routed to the EEPS analyzer. A low pressure air supply is also required and supplied via a small pump. The EEPS sampled dilution rate was set to 308:1 with a total of 9.6 liters per minute of sample flow into the instrument.

Figure 5-41. TSI EEPS 3090

5.2.8.2. Installation & Setup Requirements

The EEPS required approximately 45 minutes for setup and installation. The installation consisted of:

- Adapting a 1/4" sampling port to the 8 mm sampling line to the EEPS
- installation of the EEPS sample probe and connection of the thermodiluter and heated line

- connection of the sampling system to a compressed air source, in this case a small pump was provided by TSI
- connection of the sample line to the analyzer
- connection of all systems to electrical power (120VAC-750 watts)
- startup and warmup of the analyzer and heated line about one hour
- initial operational checks and setup.

The in-use testing setup was similar to the lab setup. The EEPS 3090 system is larger than some PEMS systems, but was manageable. In addition, it should be noted that, as with many instruments in this test program, although a PM emissions concentration may be provided, an emission rate relies on knowledge of the exhaust flow rate. TSI does not supply an exhaust flow measurement system with the EEPS. Therefore, exhaust flow data from the ERMS LFE was required to calculate emission rates in units of g/test, g/min, g/gal, or g/bhp-hr.

5.2.8.3. Comparison vs. Reference—Lab

5.2.8.3.1. Data Processing

The EEPS provides second-by-second (or faster) PM concentration data in both ug/m^3 and #/cm^3. The mass concentrations are calculated based on user-input particle densities, in this case, provided by TSI as size specific unit densities. To convert this to a PM mass emission rate for comparison to the lab and in-use references, the exhaust flow rate was provided to all vendors to determine total grams of PM emissions per test. Since data is provided on a second-by-second basis, the PM mass emission rate must be calculated on a similar basis, then total PM mass integrated over the entire test period. This data was then converted, in a uniform calculation for all vendors validated by Southern, into the reporting units of g/test, g/gal, and g/bhp-hr. Beyond the integration and conversions, the TSI EEPS data required no further processing.

5.2.8.3.2. Reference Comparison

The summary of the corrected EEPS 3090 results is provided in Table 5-44. This table provides the EEPS results, original and corrected, the reference standard results (via part 1065 methods), the difference between the two data sets, and the determination of the statistical significance of the difference based on a t-test analysis. Figure 5-42, Figure 5-43, and Figure 5-44 also present the results.

Table 5-44. Difference Between TSI EEPS PM Measurement and Gravimetric Reference Methods

Engine Setting / Cycle	TSI EEPS 3090 Difference vs. Reference (1065)	TSI EEPS 3090 Difference vs. Reference (86)	TSI EEPS 3090 Difference vs. Reference (86 EC)
DPF-OUT			
10% Load, 1200 RPM	13.9%	91.0%	62.6%
24% Load, 1800 RPM	41.1%	67.4%	0.92%
70% Load, 1800 RPM	-100%	24.6%	-156%
HDFTP	36.9%	81.5%	73.0%
INTERMEDIATE PM LOADING			
10% Load, 1200 RPM	55.2%	73.2%	57.4%
24% Load, 1800 RPM	50.8%	66.7%	38.1%
70% Load, 1800 RPM	-0.41%	28.4%	2.76%
HDFTP	52.9%	65.6%	53.3%
ENGINE-OUT			
10% Load, 1200 RPM	59.0%	71.7%	45.7%
24% Load, 1800 RPM	72.3%	81.8%	49.6%
70% Load, 1800 RPM	27.8%	37.4%	22.8%
HDFTP	58.9%	69.6%	45.7%

N/A indicates data is not available
Shading indicates a statistically significant difference (reference vs. technology)

The TSI EEPS 3090 correlated well with the 1065 reference at DPF out conditions, providing no statistically significant difference with the reference at three of four test conditions. Nevertheless, it did not correlate very well with the reference standards in other cases, providing a statistically significant difference between the EEPS results and references at intermediate and engine-out conditions. It should be noted that, as with the other TSI instruments that shared the thermodiluter, the heating of the exhaust gas stream to 150^{o}C potentially eliminated volatile particulate from the stream analyzed by the EEPS, resulting in poor correlation with the reference methods. At DPF-out conditions, the percentage differences may be large due to the very low levels of PM observed that are near the detection limits of the reference methods, even though the absolute differences are small.

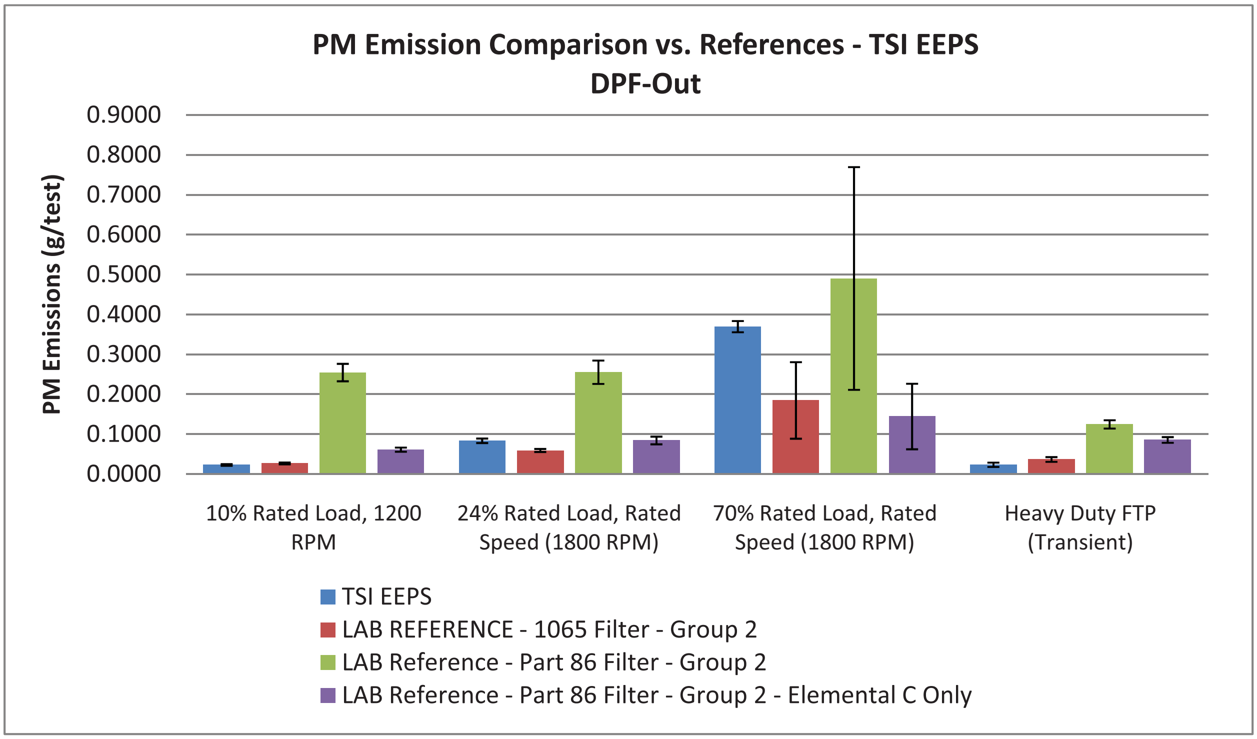


Figure 5-42. TSI EEPS 3090 and Gravimetric Reference PM Emissions—DPF-Out

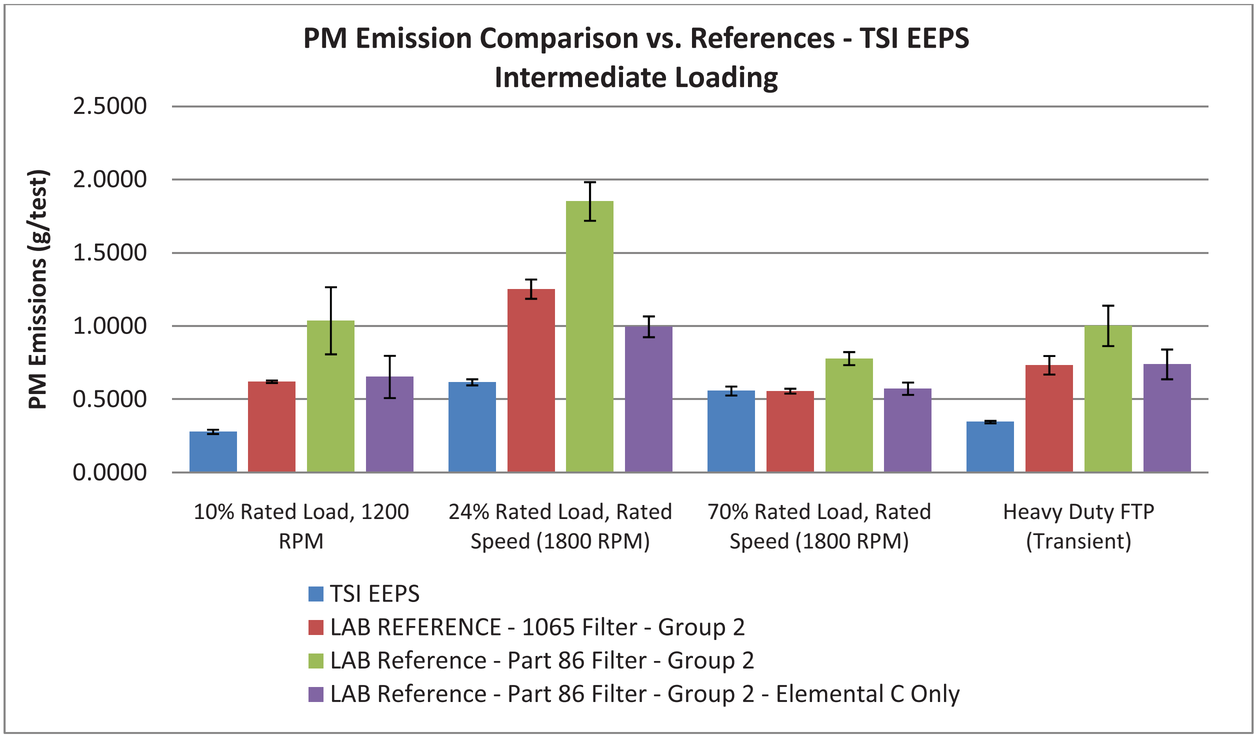


Figure 5-43. TSI EEPS 3090 and Gravimetric Reference PM emissions—Intermediate PM

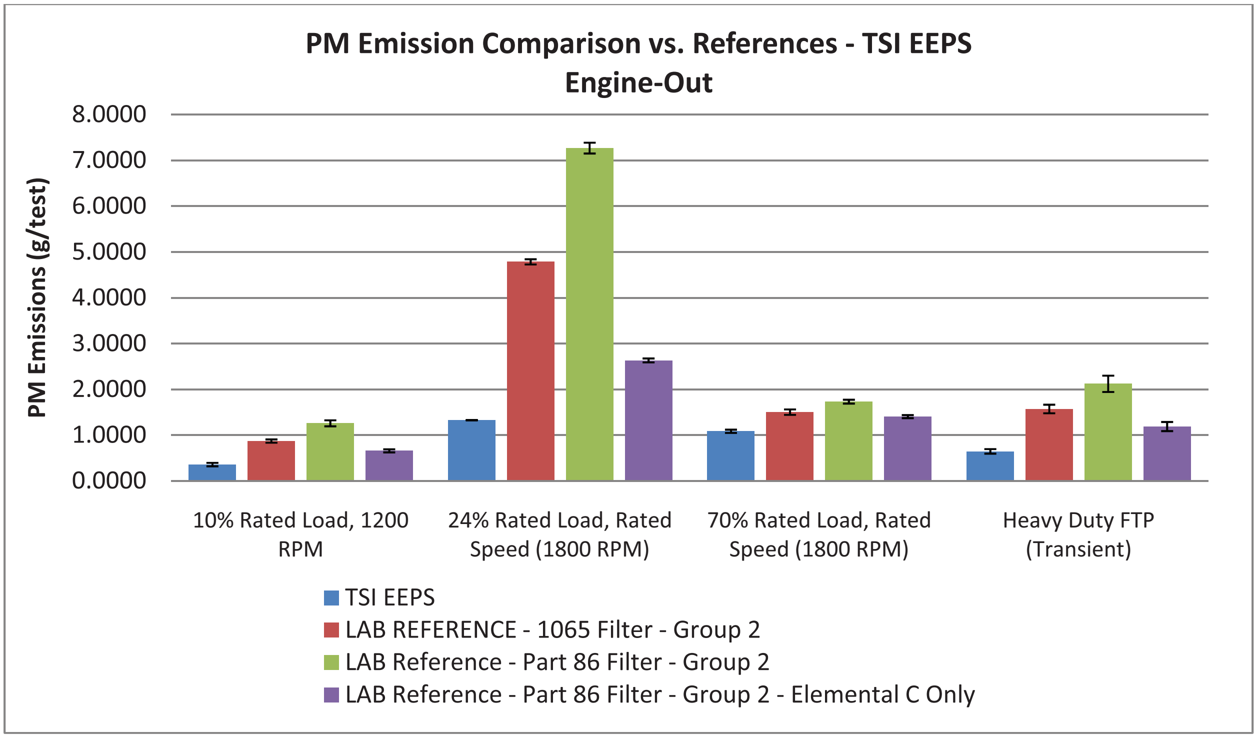


Figure 5-44. TSI EEPS 3090 and Gravimetric Reference PM emissions—Engine-Out

5.2.8.3.3. Repeatability

The test-to-test repeatability of each PM-PEMS can be evaluated by observing the coefficient of variation (CV) for each group of test runs at a specific operating condition or test cycle. The CV for the EEPS 3090 at each test condition is summarized in the table below, along with the CV for the reference methods for comparison.

Table 5-45. Coefficient of Variation for TSI EEPS 3090

Engine Setting	CV—LAB REFERENCE 1065 Filter Group 2	CV—LAB Reference Part 86 Filter Group 2	CV—TSI EEPS 3090
DPF-Out			
10% Rated Load, 1200 RPM	0.0854	0.0861	0.0947
24% Rated Load, Rated Speed (1800 RPM)	0.0654	0.115	0.0673
70% Rated Load, Rated Speed (1800 RPM)	0.521	0.569	0.0379
Heavy Duty FTP (Transient)	0.163	0.0835	0.235
Intermediate PM Loading			
10% Rated Load, 1200 RPM	0.0138	0.221	0.0517

24% Rated Load, Rated Speed (1800 RPM)	0.0526	0.0712	0.0339
70% Rated Load, Rated Speed (1800 RPM)	0.0299	0.0569	0.0553
Heavy Duty FTP (Transient)	0.0863	0.138	0.0234
Engine -Out			
10% Rated Load, 1200 RPM	0.0412	0.0517	0.106
24% Rated Load, Rated Speed (1800 RPM)	0.0118	0.0162	0.0011
70% Rated Load, Rated Speed (1800 RPM)	0.0393	0.0240	0.0330
Heavy Duty FTP (Transient)	0.0600	0.0840	0.0773

At the DPF-out, and very low levels of PM emissions, the EEPS proved to provide generally good reproducibility. CVs were somewhat variable, ranging from well below reference method CVs to somewhat higher than references. In all, the EEPS appears to provide sufficient repeatability, especially at low elemental carbon emission levels, when compared with reference methods.

5.2.8.3.4. Control Device Efficiency

In addition to evaluation of emissions, PM-PEMS may be used for evaluation of the impacts of an emission control device or novel emission reduction technology, where a direct measurement of the emissions level is not the primary target, but rather, a difference between two emission levels is targeted. To evaluate the suitability of the TSI EEPS in this application, the calculated control device efficiency (PM emission reduction level) for the DPF used in the lab tests was evaluated using the reference and TSI EEPS DPF-out and engine-out data from each set of test runs.

Table 5-46. Comparison of Control Device Evaluation Results for TSI EEPS 3090

Engine Condition	**Parameter**	**Reference—1065**	**EEPS 3090**	**Reference—86**	**EEPS 3090**	**Reference 86 Elemental Carbon**	**EEPS 3090**
10% Rated Load, 1200 RPM	DPF Control Efficiency (%)	96.9%	93.6%	79.8%	93.6%	90.7%	93.6%
	% Difference vs. Reference		3.5%		-17.3%		-3.2%
24% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	98.8%	93.7%	96.5%	93.7%	96.8%	93.7%
	% Difference vs. Reference		5.1%		2.9%		3.2%
70% Rated Load, Rated Speed (1800 RPM)	DPF Control Efficiency (%)	87.7%	65.9%	71.7%	65.9%	89.7%	65.9%
	% Difference vs. Reference		24.9%		8.0%		26.6%
Heavy Duty FTP (Transient)	DPF Control Efficiency (%)	97.7%	96.4%	94.1%	96.4%	92.8%	96.4%
	% Difference vs. Reference		1.3%		-2.4%		-3.9%

In all cases except for one, the EEPS closely predicted the control device efficiency to less than 4% of the reference measurement. At the 70% power output level, calculated efficiencies differed by almost 25% from the reference standards.

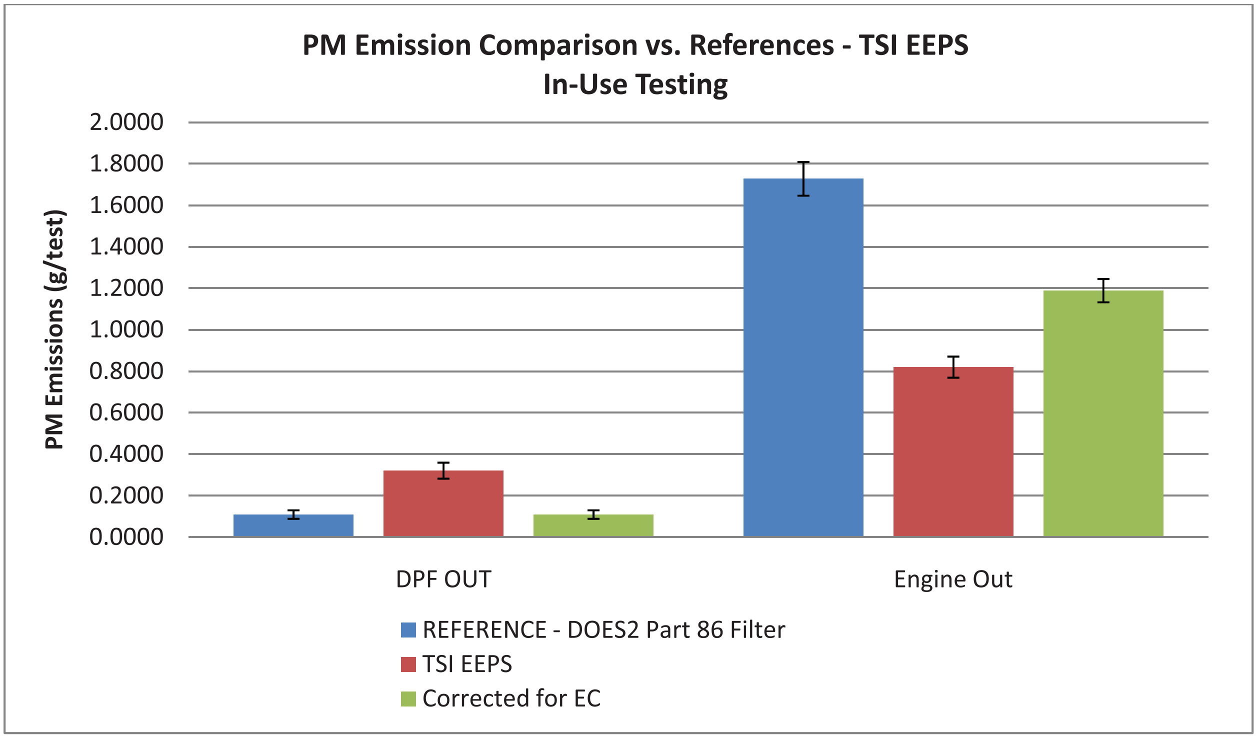
5.2.8.4. Comparison vs. References—In-Use

Comparisons of the TSI EEPS data vs. the DOES2 reference are provided in the table below. The difference versus reference standards at DPF-out is greater than 100% and is statistically significant. At engine-out, the differences are much smaller, but still statistically significant. Although one would anticipate a significantly lower measurement of PM emissions by the EEPS vs. the reference at DPF-out, due to TSI's use of the thermodiluter, the reference actually measured significantly less PM mass than the EEPS, resulting in a poor correlation of the EEPS to the reference. Comparisons at engine-out are better, yet still yield statistically significant differences. When compared to the elemental carbon results at engine-out, the difference with the reference is above 30%, much better correlation, but the difference remains statistically significant.

Table 5-47. TSI EEPS 3090 In-Use PM Emissions Comparison vs. Reference Standard

Engine Setting / Cycle	Parameter	REFERENCE—DOES2 Part 86 Filter	TSI EEPS 3090	Reference Elemental Carbon
DPF-OUT				
	Mean Emission Rate (g/test)	0.109	0.321	0.109
	CV	0.189	0.120	0.189
	% Difference vs. Reference		-194%	-194%
	Statistically Significant Difference?		YES	YES
Engine-Out				
	Mean Emission Rate (g/test)	1.73	0.820	1.19
	CV	0.0471	0.0621	0.0471
	% Difference vs. Reference		52.6%	31.0%
	Statistically Significant Difference?		YES	YES

Figure 5-45. TSI EEPS PM Emissions compared to In-use Reference Method



When comparing control device efficiency calculations using reference standard data and TSI EEPS data, there is a 35% difference between the two methods. A large portion of this difference results from the significantly higher DPF out emission rate observed with the EEPS. This indicates a poor correlation for the EEPS with this reference in these test conditions.

Table 5-48. In-Use Control Device Efficiency Determination—TSI EEPS 3090

Engine Condition	Parameter	REFERENCE—DOES2 Part 86 Filter	TSI EEPS 3090	Reference Elemental Carbon
In-Use	DPF Control Efficiency (%)	93.7%	60.9%	90.8%
	% Difference vs. Reference		35.0%	33.0%

5.2.8.5. Reliability and Operability

The TSI EEPS system operated reliably throughout the test program, both in-use and in the lab. No major operational issues were observed. There were some minor software glitches that were observed during testing, including:

- Loss of communication between equipment which required a system reboot.

5.2.9. PM-PEMS Real Time Measurement Capabilities

One of the important capabilities of the PM-PEMS evaluated here, except for one system, is the ability to perform real-time measurement of PM emissions while vehicles and engines are operated in transient conditions throughout a variety of operations. This ability allows users to measure and observe particulate emissions under typical engine operations in real-world, normal, use. This is important for the determination of impacts of actual duty cycles on emissions, identification of specific conditions where PM emissions are high, observation of transient operation and impact of transients on PM loading, and other important factors. Such observations may allow for the development of better correlations between actual, variable operating conditions and PM emissions. Improvements to the PM emissions inventory can be developed based on vehicle and engine activity data and correlation with real time PM emissions data. Systems can also be used to assess the performance of emission control devices (particulate filters, etc.) under widely varying operating conditions.

To evaluate real-time measurement capabilities of the PM-PEMS, real time data (second-by second, at a minimum) was collected from each instrument after each test. Typically, the real-time data was provided in PM concentration or other native instrument output units, and not converted to an emission rate. Since there is no reference standard at this time for real-time PM measurement, the real time data is compared to engine operating parameters and amongst other PEMS data for a qualitative assessment of real-time measurement capability.

Figure 5-46, Figure 5-47, Figure 5-48, and Figure 5-49 provide example real time measurement outputs for a single test run from all of the instruments. Also plotted is the fuel consumption rate in gal/s for the FTP cycle, which provides a potential correlation between engine operation and PM emissions.

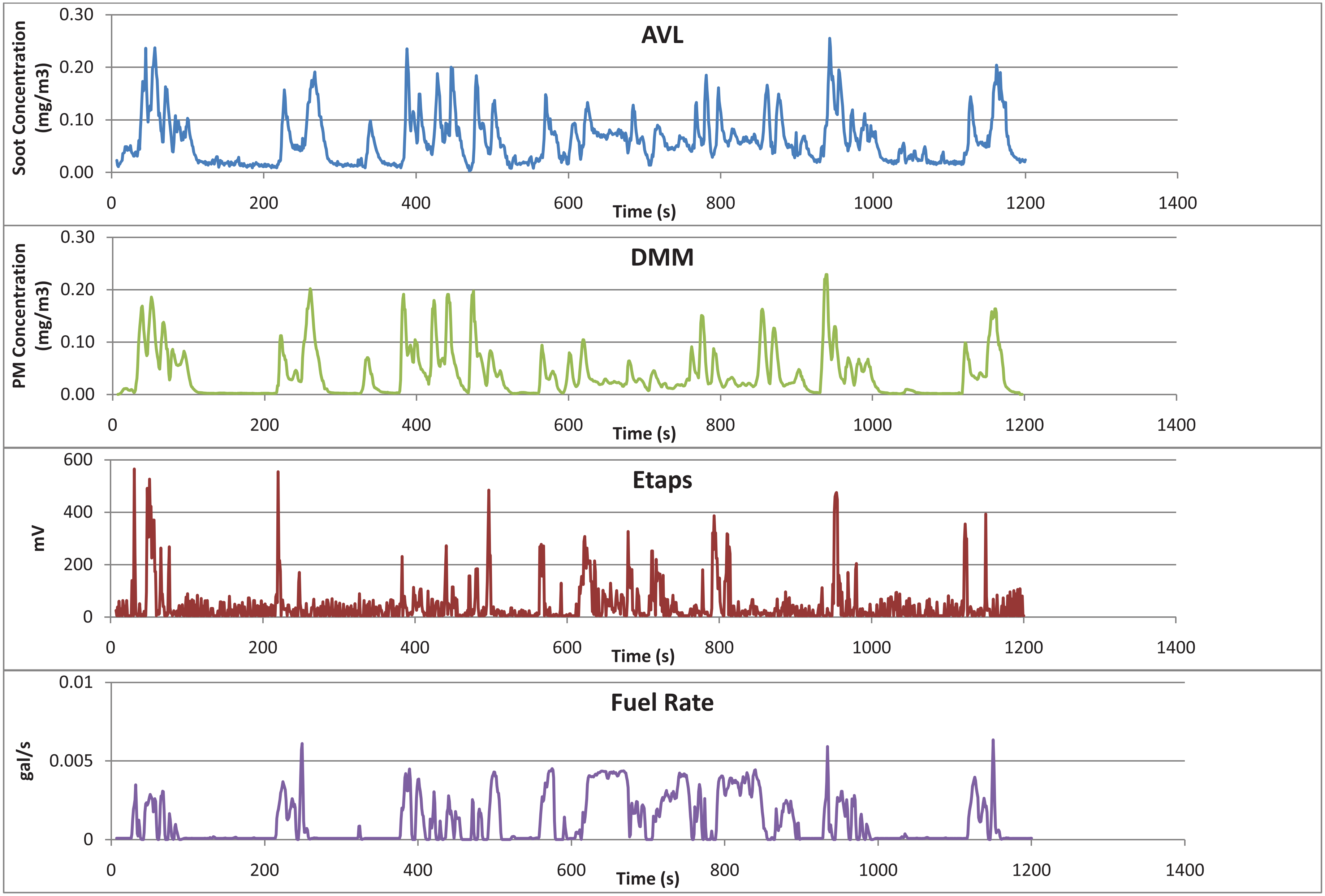


Figure 5-46. Real Time PM Measurement Results: Group 1—DPF-Out—FTP Cycle—Test #3

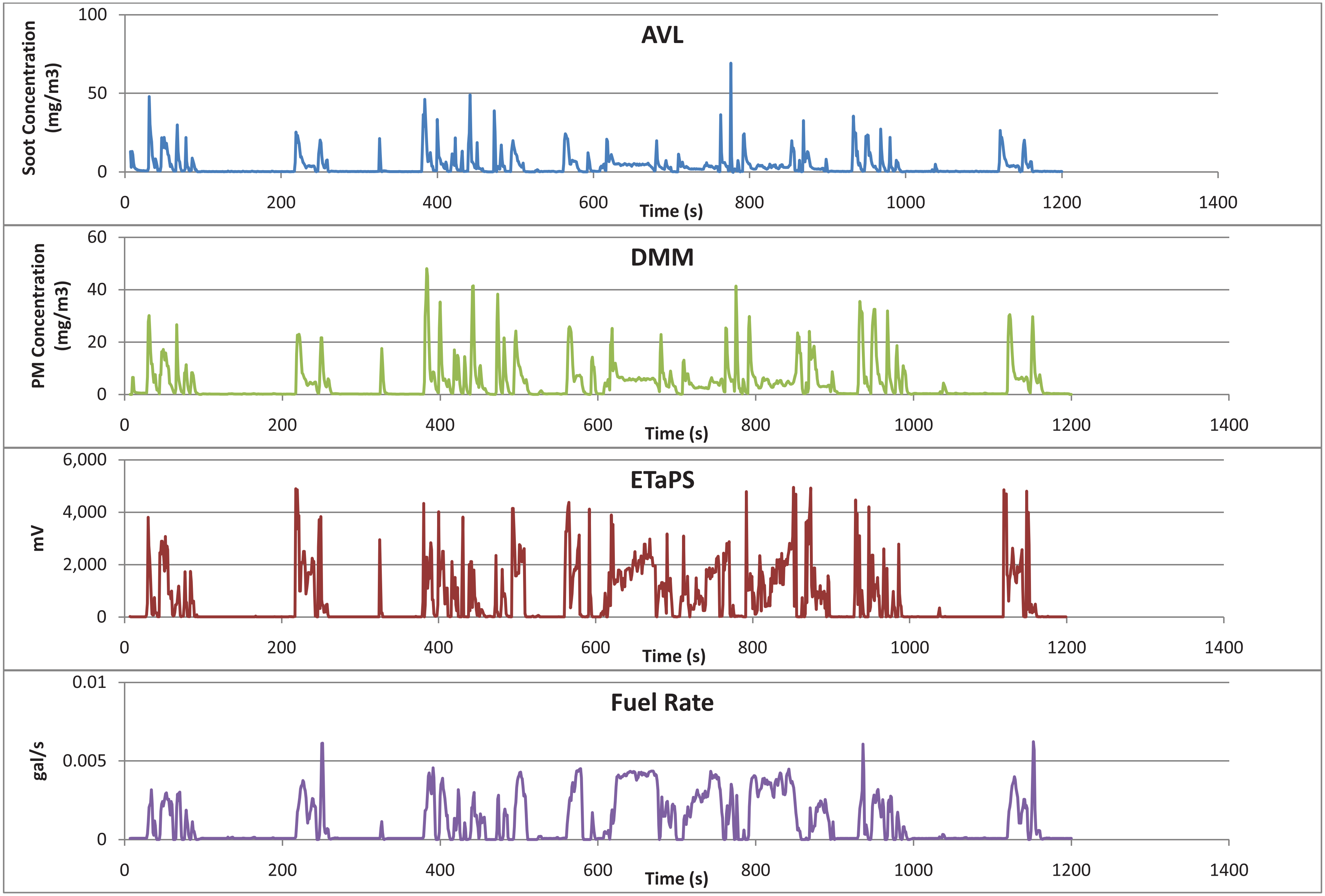


Figure 5-47. Real Time PM Measurement Results: Group 1—Engine-Out—FTP Cycle—Test #1

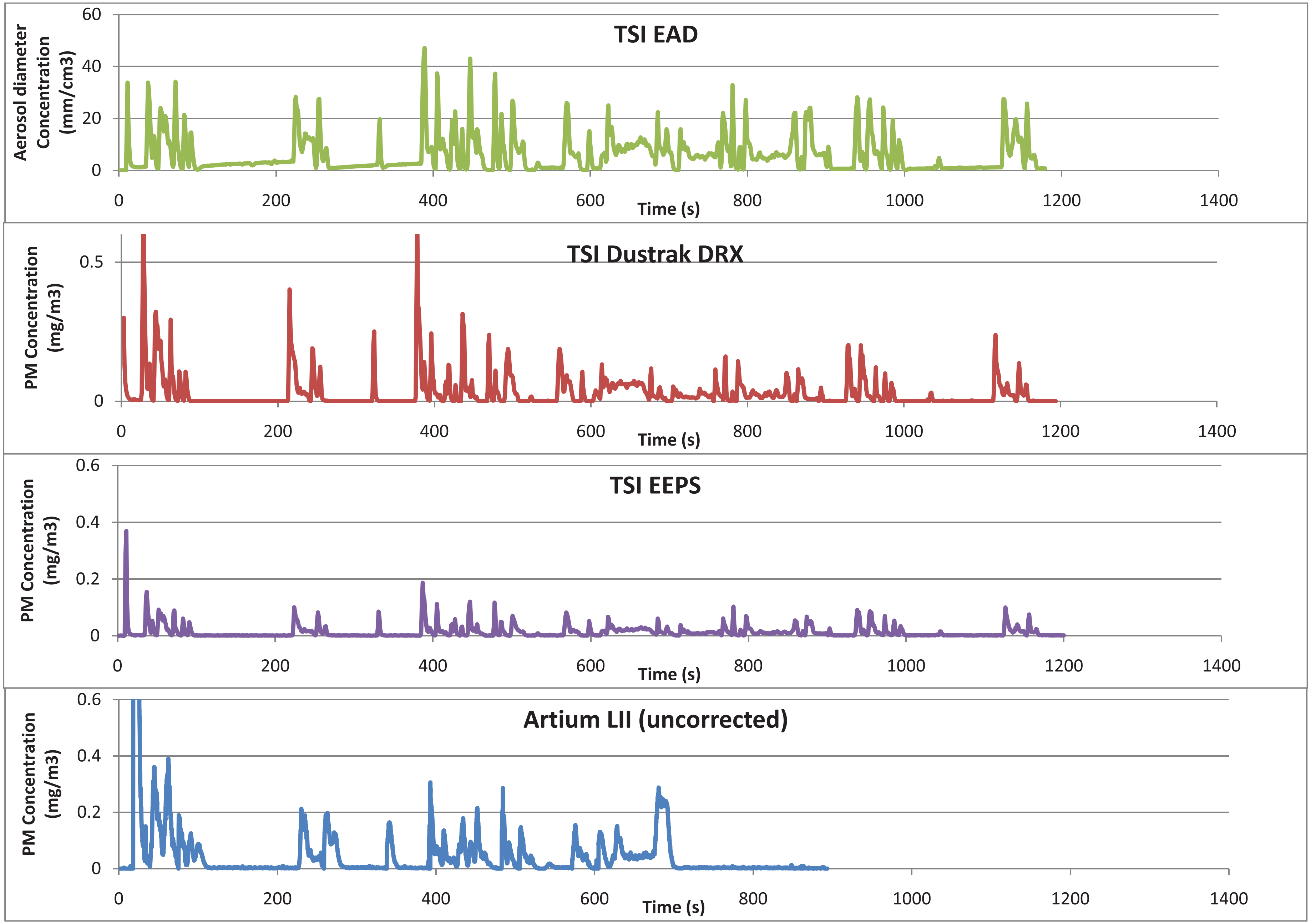


Figure 5-48. Real Time PM Measurement Results: Group 2—Engine-Out—FTP Cycle—Test #1.

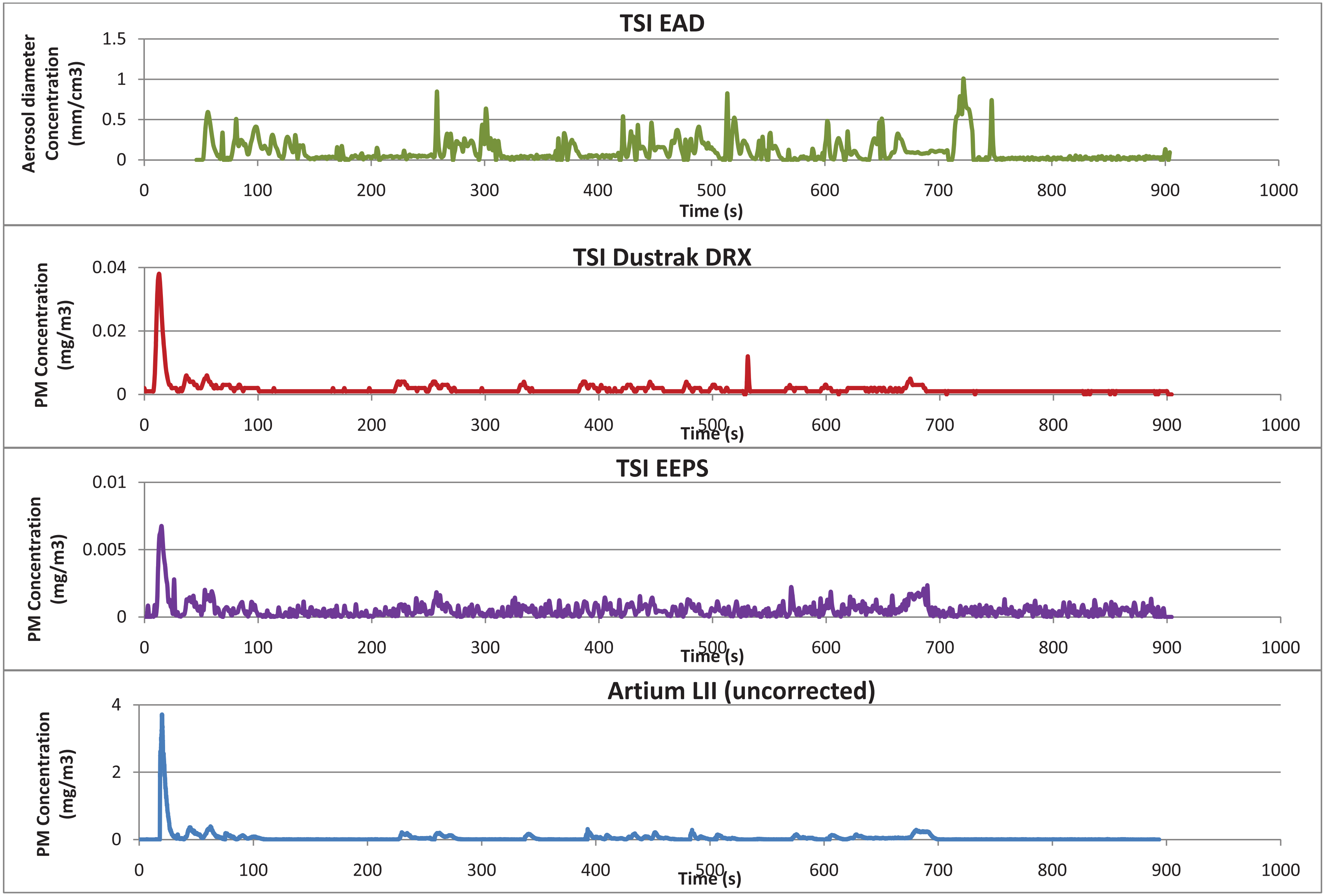


Figure 5-49. Real Time PM Measurement Results: Group 2—DPF-Out—FTP Cycle—Test #1

It should be noted that, for the engine out test run, all of the PM-PEMS evaluated provide similar responses to PM concentration changes. Although the concentration magnitudes may be different, the tracking of the PM measurement response across instruments is quite similar. Under DPF-out conditions, however, the Dekati DMM and AVL instruments track each other and the fuel rate very well, showing similar PM emissions trends as under the engine-out condition. This trend would be expected if a DPF is providing a generally consistent reduction in emissions levels across the full operating range and PM emission rates.

The Dekati ETaPS, TSI instruments, and Artium LII all produce distinctly different real-time PM outputs and emission patterns in the DPF-out test case when compared to engine out and the fuel rate for the FTP cycle. No consistent trends across these instruments are easily discernible. It should be noted that the TSI and Artium units were all sharing the TSI thermodiluter, which may have a significant impact on the PM emissions that are analyzed by each of these PM-PEMS. The EAD seemed most adept in this group at providing low-level real-time PM emissions, demonstrating the ability to measure PM emission spikes observed by the Dekati and AVL instruments. In addition, the Dekati ETaPS appears to be able to identify PM emission spikes, but has difficulty at low levels of PM emissions producing consistent output.

The real-time data collected during the test program demonstrates the ability of all of the instruments, not including the Control Sistem Micro-PSS, to provide real-time measurement of PM emissions at engine-out emissions levels. At DPF-out emission levels, two or three of the PM-PEMS systems appear to provide excellent ability to measure low level PM emissions transients, while the others appear to struggle.

6.0 CONCLUSIONS & RECOMMENDATIONS

The intent of this effort was to identify systems that may be applicable to real-world measurement of PM emissions from diesel and other mobile emission sources while operating in normal duty. Many of these have been recently developed and have not been independently evaluated and compared to reference standards in real-world applications beyond the laboratory for performance of fully integrated in-use test systems. Well validated, portable, and cost effective in-use PM measurement systems can serve critical needs in many areas including:

- The ability to verify PM emission reductions resulting from large scale implementation programs for diesel retrofits, engine repowers, and vehicle replacement, and to measure the impacts and effectiveness of these programs
- Verification of proper installation and actual effectiveness of control technologies implemented under tighter emission reduction regulations. This may include the development of compliance or inspection and maintenance programs that may be planned in conjunction with these and other regulations
- Efforts to develop more accurate emissions inventories to help guide State Implementation Programs, future regulations, implementation programs (such as diesel retrofits), research and development program development, and other actions.

The testing and evaluation of the eight individual PM measurement technologies and associated sampling, data collection, and control systems completed under this study provides valuable information regarding the performance of the systems, requirements for use, data processing requirements, and general capabilities of the systems. Several primary conclusions can be made regarding the performance and utility of the PM-PEMS systems, as well as the reference methods used and test procedures for assessing the performance of the particulate measurement systems:

1. Comparisons between particulate measurement technologies are highly dependent on the reference method used. This results primarily from the definition of particulate matter and the design of the measurement and sampling systems based on specific particulate matter types and constituents. For a reference method such as the EPA 1065 and 86 methods, particulate collection is highly dependent on the sampling and conditioning process. This can result in significant differences between methods, and, potentially, between references and PM-PEMS outputs.
2. PM-PEMS performance and comparison to reference is often dependent on system setup and operating conditions. Because PEMS manufacturers knew that comparisons were being made to the EPA 1065 method, several systems that are potentially capable of measuring a broad spectrum of particulate types were set up to focus primarily on soot measurement. These systems could be set up in a variety of manners to collect and analyze more volatile fraction particulate.
3. PM PEMS, which are designed only to measure soot concentrations, did compare more favorably to elemental carbon values, as would be expected. Those PEMS, which were measuring full spectrum particulate (organic and elemental fractions) compare favorably to the references at high organic carbon levels.

4. Repeatability of PM-PEMS PM mass measurements are typically better than reference methods in the controlled laboratory setting, especially at lower PM levels, with CVs lower than reference methods (1065). Regardless, the majority of CVs for the PM-PEMS instruments are less than 10%, which is acceptable for most applications. It should be noted that the repeatability for many PEMS systems was slightly worse in the in-use testing application. This may be a result of impacts of the in-use environment on instrument stability, as well as the slightly reduced repeatability of the test cycle in the in-use scenarios.
5. Although tested and installed as complete PM measurement systems, all of the PEMS systems evaluated required additional data streams to allow for in-use PM Mass emissions measurement. A means of measuring exhaust flow is required to be able to convert PM concentrations determined by the PM-PEMS to emission rates in terms of g/bhp-hr, g/s, g/mi or other commonly used reporting units. This can be accomplished with independent flow measurement or by coupling with a gaseous PEMS system that includes integrated exhaust flow measurement.
6. All of the PEMS evaluated appear to be generally acceptable for inspection and evaluation of emission control devices and their operation and impacts.

Upon reviewing all of the results, including the comparisons with reference standards, the installation, setup, and operating requirements, the data post-processing needs, and the instrument and system costs, one can conclude that, although some PEMS performed better vs. the references in this program, no single PM-PEMS will universally be the best choice for all potential applications. Users should evaluate and select PEMS for specific uses and programs based on the requirements of the test program, which may include:

- Expected emission level and PM type (EC vs. OC, size range, post-DPF, etc.)
- Data quality level (low accuracy, screening data or high level scientific research or regulatory information)
- Application and use of data (direct usage of emission rates, comparison between values, or use for screening and inspections)
- Cost of the equipment and available funding
- Test conditions (in-use, lab, high vibration, available power, physical space).

As an example, for an evaluation program looking at the performance of DPFs in construction equipment, one of the low cost, small PM-PEMS may be very useful, as primary objectives are for a comparative value and physical space limitations are severe. For a rigorous inventory program, a more elaborate system may be required that can provide an accurate emission rate value directly from the instrument, across a wider range of PM concentrations and types.

For future programs, it is suggested that additional evaluations be completed of the entire PM-PEMS systems, but with the ability to further evaluate the impacts of each of the individual components on PM emission rate measurement. The individual analyzers seem to have been fairly well evaluated in this and other independent programs. Nevertheless, the impacts of the full systems and the sampling and conditioning systems, as well as their adjustment and control for evaluation of multiple PM constituents should be further studied. Such studies will allow potential users to better understand the proper setup and control of the systems to achieve the measurement of specific particulate emissions being sought.

In addition, future programs should also evaluate the long term implementation of PM-PEMS under in-use operating conditions, especially harsh non-road situations. The impact of physical conditions (ambient conditions, vibration, jostling, etc.) should be evaluated over long utilization periods to determine if conditions result in deterioration of performance of the PEMS. This type of evaluation can help in the development of guidelines for implementation of PM-PEMS in-use, including calibration frequencies, installation requirements for shock and vibration protection, etc. In addition, it will provide insight into the durability of the units, as these types of systems typically are used for several days or weeks at a time in such conditions as part of large test campaigns.

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APPENDIX A. Test Engine Historical Data

Table A1.
Caterpillar C11 Historical PM Emissions Data with DOC
Hot Start Heavy Duty FTP Cycle

C11 Cat with Diesel Oxidation Catalyst		
		TPM
Test Date	Fuel	[g/bhp-hr]
30-Aug-06	ULSD	0.063
30-Aug-06	ULSD	0.064
30-Aug-06	ULSD	0.061
7-Sep-06	ULSD	0.058
7-Sep-06	ULSD	0.058
7-Sep-06	ULSD	0.056
7-Sep-06	ULSD	0.057
7-Sep-06	ULSD	0.057
7-Sep-06	ULSD	0.057
13-Sep-06	ULSD	0.055
13-Sep-06	ULSD	0.056
13-Sep-06	ULSD	0.055
13-Sep-06	ULSD	0.055
13-Sep-06	ULSD	0.056
13-Sep-06	ULSD	0.054
22-Nov-06	ULSD	0.05
22-Nov-06	ULSD	0.047
22-Nov-06	ULSD	0.046
4/25/2008	ULSD	0.077
4/25/2008	ULSD	0.071
4/25/2008	ULSD	0.073
8/12/2008	ULSD	0.0696
8/12/2008	ULSD	0.0652
8/12/2008	ULSD	0.0603
9/12/2008	ULSD	0.0669
9/12/2008	ULSD	0.0659
9/12/2008	ULSD	0.0634
	Average	**0.0599**
	Std Deviation	**0.0075**
	CV (%)	**12.45%**

Table A2.
Caterpillar C11 Historical PM Emissions Data, Engine-Out
Hot Start Heavy Duty FTP Cycle

Date	Fuel	PM level (g.bhp-hr)
10/8/2006	ULSD	0.094
11/21/2006	ULSD	0.070
11/21/2006	ULSD	0.068
11/21/2006	ULSD	0.073
7/15/2008	ULSD	0.097
7/15/2008	ULSD	0.081
7/15/2008	ULSD	0.080
6/13/2008	ULSD	0.071
6/13/2008	ULSD	0.071
6/13/2008	ULSD	0.070
7/25/2008	ULSD	0.107
7/25/2008	ULSD	0.091
7/25/2008	ULSD	0.100
	Average	**0.0824**
	StDev	**0.0137**
	CV	**16.6%**

Table A3.
Caterpillar C11 PM Emissions Data with DPF
Hot Start Heavy Duty FTP Cycle

Date	Fuel	PM level (g.bhp-hr)
7/11/2008	ULSD	0.0057
7/11/2008	ULSD	0.0056
7/11/2008	ULSD	0.0058
6/11/2008	ULSD	0.0039
6/11/2008	ULSD	0.0035
6/11/2008	ULSD	0.0052
7/24/2008	ULSD	0.0054
7/24/2008	ULSD	0.0063
7/24/2008	ULSD	0.0060
	Mean	**0.0053**
	StDev	**0.000948**
	CV	**18.0%**

APPENDIX B: PM PEMS VENDOR SPECIFICATIONS AND INSTALLATION REQUIREMENTS

Monitor manufacturer, model:	Artium, LII-200
Sample rate, Hz	20 Hz
Applicable particle sizes	10—100 nm
Type of PM measured (full spectrum or limited ...)	soot only (EC only)
Mass concentration method	measures active surface area; mass is inferred
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	5 ug / m^3—20 g / m^3
Accuracy or repeatability	± 5 % of reading
Detection limit	2 ug / m^3
Number (y / n)	n
Size distributions (y / n)	n
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	main module, heated sample line, common tubing probe, low pressure air supply
Describe all onboard reagents, gases, filters, consumables, etc.:	none
Number of modules, probes, support equipment required (not including sample lines)	3
Main module volume, ft^3	10 ft^3
Largest support module volume, ft^3	< 1 ft^3 (low pressure air pump)
System total weight, lb	260 lb
Req'd support brackets, braces for in-use tests, description / number	more than two brackets likely to be required for in-use tests
Sampling method (direct, raw exhaust; diluter, etc.)	direct sample of raw exhaust into laser cell
Vibration sensitivity?	likely to be moderately sensitive; they have done some on-road work
Power supply voltage, type (AC / DC)	110 VAC
Power supply current, A	not specified; assume > 720 W
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	likely > 12 h
Calibration operations automated?	specification states instrument is self-calibrating
Level of operator intervention required for calibrations, cleaning, maintenance	not specified
Operator's training time, h	likely > 8 h
Data acquisition (onboard, external PC required, external datalogger required)	external PC likely required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	automated onboard to a large extent
Cost	likely >> $100,000

Monitor manufacturer, model:	AVL 483 Micro Soot Sensor
Sample rate, Hz	specification is confusing. Exhaust conditioning unit claims 5 Hz, other spec's cite 100 Hz with < 1 s rise time
Applicable particle sizes	not specified
Type of PM measured (full spectrum or limited ...)	soot only
Mass concentration method	direct measurement
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	50 mg / m^3 maximum; wide range available with proprietary diluter
Accuracy or repeatability	± 3 % in diluter ranges likely to be used in this test series
Detection limit	specification is unclear. Interpreted as 0.01 mg / m^3 as noise
Number (y / n)	n
Size distributions (y / n)	n
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	probe, heated line, probe-mounted proprietary diluter, measuring unit, sample conditioning unit, voltage converter, dilution pump unit?
Describe all onboard reagents, gases, filters, consumables, etc.:	"fine filter" in sample train
Number of modules, probes, support equipment required (not including sample lines)	5 or 6. It's unclear if a separate dilution air pump is required or part of the sample conditioning unit
Main module volume, ft^3	approx. 2 ft^3
Largest support module volume, ft^3	approx. 1 ft^3
System total weight, lb	approx. 100 lb total
Req'd support brackets, braces for in-use tests, description / number	many; must support at least three major boxes
Sampling method (direct, raw exhaust; diluter, etc.)	direct sampling of raw exhaust with proprietary probe
Vibration sensitivity?	not specified
Power supply voltage, type (AC / DC)	12 VDC
Power supply current, A	approx. 100 A; generator or big batteries needed
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	pollutant dependent
Calibration operations automated?	no
Level of operator intervention required for calibrations, cleaning, maintenance	major
Operator's training time, h	> 8
Data acquisition (onboard, external PC required, external datalogger required)	external PC required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	extensive data processing available, including mass concentrations and time stamps
Cost	likely \$25,000 < \$\$ < \$100,000

Monitor manufacturer, model:	Dekati, Dekati Mass Monitor DMM—230
Detection principle	particle charging, intertial and electrical mobility classification
Sample rate, Hz	1 Hz
Applicable particle sizes	0—1200 nm
Type of PM measured (full spectrum or limited ...)	full spectrum
Mass concentration method	derived from surface area and diameer-related size distributions
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	0—5 mg/m^3; about 70:1 dilution required for raw exhaust
Accuracy or repeatability	not specified
Detection limit	European study implies < 1 % of span
Number (y / n)	n
Size distributions (y / n)	y
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	main module, proprietary probe (possibly with diluter), diluter, heated sample line, vacuum pump, low pressure air
Describe all onboard reagents, gases, filters, consumables, etc.:	not specified. Internal filters and cleaning are likely required
Number of modules, probes, support equipment required (not including sample lines)	4
Main module volume, ft^3	450 x 266 x 400 mm; 17.7” x 10.5” x 15.7”; 1.6 ft^3
Largest support module volume, ft^3	diluter, vacuum pump, or low pressure air likely < 1 ft^3
System total weight, lb	110 lb main module, likely 40 lb for vacuum pump and low pressure air: approx. 150 lb total
Req’d support brackets, braces for in-use tests, description / number	> 4
Sampling method (direct, raw exhaust; diluter, etc.)	dilution required; proprietary probe and diluter available
Vibration sensitivity?	not specified
Power supply voltage, type (AC / DC)	not specified; likely 110 VAC
Power supply current, A	not specified; likely 600 W for main module, 400 W total for heated sample line, vacuum pump, low pressure air: approx. 1000 W total
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	not specified; depends on source cleanliness; likely to be relatively short for engine-out (2.5—8 h)
Calibration operations automated?	no
Level of operator intervention required for calibrations, cleaning, maintenance	major; must open cabinet for cleaning, filter changes, etc.
Operator’s training time, h	≈ 8
Data acquisition (onboard, external PC required, external datalogger required)	external PC required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	Labview-based analysis probably reasonably complete
Cost	\$25,000—\$100,000

Monitor manufacturer, model:	Dekati, ETaPS
Sample rate, Hz	continuous; < 1 Hz
Applicable particle sizes	not specified
Type of PM measured (full spectrum or limited ...)	possibly full spectrum, but specifications are unclear
Mass concentration method	not specified; output is a distant surrogate for mass
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	0.01—100 mg / m^3
Accuracy or repeatability	not specified
Detection limit	0.01 mg / m^3
Number (y / n)	n
Size distributions (y / n)	n
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	On-stack sensor, electronics module, sheath air supply
Describe all onboard reagents, gases, filters, consumables, etc.:	none
Number of modules, probes, support equipment required (not including sample lines)	3
Main module volume, ft^3	< 1 ft^3
Largest support module volume, ft^3	< 1 ft^3
System total weight, lb	20—60 lb, including sheath air supply
Req'd support brackets, braces for in-use tests, description / number	two brackets likely: One to brace on-stack unit, one for sheath air
Sampling method (direct, raw exhaust; diluter, etc.)	full flow; rated 0 if tailpipe is correct size for instrument
Vibration sensitivity?	very sensitive
Power supply voltage, type (AC / DC)	12 VDC
Power supply current, A	low A for ETaPS, but sheath air needs about 30
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	unknown. Approximately 2.5 h, based on experience
Calibration operations automated?	no
Level of operator intervention required for calibrations, cleaning, maintenance	major
Operator's training time, h	< 2 h likely; very simple unit
Data acquisition (onboard, external PC required, external datalogger required)	external datalogger required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	all data must be post-processed
Cost	likely < $25,000

Monitor manufacturer, model:	TSI, DustTrak Model 8520
Detection principle	laser photometry (optical diameter)
Sample rate, Hz	1 Hz
Applicable particle sizes	100—10,000 nm
Type of PM measured (full spectrum or limited ...)	full spectrum likely
Mass concentration method	derived; manual implies (page 32) that data must be correlated with CVS and dynamometer results
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	0.001—100 mg/m^3
Accuracy or repeatability	not specified
Detection limit	likely << 1% of span
Number (y / n)	n
Size distributions (y / n)	n
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	inlet cyclone for sizing, main module, diluter, common tubing probe with heated sample line
Describe all onboard reagents, gases, filters, consumables, etc.:	internal filters
Number of modules, probes, support equipment required (not including sample lines)	4
Main module volume, ft^3	8.7” x 6.9” x 3.4”; 0.1 ft^3
Largest support module volume, ft^3	likely diluter is TSI 379020 rotating disk thermodiluter with separate air supply; module is 8.8” x 10.2” x 12.3”; 0.6 ft^3
System total weight, lb	approx. 30 lb (diluter and air supply outweigh the monitor)
Req’d support brackets, braces for in-use tests, description / number	2
Sampling method (direct, raw exhaust; diluter, etc.)	diluter likely required to prevent moisture condensation
Vibration sensitivity?	likely very robust. Designed for field work
Power supply voltage, type (AC / DC)	six VDC from C-cell batteries; diluter requires 110 VAC
Power supply current, A	250 W; approx. 20 A @ 12 VDC with inverter
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	depends on concentrations and particle sizes; likely < 2.5 h on a dirty stack
Calibration operations automated?	no
Level of operator intervention required for calibrations, cleaning, maintenance	major; disassembly and cleaning required
Operator’s training time, h	minimal
Data acquisition (onboard, external PC required, external datalogger required)	approximately 8 h at 1 Hz (31000 samples available)
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	software is limited; significant post-processing is likely
Cost	< $25,000

Monitor manufacturer, model:	TSI, Electronic Aerosol Detector EAD 3070A
Detection principle	corona charging and current detection
Sample rate, Hz	3.75 Hz, max
Applicable particle sizes	10—1000 nm
Type of PM measured (full spectrum or limited ...)	full spectrum
Mass concentration method	surrogate; reports diameter concentration only
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	depends on average diameter of particulate. Full span @ 50 nm ≈ 3 mg/m^3; full span @ 600 nm ≈ 250 mg/m^3
Accuracy or repeatability	not specified
Detection limit	not specified
Number (y / n)	n
Size distributions (y / n)	n
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	diluter, low pressure air, common tubing probe, heated sample line, main module
Describe all onboard reagents, gases, filters, consumables, etc.:	no consumables; some cleaning required
Number of modules, probes, support equipment required (not including sample lines)	four
Main module volume, ft^3	15” x 11” x 5.3”, 0.5 ft^3
Largest support module volume, ft^3	< 1 ft^3 (diluter)
System total weight, lb	≈ 50 lb, incl. diluter and low pressure air supply
Req’d support brackets, braces for in-use tests, description / number	3
Sampling method (direct, raw exhaust; diluter, etc.)	diluter required
Vibration sensitivity?	not specified
Power supply voltage, type (AC / DC)	not specified; assume 110 VAC
Power supply current, A	not specified; assume 200 W for main module, 300 W for low pressure air, diluter, and heated sample line
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	likely > 12 h
Calibration operations automated?	no; factory calibration only, zero calibration in field
Level of operator intervention required for calibrations, cleaning, maintenance	major -- must open case for cleaning
Operator’s training time, h	likely < 8
Data acquisition (onboard, external PC required, external datalogger required)	external PC required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	TSI proprietary “Aerosol Instrument Manager for Condensation Particle Counters and Electrical Aerosol Detector” software available, but extensive post-processing is likely to yield mass concentrations
Cost	\$25,000—\$100,000

Monitor manufacturer, model:	TSI, Model 3090 Engine Exhaust Particle Sizer Spectrometer (EEPS)
Sample rate, Hz	10
Applicable particle sizes	5.6—560 nm
Type of PM measured (full spectrum or limited ...)	likely to be full spectrum
Mass concentration method	derived from particle count, size distribution, inferred density
Available mass concentration span (expected value for nonroad diesel engines ≈ 100 mg/m^3)	specifications imply 4 orders of magnitude, starting at "< 1 ug / m^3", or likely to about 10 mg / m^3. Implies a 10:1 dilution will be required.
Accuracy or repeatability	not specified
Detection limit	200 particles / cm^3, "corresponding to < 1 ug / m^3"
Number (y / n)	y
Size distributions (y / n)	y
Describe all modules, sample lines, sample line lengths, probes, dilution apparatus, support equipment, etc.:	main module, likely requires a diluter, common tubing probe, heated sample line to diluter
Describe all onboard reagents, gases, filters, consumables, etc.:	none
Number of modules, probes, support equipment required (not including sample lines)	three
Main module volume, ft^3	27.7" x 13.5" x 17.3"; 3 ¾ ft^3
Largest support module volume, ft^3	likely about 1 ft^3 for diluter
System total weight, lb	likely about 90 lb, including diluter
Req'd support brackets, braces for in-use tests, description / number	> 2 based on large main module and diluter
Sampling method (direct, raw exhaust; diluter, etc.)	raw exhaust, likely through diluter
Vibration sensitivity?	not specified
Power supply voltage, type (AC / DC)	110 VAC
Power supply current, A	250 W
Maximum operating time between calibrations, maintenance, cleanings, desorption, regeneration, etc.	specifications state > 12 h
Calibration operations automated?	not specified. No calibration information available in manual either.
Level of operator intervention required for calibrations, cleaning, maintenance	major if the instrument must be returned to the factory for calibration
Operator's training time, h	likely 2—8 h
Data acquisition (onboard, external PC required, external datalogger required)	external PC required
Data processing and algorithms (mass concentrations, supporting data streams, timestamps available)	extensive processing available in proprietary software package
Cost	$25,000—$100,000

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Evaluation of On-Board Real-Time Particulate Emissions Measurement Technologies

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