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2007 DIESEL PARTICULATE MEASUREMENT RESEARCH

Phase 3 Final Report

May, 2007

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COORDINATING RESEARCH COUNCIL, INC.
3650 MANSELL ROAD·SUITE 140·ALPHARETTA, GA 30022

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Prepared by

Imad A. Khalek, Ph.D.

Final Report
Project E-66-Phase 3

Prepared for

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, GA 30022

Sponsored by:

Coordinating Research Council
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SOUTHWEST RESEARCH INSTITUTE®
P.O. Drawer 28510 6220 Culebra Road
San Antonio, Texas 78228-0510

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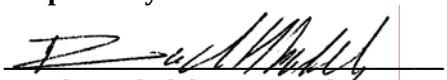

Imad A. Khalek, Principal Engineer

Approved:

For: Daniel W. Stewart,
Director of Research

Reviewed by:

Terry L. Ullman,
Assistant Director of Research

DEPARTMENT OF ENGINE AND EMISSIONS RESEARCH
ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION

FOREWORD

Project E-66 was funded by the Coordinating Research Council (CRC), Department of Energy / National Renewable Energy Laboratory (DOE / NREL), Environmental Protection Agency (EPA), Engine Manufacturers Association (EMA), and California Air Resources Board (CARB). The sponsors were represented by Mr. Brent Bailey and Dr. Chris Tennant from CRC, Dr. Doug Lawson from NREL, Dr. Bruce Cantrell and Mr. Matt Spears from EPA, Dr. Shirish Shimpi from Cummins, and Mr. Hector Maldonado from CARB.

The SwRI Principal Investigator and Project Manager was Dr. Imad Khalek, Principal Engineer. Technical staff members who largely contributed to this work were Mr. Daniel Preece, Principal Technician, Mr. Joe Sosa, Senior Technician, Mr. Robert West, Staff Technician, Ms. Kathy Jack, Research Assistant, Mr. Keith Echtle, Laboratory Assistant Manager, and Mr. Ernest Kruger, Laboratory Manager.

The work was initiated and reviewed by the E-66 Panel members who are listed below in alphabetical order. Dr. Steve Cadle was the Chairman and Dr. Shirish Shimpi was the Co-Chairman of the E-66 Panel. Mr. Brent Bailey and Dr. Chris Tennant from CRC were the Project Managers representing the sponsors.

Mr. Adewale Aoshinuga Aoshinuga, SCAQMD
Mr. Brent Bailey, CRC
Dr. Ewa Bardasz, The Lubrizol Corp.
Dr. Nick Barsic, Deere & Company
Mr. Mike Bogdanoff, SCAQMD
Dr. Steve Cadle, General Motors Corp.
Dr. Bruce Cantrell, EPA
Mr. King Eng, Shell Global Solution (U.S.), Inc.
Mr. Tim French, EMA
Mr. Rob Graze, Caterpillar, Inc.
Dr. Doug Lawson, NREL
Mr. Hector Maldonado, CARB
Dr. Matti Maricq, Ford Motor Co.
Dr. Mani Natarajan, Marathon Petroleum Co.
Dr. Shirish Shimpi, Cummins Inc.
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Mr. Joe Suchecki, EMA
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SwRI appreciates AVL, Cummins, Horiba, Sensors, and Sierra for providing their partial flow sampling systems that included the SPC, Cummins, MDLT, MPS, and BG3, respectively, and the personnel listed below, to support Phase 3 of Project E-66. SwRI also thanks EPA and Caterpillar for the additional support through the participation of their staff.

AVL North America, Inc.
Mr. Bill Silvis, initial contact and approval to participate in Phase 3
Dr. Shahin Nudehi, SPC setup, calibration, and operation
Mr. Gerald Marek, SPC setup and calibration

Caterpillar, Inc.
Mr. Rob Graze, Sierra BG3 setup and inspection during transient operation in Task 7.2

Cummins Inc.
Dr. Shirish Shimpi and Mr. Bill Martin, initial contact and approval to participate in Phase 3
Mr. Bret Rankin, AEI/CUM system setup, calibration, and operation

Horiba Instruments Ltd
Mr. Neal Harvey, initial contact and approval to participate in Phase 3
Mr. Otsuki Yoshinori, MDLT setup, calibration, and operation
Mr. Dave Laskowski, MDLT setup and calibration
Mr. Ichiro Asano, MDLT setup and supervision
Dr. Qiang Wei, MDLT setup and supervision
Dr. Mike Akard, MEXA 1370 PM (Particle Analysis Instrument) setup, calibration, and operation

Sensors, Inc.
Mr. Atul Shah, initial contact and approval to participate in Phase 3
Dr. David Booker, MPS setup, calibration, and operation

Sierra Instruments, Inc.
Mr. Del Pier, initial contact and approval to participate in Phase 3
Mr. Gregory Pier, BG3 setup, calibration, and operation

US Environmental Protection Agency
Dr. Bob Giannelli, Sensors MPS setup, calibration, and operation

EXECUTIVE SUMMARY

Phase 3 of Project E-66 was conducted using the same engine and aftertreatment system used in Phase 1 and Phase 2, namely a 1998 DDC Series 60 heavy-duty diesel engine (HDDE) equipped with a continuously regenerative technology diesel particulate filter (CRT-DPF). Two exhaust configurations were used; one exhaust configuration included a CRT-DPF without Bypass and the other included a mix of aftertreatment and non-aftertreatment exhaust, namely a CRT-DPF with Bypass. The CRT-DPF with Bypass was used to elevate the particulate matter (PM) emission level to about 80 percent of 2007 PM standard in order to increase the PM mass deposit on the sample filter used for PM collection. Engine tests included the heavy-duty on-highway federal test procedure (FTP) transient cycle, the nonroad transient cycle (NRTC), and full and 10 percent load at rated engine speed. The partial flow sampling system (PFSS) units evaluated were, in alphabetical order, an AVL-SPC, Cummins-AEI, Horiba-MLDT, Sensor-MPS, and a Sierra-BG3. Two CVS secondary dilution systems were used as reference comparisons, a long and a short residence time tunnel.

Compared to results obtained during 2002, all PFSS units had improved their response times by providing sampling that was proportional to exhaust flow with a response time of 200 ms or faster. Most PFSS units also showed a correlation coefficient (R^2) higher than 99 percent and a standard error better than 5 percent between the engine total exhaust flow and the sample flow extracted from the exhaust during transient engine operation. The response time demonstrated in this program was sufficient to run a PFSS in real time under transient engine operation.

The BG3, MDLT, and SPC PFSS units gave similar performance to that of the CVS when used as CVS secondary dilution systems for engine exhaust treated with a CRT-DPF without Bypass. For these experiments, the PM emission level was well below 10 percent of the 2007 standard and very close to the level obtained with the tunnel blank filters used for PM collection from the full flow CVS without engine operation. Similar results were also obtained when the PFSS units were used as single diluters on engine exhaust using the CRT-DPF without Bypass. This part of the program showed that when the PM emission level is below 10 percent of the 2007 PM standard, it is challenging to discern differences between the performance of a PFSS and a CVS due to the very low PM emission level. Thus, both systems may be acceptable for PM emission measurement using a CRT-DPF without Bypass.

The AEI/CUM PFSS gave lower PM emissions than that of the CVS when using a CRT-DPF without Bypass. This is likely because of the high dilution air temperature of 47 °C that was used with that system compared to a dilution air temperature of about 25 °C that was used with the CVS. The MPS PFSS gave higher PM emissions under similar engine operating conditions without Bypass. The MPS was a prototype system that was recently introduced to the project and was not clear why it performed in this manner.

When the PFSS units were used for engine exhaust treated with the CRT-DPF with Bypass at an approximate PM emission level of 80 percent of the 2007 standard, the PM emission results were not consistent. While the PM emission results using most of the PFSS units agreed with the CVS under steady-state engine operation, the results for the SPC unit were 2.5 times higher for engine rated speed, 100 percent load, but were 50 percent lower for rated speed, 10 percent load. Under transient engine operation over the FTP and NRTC cycles, the SPC unit

gave similar PM emissions to that of the CVS, while the MDLT, BG3, and the AEI/CUM gave higher PM results, and the MPS gave lower PM results. More work is needed to verify the performance of the PFSS units under transient engine operation at an emission level near the 2007 PM standard. Perhaps this work should be done separately with each individual PFSS manufacturer.

In order to have a qualitative assessment of the PM composition collected by each of the PFSS units, quartz filter analysis for organic carbon (OC), elemental carbon (EC) and sulfate was determined using the Horiba MEXA 1370-PM. Generally, the AEI/CUM collected less sulfur compounds than the other systems. The AEI/CUM was the only system using a dilution air temperature of 47^{o}C, a temperature that perhaps minimized sulfuric acid droplet formation or collection by the filter. This dilution air temperature or other characteristics of the AEI/CUM system may have resulted in this observation. Another important observation from quartz filter analysis was the low EC emission levels reported by the MPS, suggesting that either solid particles were lost in the sampling train or the analytical method was not accurate when the amount of EC deposited on the filter is very small, below 0.5 μg. The quartz filter results also confirmed the higher PM emissions obtained with the SPC at the rated speed, 100 percent load. OC, EC, and sulfate were all higher than the rest of the systems at this condition. This suggests that the SPC observations may be related to both the particle phase and the gas phase levels of PM. However, the EC phase obtained using the MEXA 1370 method may be overestimated due to the potential formation of EC from OC by pyrolysis during filter analysis. Thus, the quartz filter analysis was not reliable to explain the results obtained with the SPC under steady-state engine operation.

Upon the examination of the data by AVL, AVL speculated that the difference may be a mixing issue between the CRT-DPF flow stream and the by-pass flow stream, prior to sampling by the SPC. This is in spite of long mixing lengths (24 diameters) and turbulent flow (high Reynolds numbers). Additional work to resolve this issue was requested and after the needed funds were appropriated, tests were carried out. The tests confirmed that the sample received by the SPC was indeed well mixed and that there must have been some other reason for the high PM results obtained by the SPC for the rated speed, 100 percent load condition. Additional tests carried out by AVL at SwRI, after the conclusion of the mixing study, revealed that when SPC matched CVS system parameters of dilution ratio, dilution air temperature and residence time, there was an improved agreement between the CVS and the SPC. Similar observations were made in an earlier study carried out at SwRI, but with pre-2007 engines using pre-2002 PFSS units. In light of these observations, discussions between EPA, EMA and instrument suppliers of PFSS units are planned to determine if a consensus can be reached in setting targets on CVS and PFSS parameters to enable the use of PFSS units as an alternative to the full flow CVS sampling system.

The effect of residence time in the secondary dilution tunnel on PM mass was evaluated as part of this Phase 3 of the study. Increase in residence time in the secondary dilution tunnel led to increased PM weight gain on the Teflo filter. By increasing the residence time from 0.75 to 15 seconds, the PM emissions increased by a factor of 2.8 from 0.25 to 0.7 mg/hp-hr, but the PM emission level remained at a level below 10 percent of the 2007 standard. A similar increase was observed with the real time DMM-230 and the EEPS instruments.

Fuel properties were indicated by this work to influence PM emissions. The fuel used in Phase 2 had 1.7 times more sulfur and 11 times more polyaromatics than the fuel used in Phase 3, and Phase 2 PM results were six times higher than Phase 3. The differing results for Phases 2 and 3 suggest that fuel properties may be responsible. More investigation is required to determine if the higher PM was due to fuel properties.

Several real time particle instruments were evaluated. These were the TSI engine exhaust particle sizer (EEPS) and the Dekati Mass Monitor (DMM-230). Since these instruments did not use filter-collected PM as a particle capture method, they provided additional insight into the continuing investigation of PM filter artifacts. Although both of these instruments used slightly different particle measurement techniques, they agreed reasonably well, and more importantly, suggested that even the least artifact prone filter media (Teflo) still included artifact. These results are considered preliminary and most agree that additional work beyond the scope of Project E-66 is required before full understanding of filter artifact and real-time exhaust PM measurement is achieved.

Overall, Phase 3 of Project E-66 verified the greatly improved and now acceptable response time of the PFSS units tested in this program. It also showed that at a PM emission level below 10 percent of the 2007 standard, both the CVS as well as the PFSS units could be used interchangeably to produce similar results under steady-state and transient engine operation. However, at a PM emission level near the 2007 standard, more investigation is needed to compare the performance of the two systems while carefully taking into account dilution and sampling parameters such as residence time, dilution air temperature, dilution ratio, and filter face velocity. Currently, under the code of federal regulation (CFR) Part 1065, which is applicable to this work, EPA allows a wide dynamic range of dilution and sampling parameters to be used and discussions between EPA and EMA should continue to focus on tightening those parameters as much as practically possible in order to improve the chance of obtaining similar results using different PM sampling as well as PM measurement systems.

Phase 3 of Project E-66 also highlighted the usefulness of using real time particle instruments to measure PM at near or well below the 2007 PM standard. The ease of use, high sensitivity, and fast response time (less than one second) of these instruments make them good candidates for particle measurement instead of using the filter collection technique. However, more work is needed to establish a standard protocol to calibrate and demonstrate the accuracy of these systems in measuring PM mass.

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1.0 BACKGROUND

The full flow CVS has been routinely used as a means to dilute and cool the engine exhaust and provides for the collection of particulate matter (PM) on a filter at a temperature below 52^{o}C using a secondary dilution tunnel that is coupled to the full flow tunnel. Due to space limitations and costs associated with building a full flow CVS, the engine manufacturers have expressed interest in using a partial flow sampling system (PFSS) as a substitute for the full flow CVS for engine certification under transient operation. The recent introduction of the non-road transient cycle also makes the use of a PFSS more attractive than the full flow CVS because large non-road engines would require a large CVS with a proportionately large flow rate, on the order of 10,000 cubic feet per minute (cfm).

In early 2001, the EPA and EMA had agreed to cast a “no" vote on the draft International Organization for Standardization (ISO) 16183 document, especially the part related to the use of partial flow sampling systems for the measurement of PM mass from heavy duty diesel engines (HDDEs) running under transient operation. Such action by the US stemmed from preliminary findings from testing commissioned by EMA and EPA at SwRI suggesting a major disagreement between the PFSS and the currently accepted full flow CVS method [1]. As a result of the US action, the ISO members decided to delay publishing of the official ISO 16183 document and gave the US group more time to investigate the performance of the PFSS relative to the CVS, and to present the findings to the ISO group with recommendations.

EPA, EMA, and CARB joined together in sponsoring a research project at SwRI designed to investigate PM measurement using several PFSS units and a full flow CVS [2]. The work included several commercially available 2001 MY PFSS units, the AVL SPC, Horiba MDLT, and Sierra BG2. The work was conducted in an effort to make recommendations to the ISO workgroup developing the final ISO 16183 document.

The main conclusion of the early work was that all the PFSS units gave lower PM emission results than the full flow CVS. The discrepancy was mainly due to a fundamental problem related to the slow response of the PFSS to the changes in engine exhaust flow under transient engine operation. Furthermore, there were issues related to differences in the dilution parameters that also added to the discrepancy between the CVS and PFSSs performance relative to volatile PM.

At the conclusion of the early work, EPA, EMA, and CARB recommended that more work was needed, particularly related to PFSS response time, before the US could accept the use of a PFSS for engine certification. The use of a PFSS for PM engine emissions certification under transient testing is currently not accepted by EPA, unless written approval from EPA in accordance with CFR Part 1065, Sub-Part 1065.12 [3], titled, “Approval of Alternative Procedures” is given, even if the PFSS meets ISO 16183.

In light of the EPA 2007 PM sampling protocol and the improvement made by the PFSS manufacturers relative to response time, the CRC Real World Vehicle Emissions and Emissions Modeling Group initiated the work under Phase 3 of Project E-66 to investigate the performance of PFSS compared to the full flow CVS using the 2007 PM sampling protocol with a diesel engine that meets the 2007 PM standard.

2.0 INTRODUCTION

Project E-66 focused on four main objectives. Objective 1 was to improve PM emission measurement from low emitting diesel engines that meet the 2007 EPA standard of 0.01g/hp-hr. Objective 2 was to investigate and identify a potential real time PM method that may serve as an alternative to the currently prescribed filter-based method. Objective 3 was to investigate and improve the correlation between PM measured by the PFSS and the full flow CVS. Objective 4 was to develop and implement a quality assurance/quality control (QA/QC) plan, and to provide a QA/QC plan that defines QA procedures to support the 2007 PM measurement method.

SwRI developed an approach that used seven tasks to address Project E-66 objectives in a technically sound and efficient manner. Results of Tasks 1, 2, 3, and 4 were reported in Phase 1 Final Report, which was submitted to CRC in May 2005 [4]. Results of Tasks 5 and 6 were reported in Phase 2 Final Report, which was submitted to CRC in December 2005. Results of Task 7, is covered in this report, focusing on the performance of several PFSS units compared to the full flow CVS.

Task 7 included two Subtasks:

- Subtask 7.1 was to use four PFSS units, the AEI/CUMmins, AVL SPC, Horiba MDLT, and Sierra BG3, as secondary dilution tunnels coupled to the full flow CVS and to compare their performance in determining PM emissions with both a short and a long residence time secondary tunnel made by SwRI.
- Subtask 7.2 was to use the four PFSS units with another PFSS provided by Sensors, the MPS, on raw engine exhaust and compare their performance in determining the PM emissions with that of the full flow CVS using the short residence time CVS secondary tunnel.

Subtasks 7A and 7B were also added to Phase 3. These subtasks were a carry over from Phase 2 and were meant to resolve questions on the effect of residence time on PM emissions observed using real time PM instruments, and whether these observations were also substantiated by PM samples taken using Teflon membrane filters (Teflo). Subtask 7A began before Subtasks 7.1 and 7.2, and it included an experimental investigation of the effect of secondary tunnel residence time on PM measurement using Teflo filters. Subtask 7B was completed after finishing Subtasks 7.1 and 7.2, and it included an experimental investigation with all the PFSS units and with the secondary tunnels using quartz filters instead of Teflo filters. The quartz filters were analyzed for organic carbon (OC), elemental carbon (EC), and sulfate using the Horiba MEXA 1370 PM.

Subtasks 7A and 7.1 were performed using a 1998 DDC Series 60 HDDE equipped with a CRT-DPF without Bypass. The engine was operated using ultra-low sulfur diesel (ULSD) fuel with 4 ppm sulfur content. The PM measurement was determined by pre- and post-weighing Teflo filters, and by using real time instruments such as the DMM-230 and the EEPS. Subtasks 7.2 and 7B used the same engine and fuel as in Subtasks 7A and 7.1, but with and without Bypass.

3.0 EXPERIMENTAL SETUP AND PROCEDURES

This section covers the experimental setup applicable to Phase 3 of Project E-66.

3.1 Engine and Exhaust Configuration

The engine used in this program, shown in Figure 1 and described in Table 1, was a 1998 DDC Series 60, turbo-charged, HDDE. The engine was provided by SwRI and has more than 1,500 hours of operation on various projects prior to Project E-66. The engine exhaust was equipped with a CRT-DPF without Bypass for Subtasks 7A and 7.1. For Subtasks 7.2 and 7B, the engine was used with and without Bypass. The purpose of the Bypass was to elevate the PM emission level to 0.008 g/hp-hr, 80 percent of the 2007 PM emission standard. The Bypass, shown in Figure 2, consisted of a 2 inch pipe with a 3 inch uncatalyzed honeycomb ceramic substrate with 600 cells per square inch. The Bypass stream was introduced downstream from the outlet of the CRT-DPF, counter to the exhaust stream flow exiting the CRT-DPF to enhance mixing between the two streams prior to any measurement taken by any PFSS. It should be noted that the engine and aftertreatment system were meant to simulate PM emissions that could be encountered from post 2007 HDDEs; however, 2007 HDDE emissions levels are not only governed by PM limits. NOx is also a challenge and the very low emission levels for PM using the CRT-DPF without Bypass may not be an appropriate representation of what PM emission levels will actually result when the engine and aftertreatment system is tuned for both PM and NOx. The PM emission levels obtained using the CRT-DPF with Bypass help us understand the effect of sampling system parameters on PM over a range of PM emission levels likely to occur with the required NOx emission limit, especially without a NOx aftertreatment system.

FIGURE 1. ENGINE AND EXHAUST CONFIGURATION WITHOUT A BYPASS

TABLE 1. ENGINE IDENTIFICATION INFORMATION

Item	Description	Value
1	Engine Serial Number	06R0422316
2	Engine Model	6067TK60
3	Engine Family	Series 60
4	Model Year Designation	1998
5	Type of Electronic Control Module (ECM)	DDEC-III
6	EPA Certification Number	874
7	Power Rating	400 hp at 1,810 rpm
8	Torque Rating	1,550 lb-ft at 1200 rpm
9	Injection System	Electronically Controlled Unit Injectors
10	Induction System	Turbocharged-Waste Gated-Aftercooled

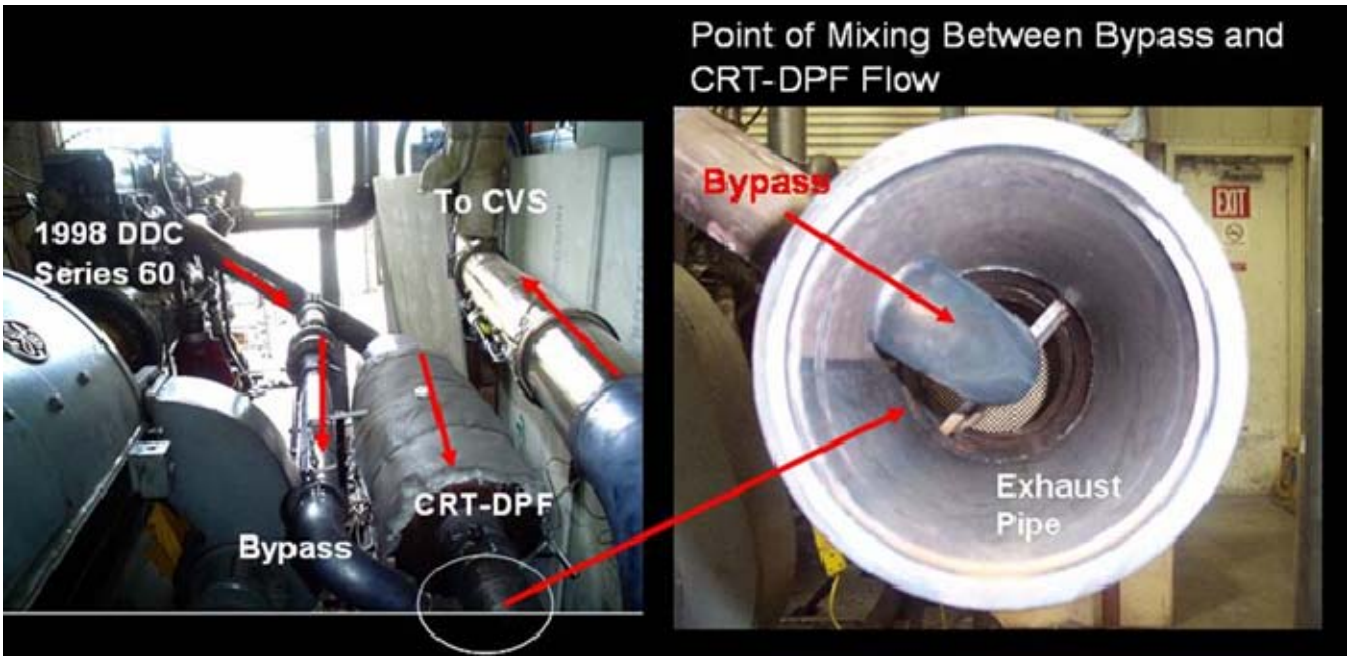


FIGURE 2. ENGINE EXHAUST CONFIGURATION WITH BYPASS

3.2 Fuel

Phase 3 ultra low sulfur diesel (ULSD) fuel was supplied by Chevron Phillips. It was a new batch of fuel that was different from the fuel used in Phases 1 and 2 of Project E-66. The earlier batch of fuel was no longer available, and the CRC committee overseeing the fuel procurement provided the new batch. Phase 3 ULSD fuel had lower sulfur and total aromatics with a higher API gravity compared to Phases 1 and 2 ULSD fuel, as shown in Table 2.

TABLE 2. ULTRA LOW SULFUR DIESEL FUEL PROPERTIES

Property	ASTM	Phase 2	Phase 3	Ratio[1]
API Gravity (60°F)	D287	34.5	40.0	0.86
Distillation IBP, °F	D86	382.0	370.4	1.03
10% recovery, °F	D86	441.0	429.0	1.03
50% recovery, °F	D86	511.0	518.1	0.99
90% recovery, °F	D86	608.0	594.7	1.02
FBP, °F	D86	654.0	634.4	1.03
Sulfur, ppm	D5453	6.9	3.8	1.82
Aromatics	D5186			
1 Ring Aromatics, wt%		23.8	13.1	1.82
2 Ring Aromatics, wt%		9.8	1.3	11
3+ Ring Aromatics, wt%		2.2		
Total Aromatics		35.8	14.4	2.49

[1] Ratio of Phase 2 over Phase 3 fuel properties

3.3 Fuel Handling System

The fuel handling system is shown in Figure 3. The mass flow of fuel provided to the engine was measured by a Micro Motion Model D flow meter. The meter was positioned upstream of the day tank. The mass flow meter signal rise time was adequately fast and similar to the intake air flow sensor (0 to 90 percent in 50 ms). However, because of its position upstream of the day tank, there is usually a lag time between actual engine fuel flow and measured fuel flow on the order of a few seconds. Thus, the real time fuel flow measurement information was not added to the intake air flow to provide total exhaust flow in real time, as a feedback to the PFSS. However, integrated fuel flow was added to integrated air flow in order to determine total exhaust flow for the purpose of calculating brake-specific PM emissions.

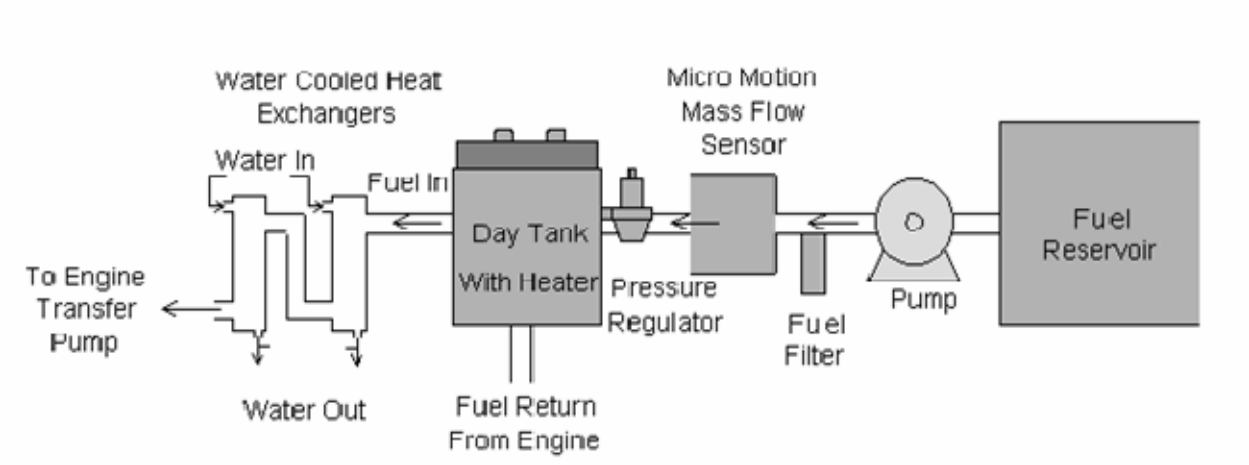


FIGURE 3. FUEL HANDLING SYSTEM

3.4 Intake Air Measurement

A Sensyflow P, Model DN 150, thermal air-mass flow meter with an operating flow range from 0-2400 kg/hr was mounted on the intake air system of the engine, as shown in Figure 4. The meter was set to issue an average output voltage signal every 51 milliseconds, based on 17 data points sampled at a rate of one data point per 3 milliseconds. A National Institute of Standardization and Testing (NIST) traceable calibration sheet was provided with the flow meter.

FIGURE 4. INTAKE AIR FLOW MEASUREMENT SYSTEM MOUNTED ON ENGINE INTAKE

3.5 General Overview of Dilution Systems Configurations

Dilution systems that meet the EPA 2007 sampling protocol were used throughout Phase 3. All dilution systems were equipped with an inertial separator in the sampling stream prior to the PM collection filter, and also controlled the sampling train temperature to maintain a filter face temperature of 47 ± 5^{o}C. All dilution systems were equipped with 47 mm filter holders, except for the Sensors MPS, where the filter holder accommodated only a 25 mm filter.

Seven dilution systems were tested during Phase 3. These were the SwRI long (SwL) and short (SwS) secondary dilution tunnels that were only connected to the CVS; five partial flow systems were used as either secondary tunnels connected to the CVS or as partial flow tunnels connected directly to the exhaust pipe. Three of these five are commercially available systems; these are AVL SPC, Sierra BG3, and Horiba MDLT. Two prototype PFSS were the Cummins AEI/CUM and Sensors MPS. The SPC, BG3, MDLT, and AEI/CUM were used in Tasks 7.1, 7.2, and 7B. The MPS was only used in Tasks 7.2 and 7B.

Figure 5 shows the experimental setup for task 7.1, which consisted of all dilution systems coupled to the full flow CVS. The sampling probe for each system was installed in the sample zone of the 24 inch tunnel within a diameter of about 8 inches from the center line.

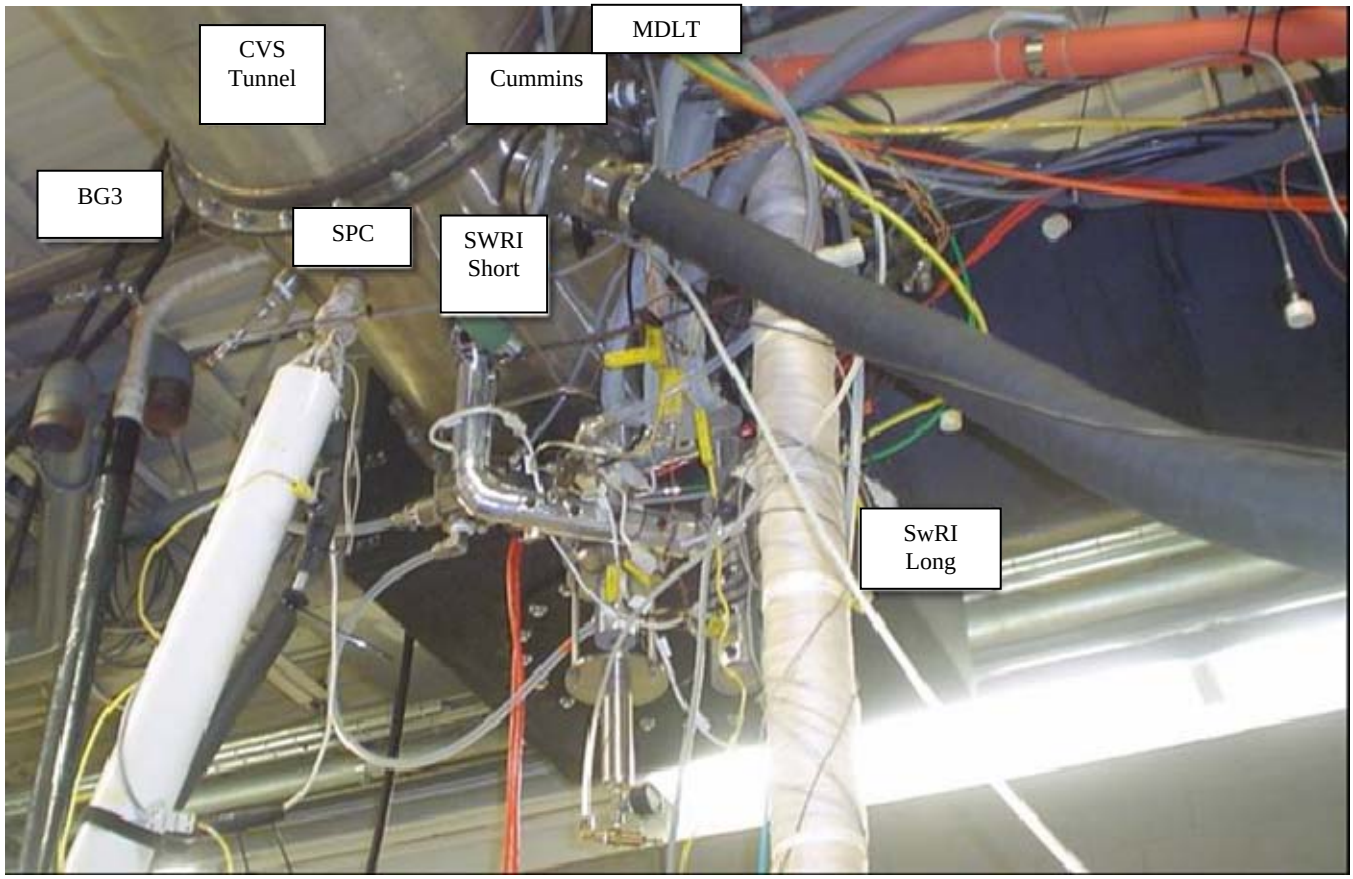


FIGURE 5. SECONDARY DILUTION SYSTEMS MOUNTED ON FULL FLOW CVS TUNNEL

Figures 6 and 7 show the experimental setup of the PFSS units mounted along a 5 inch diameter engine exhaust pipe. The first PFSS was the MPS, which was mounted on the raw exhaust pipe at about 12 exhaust pipe diameters from the mixing point between the CRT-DPF outlet and the Bypass. The MPS sampling probe was followed by the BG3, MDLT, AEI/CUM, and SPC sampling probes, respectively, as described in Table 3. All sampling probes were mounted at the exhaust pipe centerline facing the flow. The linear pipeline distance between any two sampling probes was about 14 inches. The distance between the exit of the CRT-DPF and the inlet probe of the last PFSS (SPC) was about 24 exhaust pipe diameters.

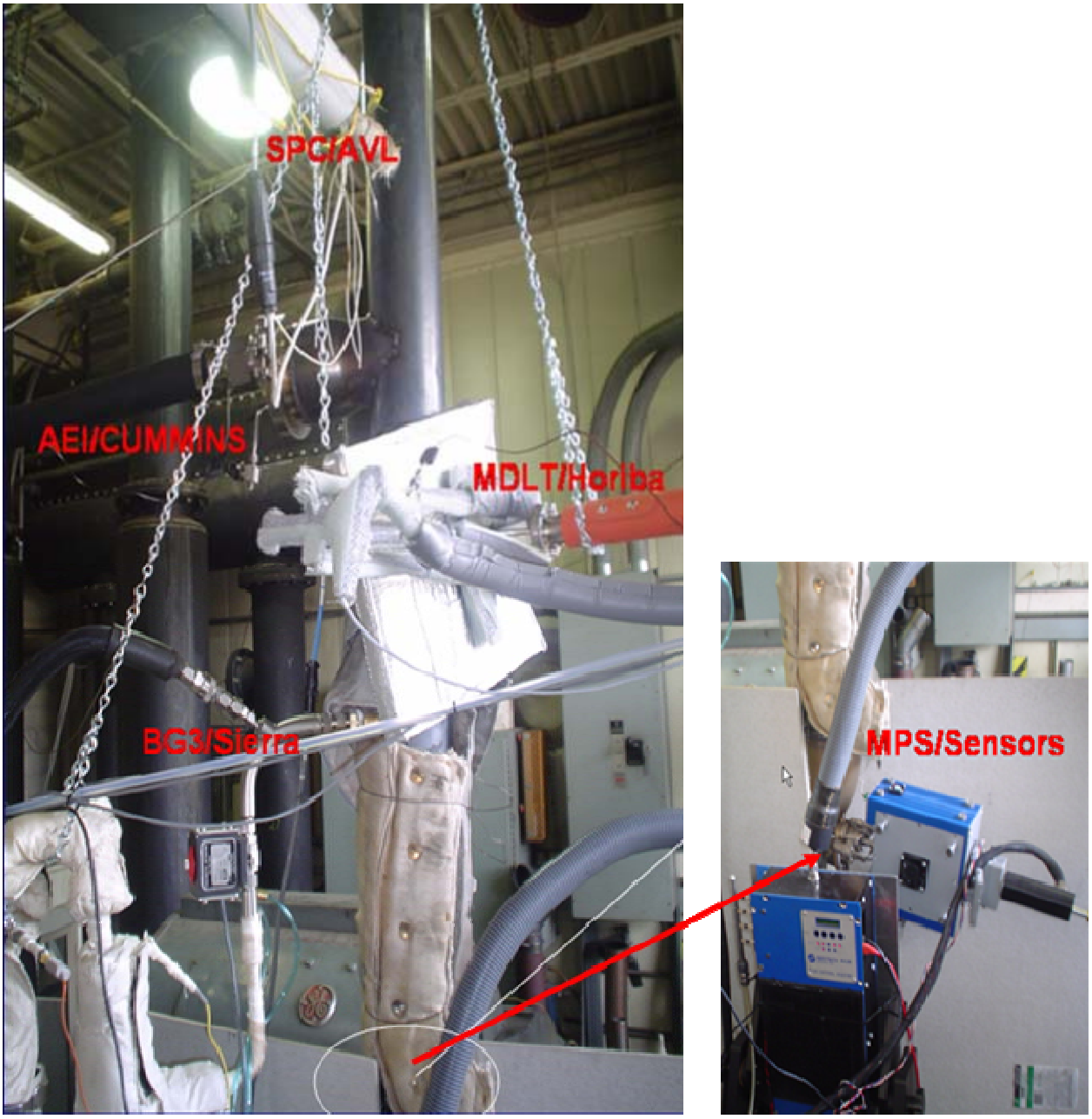


FIGURE 6. PARTIAL FLOW SAMPLING SYSTEMS MOUNTED ON ENGINE EXHAUST PIPE

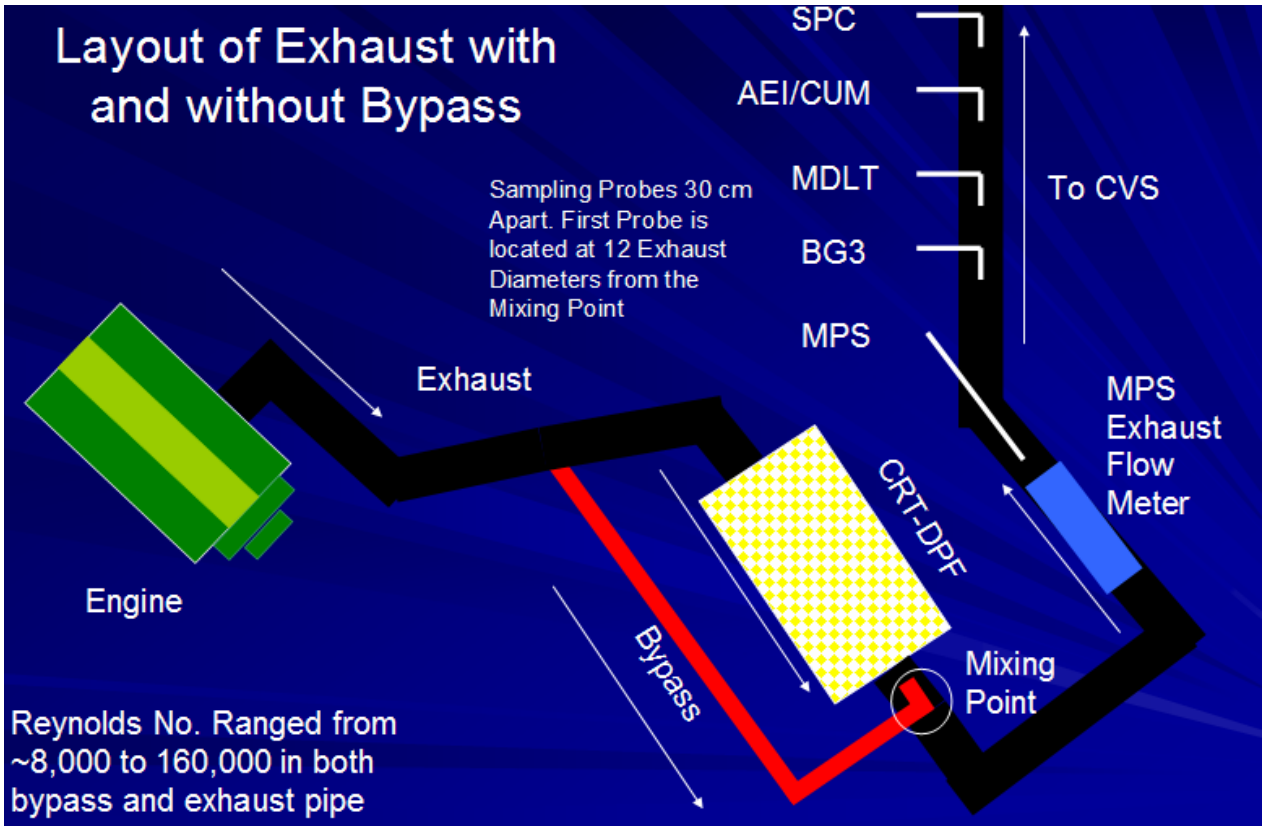


FIGURE 7. ENGINE, EXHAUST FLOW METER, AND PARTIAL FLOW SAMPLING SYSTEMS LAYOUT

TABLE 3. ORDER AND LOCATION OF PFSS UNITS ALONG THE EXHAUST PIPE

PFSS	Location Order Along the Exhaust Pipe Relative to Outlet of CRT-DPF	Exhaust Sampling Probe Location Away from CRT-DPF and Bypass Mixing Point
MPS	1st	12 x D[1]
BG3	2nd	15 x D[1]
MDLT	3rd	18 x D[1]
AEI/CUM	4th	21 x D[1]
SPC	5th	24 x D[1]
[1]D = 5 inches		

3.6 Operational Characteristics of Dilution Systems Used on Full Flow CVS

Table 4 shows the main characteristics of each of dilution systems used under Task 7.1. All dilution systems used similar filter face velocities and dilution ratios. The residence time ranged from 0.4 to 1.5 seconds, except for the SwL where the residence time was about 15 seconds. The dilution air temperature was between 18°C and 30°C, except for the AEI/CUM, where the dilution air temperature was targeted at 47°C.

TABLE 4. OPERATIONAL CHARACTERISTICS OF DILUTION SYSTEMS USED ON FULL FLOW CVS

Dilution System	Residence Time, seconds	Dilution Air Temperature, °C	Filter Face Temperature, °C Min to Max	Filter Face Velocity, cm/sec	Dilution Ratio	Dilution Exhaust Interface Strategy
Rated Power Condition						
BG3	~ 1.5	24 to 26	38 to 42	88 to 90	2	[1]Porous Wall
AEI/CUM	~1	47	47	90 to 91	2	[2]Annular Mixing
MDLT	~1	28 to 30	44 to 51	90 to 91	2	[1]Multiple Mixing Tees
SPC	~1	18 to 20	47 to 49	88 to 89	2	[1]Mixing Tee
SwL	~15	25 to 27	42 to 48	90 to 91	2	[1]Mixing Orifice
SwS	~0.4	25 to 27	45 to 51	90 to 91	2	[3]Mixing Tee
Hot-Start FTP Transient Cycle						
BG3	~ 1.5	24 to 26	44 to 49	88 to 90	1.5	[1]Porous Wall
AEI/CUM	~1	47	47	90 to 91	1.5	[2]Annular Mixing
MDLT	~1	28 to 30	47 to 50	90 to 91	1.5	[1]Multiple Mixing Tees
SPC	~1	25 to 26	47 to 49	88 to 89	1.5	[1]Mixing Tee
SwL	~15	25 to 27	43 to 47	90 to 91	1.5	[3]Mixing Orifice

[1] Secondary dilution air was introduced to sample probe right at the exit from full flow CVS tunnel
[2] Secondary dilution air was introduced into the sampling probe inside the CVS tunnel
[3] Secondary dilution air was introduced to sampling probe at the inlet of the cyclone at a distance of 30 cm from the exit of the CVS.

3.7 Operational Characteristics of Partial Flow Sampling Systems Used on Engine Exhaust

Table 5 shows some of the operational characteristics of the PFSS units used on engine exhaust. Under transient engine operation, all commercially available PFSSs extract a sample flow from the exhaust that is proportional to exhaust flow rate by varying the dilution ratio. The AEI/CUM PFSS achieves proportionality to engine exhaust flow rate by varying the filter face velocity while maintaining the dilution ratio at a constant level.

TABLE 5. OPERATIONAL CHARACTERISTICS OF PARTIAL FLOW SAMPLING SYSTEMS USED ON ENGINE EXHAUST

Dilution System	Residence Time, seconds	Dilution Air Temperature, °C	Filter Face Temperature, °C Min-Max	Filter Face Velocity, cm/sec	Dilution Ratio[1]	Flow Determination of Sample Extracted from Engine Exhaust
BG3	~ 1.5	22 to 30	45 to 49	88 to 90	8 to 68	Difference Between Filter and Dilution Air Flow
AEI/CUM	~1	46 to 48	46 to 48	12 to 100	8	Difference Between Total Flow and Dilution Air Flow
MDLT	~1	28 to 30	45 to 49	90 to 91	8 to 68	Difference Between Filter and Dilution Air Flow
SPC	~1	18 to 20	45 to 49	88 to 89	8 to 68	Difference Between Filter and Dilution Air Flow
MPS[3]	~1.5	28 to 32	48 to 52	96 to 100	11 to 95	Measured Directly Using Capillary Laminar Flow Element
SwL[2]	~15	25 to 27	45 to 49	90 to 91	7 to 56	N/A
SwS[2]	~0.4	25 to 27	45 to 49	90 to 91	7 to 56	N/A

[1] Dilution ratio range under transient operation

[2] Systems are only used as secondary tunnels on CVS. Dilution ratio reflects the total dilution ratio including the CVS dilution ratio. The secondary dilution ratio was about 2.5.

[3] The MPS was the only system that used a 25 mm instead of a 47 mm Teflo filter. This resulted in about 3.5 times lower volume flow rate than the rest of the systems, and also in lower filter weight gain.

All PFSS units determined the sample flow extracted from the engine exhaust indirectly by taking the difference between the total flow and the dilution air flow, except the MPS where the sample flow was measured directly using a capillary tube.

The BG3, MDLT, and the SPC used a feedback signal from the intake air measurement system in order to vary the sample flow in proportion to the exhaust flow. The MPS, however, used a feedback signal from a 5 inch Sensors pitot tube exhaust flow meter mounted upstream of the MPS, shown in Figure 7. The AEI/CUM used the intake air flow feedback signal to proportionally vary the filter face velocity.

3.8 Particle Instruments

During Phase 3 of the E-66 program, three different particle instruments were used, including the TSI Engine Exhaust Particle Sizer (EEPS), the Dekati Mass Monitor (DMM-230), and the Horiba MEXA 1370-PM. The EEPS and DMM-230 instruments were used in Phases 1 and 2 of Project E-66 and correlated well with the PM measurement using Teflo filters when engine exhaust was equipped with CRT-DPF and a Bypass. It is expected that these instruments will give the right trend in particle mass changes. The MEXA 1370-PM was only used in Task 7B to analyze the PM collected during experiments for organic carbon, elemental carbon, and sulfate.

Prior to Phase 3 work, both the EEPS and the DMM-230 were sent to the manufacturers to fix problems that occurred during Phase 2. For the EEPS, it was difficult to zero the instrument before each engine run to minimize zero drift. The EEPS problem was corrected by TSI by changing the electrode plates and the electrometers. After the instrument was fixed by TSI, we were able to zero the instrument before and after each experiment without experiencing any problems. For the DMM-230, the sub-30 nm current was reading negative, excluding any contribution of this size range to PM mass, although the contribution is generally very small. The instrument was thoroughly cleaned by Dekati and operated properly without any problems.

3.8.1 Engine Exhaust Particle Sizer (EEPS)

The EEPS [5], shown in Figure 8, is a particle sizing instrument that measures the number-weighted size distribution of particles every 200 ms. The EEPS covers a size range from 5.6 nm to 560 nm with a resolution of 16 channels per decade. The EEPS is a mobility-based particle sizing instrument similar to the SMPS. An aerosol stream enters the instrument through a 1 µm cut cyclone at a nominal flow rate of 10 lpm and a pressure of 1 bar. The aerosol is then subjected to two unipolar diffusion chargers. First, the aerosol is exposed to a negative charger to reduce the number of highly positively charged particles and to prevent overcharging in the second charger. Second, the aerosol is exposed to a positive charger that puts a predictable net positive charge on the particles. The positively charged aerosol enters the mobility section that consists of 22 electrometers and a central rod that is divided into three insulated sections each maintained at a different voltage level. The upper section is set at 85 volts, the middle section is set at 470 volts, and the lower section is set at 1200 volts. Small particles are deposited first on the upper electrometers and large particles are deposited on the bottom electrometers.

While the EEPS is primarily designed to measure particle number-weighted size distribution, particle mass is calculated by assuming that the particles are spherical with a density of 1 g/cm³. This assumption gave a particle mass that correlated very well (R^2> 0.95) with the filter-based PM measurement method using Teflo filters [4]. However, there are several issues, listed below, that need more research to apply the EEPS for particle mass measurement.

1. Electrometer to electrometer interference and back correction
2. Current noise in the upper stages and their effect on particle mass measurement
3. Zero drift
4. Ability to provide good prediction of large particle (Dp > 100 nm) charging efficiency
5. True particle density
6. NIST traceable accuracy
7. Ability to zero and span

Thus, it is expected that the EEPS will yield qualitative trends in particle mass emission from diesel engines.

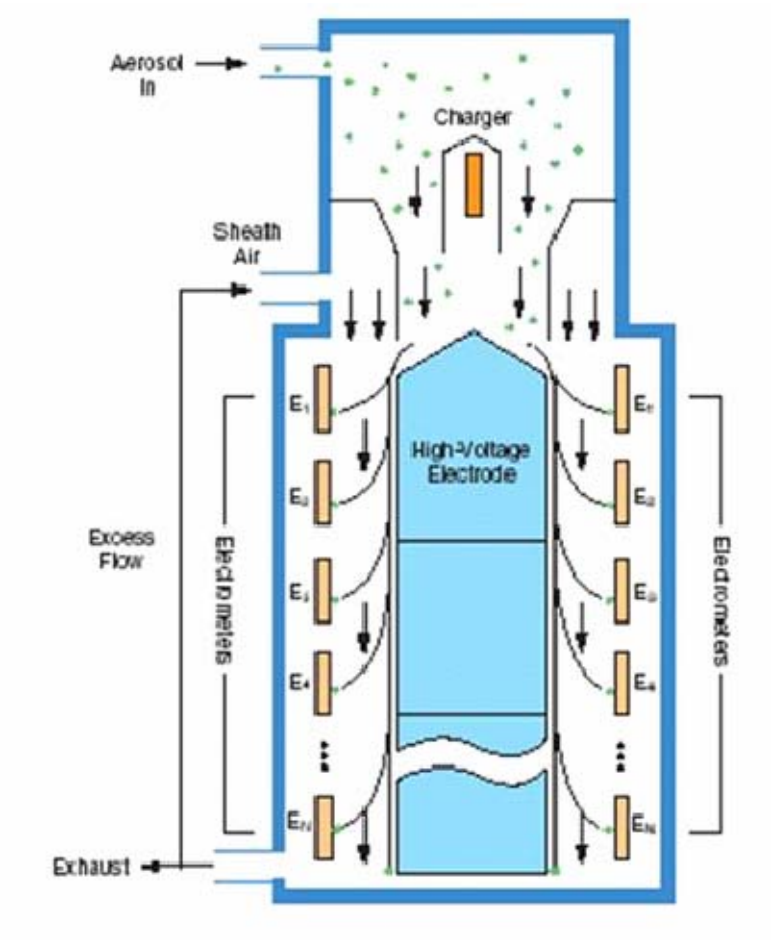


FIGURE 8. ENGINE EXHAUST PARTICLE SIZER (EEPS)

3.8.2 Dekati Mass Monitor (DMM-230)

The DMM-230 [6], shown in Figure 9, measures the mass concentration of particles on a second-by-second basis. The DMM-230 is based on the electrical low pressure impactor (ELPI) technology produced by Dekati. The DMM-230 basically measures the number-weighted aerodynamic particle size distribution using a combination of particle charging, series of impaction rods, and a series of electrometers that are connected to the impaction rods to provide information on number concentration from the current read by the electrometers.

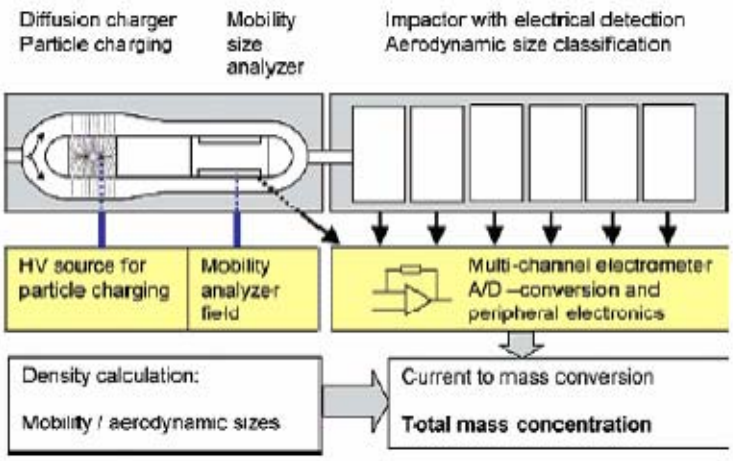


FIGURE 9. SCHEMATIC OF DMM-230 MASS MONITOR

In order to determine the mass-weighted distribution from the number-weighted distribution, the DMM-230 determines the average density of particles by matching the mean aerodynamic diameter with the mean mobility diameter. The DMM-230 determines the mean aerodynamic diameter from the measured aerodynamic size distribution, and it measures the mobility mean diameter from the current measured in the mobility section for sub-30 nm particles (I_{mob}) and the total current (I_{tot}), assuming a lognormal distribution, using the following equation [6]:

$$d_p = 59\left(\frac{0.938}{\frac{I_{mob}}{I_{tot}} - 0.124} - 1\right)^{(1/2.13)}$$

where dp is the mean mobility diameter, I_{mob} is the current measured by the mobility electrometer, and I_{tot} is the total current measured by the mobility electrometer and the impactor electrometers (I_{mob} + $I_{impactor}$). If the distribution is bimodal, the DMM-230 assumes an average density of 1 g/cm³. The aerosol flow rate through the DMM-230 is 10.5 lpm.

It was demonstrated in Phase 1 of Project E-66 [4] that the DMM-230 correlated very well ($R^2 > 0.95$) with the filter-based measurement method using Teflo filters at a PM emissions level near the 2007 PM standard.. However, there are still several issues, listed below, similar to those mentioned with the EEPS that need to be examined.

1. Validity of assuming a monomodal distribution downstream of a CRT-DPF
2. Validity of using a density of 1 g/cm³ if the distribution is bimodal
3. Accuracy in predicting charging efficiency
4. Zero drift
5. Diffusion of small particles to upper stages
6. NIST traceable accuracy
7. Ability to zero and span

Thus, it is expected that the DMM-230 will yield qualitative trends in particle mass emissions from diesel engines.

3.8.3 Horiba MEXA 1370-PM

The Horiba MEXA 1370-PM [7], shown in Figure 10, provides information on PM organic carbon, elemental carbon, and sulfate. It was used for a limited time in Task 7B. This instrument is different from the Sunset Laboratory semi-continuous OC/EC because it requires a different handling of the quartz filters used. In order to establish a clean filter baseline, the quartz filters are first baked in a muffle furnace at a high temperature of 1000°C prior to PM collection. PM collection on a quartz filter takes place in the engine laboratory for a specified test. After PM collection, the filter is brought back for analysis by the MEXA 1370-PM.

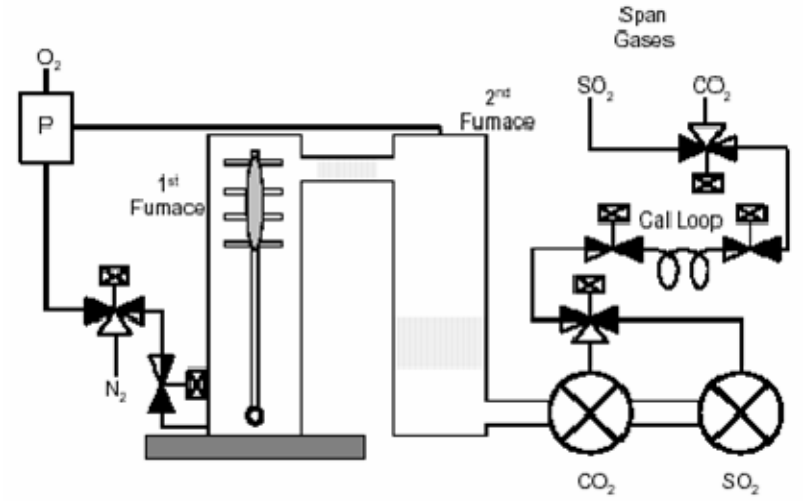


FIGURE 10. MEXA 1370-PM FLOW SCHEMATIC

Filter analysis is performed by first passing a nitrogen stream over the quartz filter, placed inside the first furnace that is maintained at a temperature of 980°C, as shown in Figure 10. The OC portion of PM quickly desorbs and oxidizes with oxygen that is introduced upstream of a second furnace to produce CO_2. The sulfate portion of PM decomposed at high temperature and reduced to SO_2. The CO_2 and SO_2 concentrations are detected via a CO_2 detector and a SO_2 detector, respectively. The elemental carbon portion of PM is analyzed by passing an oxygen stream over the filter to oxidize the elemental carbon into CO_2 that is detected by the CO_2 sensor. One concern about this instrument is the possibility of converting OC to EC through pyrolysis during filter analysis. The instrument does not provide any correction to this

process, and there is also no mechanism to detect it if it takes place. Thus, the OC/EC fraction obtained with this instrument is considered qualitative rather than quantitative in nature.

3.9 Procedures

Pall Teflo 47 mm filters, 2 µm pore size, were used for PM collection in all experiments, except for Task 7B, where quartz filters were used. Pall Teflo 25 mm filters, 3 µm pore size, were used with the MPS. Two steady-state tests that included engine rated speed, 100 and 10 percent load, shown in Figure 11, and the FTP transient cycle, shown in Figure 12, and the nonroad transient cycle (NRTC), shown in Figure 13, were used throughout this work.

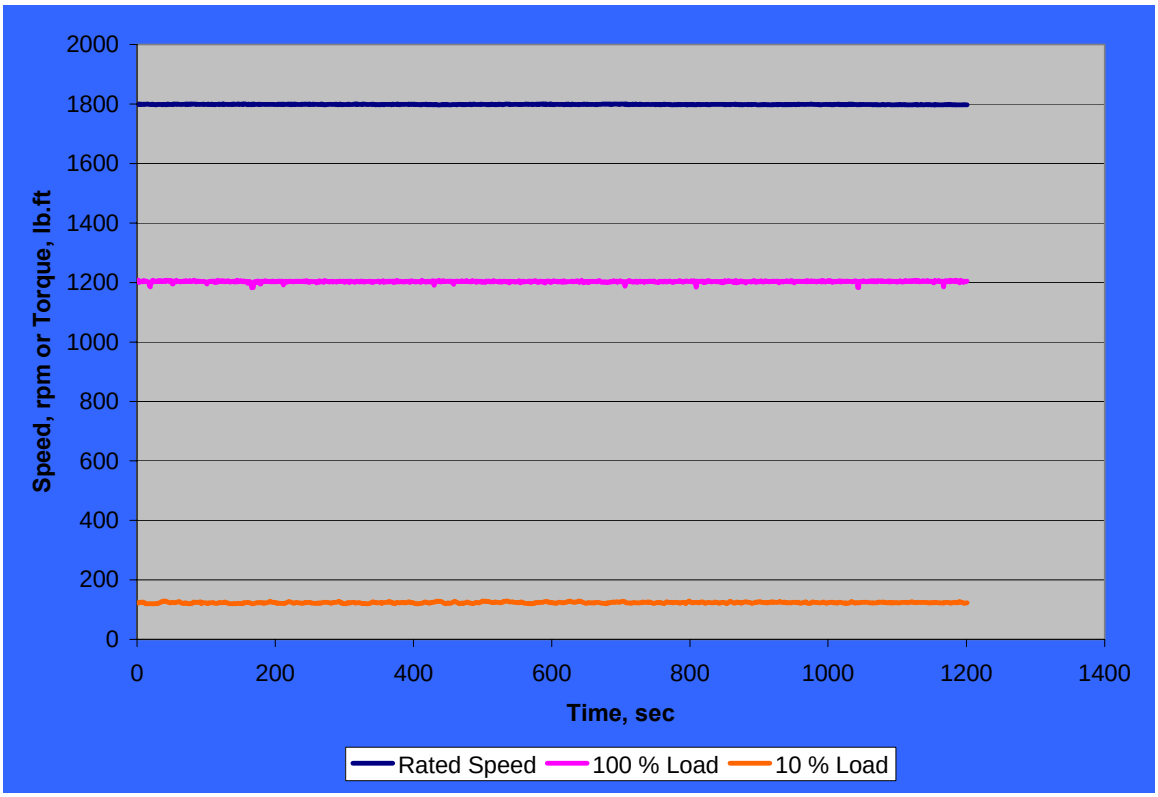


FIGURE 11. ACTUAL SIGNALS OF SPEED AND TORQUE FORTHE STEADY-STATE ENGINE OPERATION

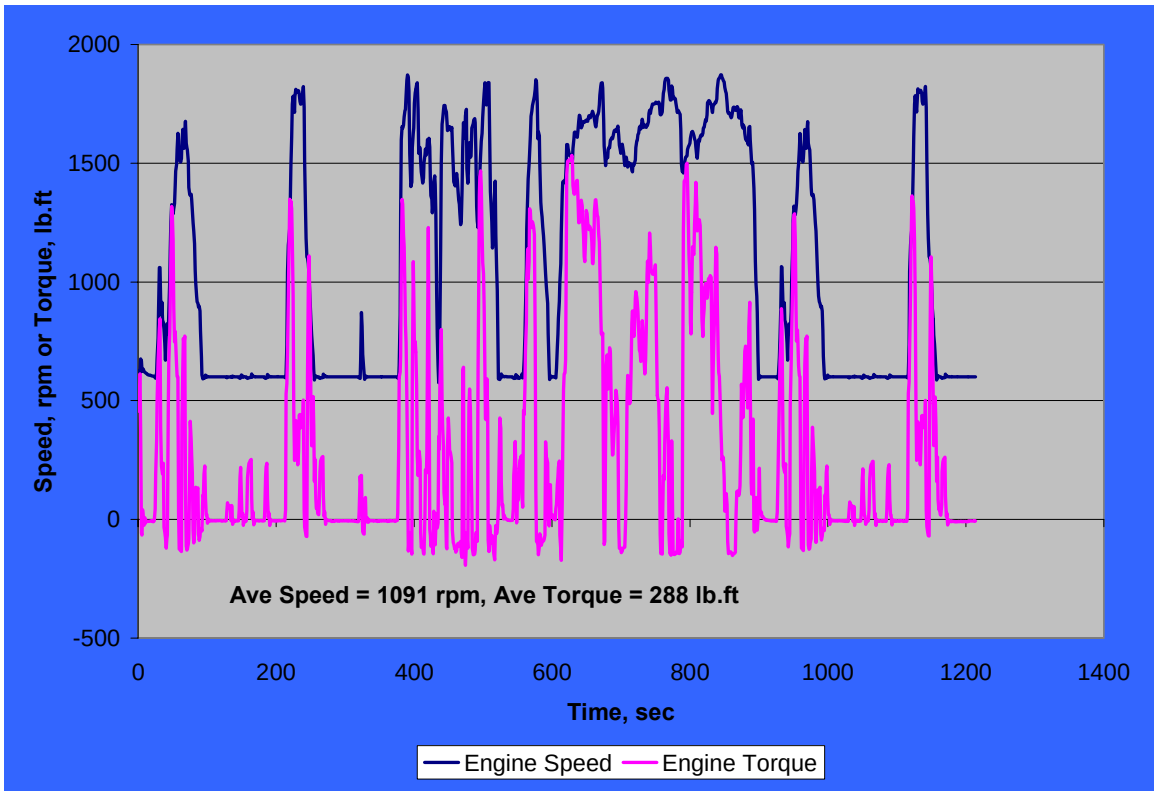


FIGURE 12. ACTUAL SIGNAL OF SPEED AND TORQUE FOR THE FTP TRANSIENT CYCLE

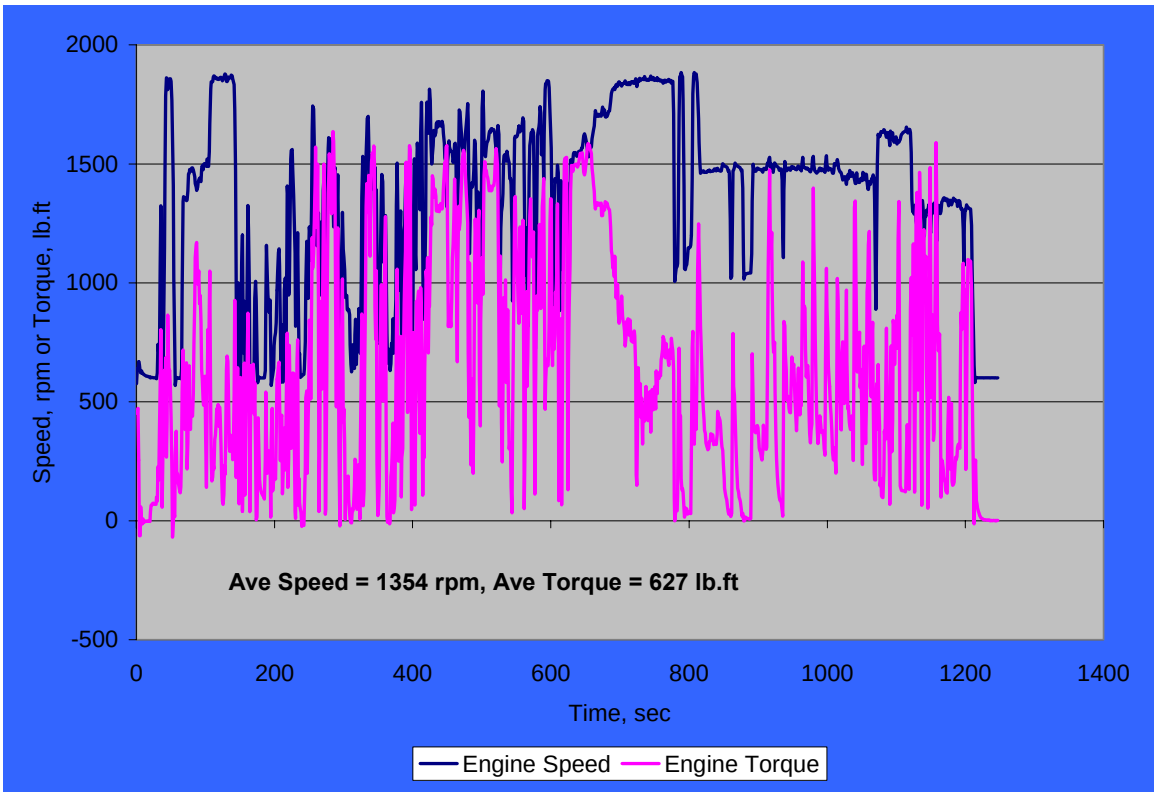


FIGURE 13. ACTUAL SIGNAL OF SPEED AND TORQUE FOR THE NONROAD TRANSIENT CYCLE

Task 7A was the first task performed under Phase 3. The purpose of Task 7A was to investigate the influence of secondary dilution residence time on PM measurement using Teflo filters. Task 7A was mainly performed to extend the work performed in Phase 2 that was done with real time particle instruments, and to add to it gravimetric measurements using Teflo filters. The engine was operated at rated speed, 100 percent load using CRT-DPF without Bypass. This engine condition was chosen because after the CRT-DPF, the PM is mainly composed of organic hydrocarbon and sulfuric acid, as was determined in Phase 2 of Project E-66. A range of secondary residence times between 0.75 second and 15 seconds were used during the experiments, as shown in Table 6. The sampling time was for 30 minutes with five repeats at each residence time. The secondary dilution ratio was maintained at 2, and the filter face temperature was maintained at 47^{o}C +/- 5^{o}C throughout all experiments.

TABLE 6. TEST MATRIX FOR RESIDENCE TIME EXPERIMENTS AT RATED SPEED, 100 PERCENT LOAD

Residence Time, sec	Filter Face Velocity, cm/sec	Sampling Time, min	No. of Repeats
15	80	30	5
11	80	30	5
8	110	30	5
0.97	80	30	5
0.75	110	30	5

For Task 7.1, six different dilution systems were coupled to the full flow CVS and used in parallel to compare the PM measurement determined by each system under steady-state and transient engine operation, as shown in Table 7. At each engine condition, seven repeats were performed. The duration of each repeat was 30 minutes at rated speed, 100 percent load, and 20 minutes for the hot-start FTP transient cycle.

For Task 7.2, eight repeats were performed at rated speed, 10 and 100 percent load, hot-start FTP transient cycle, and the non-road transient cycle (NRTC), as shown in Table 8. First, the work was performed with an exhaust configuration using CRT-DPF without Bypass followed by CRT-DPF with Bypass. A tunnel blank measurement was performed before and after a series of seven repeats at each engine operating condition. Prior to a series of three steady-state or transient engine operations, the engine and dilution systems were conditioned for 20 minutes at rated speed, 100 percent load. A 20-minute engine-off soak period was maintained between transient runs.

TABLE 7. TEST MATRIX FOR COMPARING THE PERFORMANCE OF DIFFERENT DILUTION SYSTEMS COUPLED TO THE FULL FLOW CVS

Test Number	Sw-S	Sw-L	SPC	BG3[1]	Cummins	MDLT	Comments
Rated Power Condition (30 minutes test)							
1	A-Sw-S1	A-Sw-L1	A-SPC-1	A-BG3-1	A-Cum-1	A-MDLT-1	Tunnel Blank
2	A-Sw-S2	A-Sw-L2	A-SPC-2	A-BG3-2	A-Cum-2	A-MDLT-2	
3	A-Sw-S3	A-Sw-L3	A-SPC-3	A-BG3-3	A-Cum-3	A-MDLT-3	
4	A-Sw-S4	A-Sw-L4	A-SPC-4	A-BG3-4	A-Cum-4	A-MDLT-4	
5	A-Sw-S5	A-Sw-L5	A-SPC-5	A-BG3-5	A-Cum-5	A-MDLT-5	
6	A-Sw-S6	A-Sw-L6	A-SPC-6	A-BG3-6	A-Cum-6	A-MDLT-6	
7	A-Sw-S7	A-Sw-L7	A-SPC-7	A-BG3-7	A-Cum-7	A-MDLT-7	
8	A-Sw-S8	A-Sw-L8	A-SPC-8	A-BG3-8	A-Cum-8	A-MDLT-8	
9	A-Sw-S9	A-Sw-L9	A-SPC-9	A-BG3-9	A-Cum-9	A-MDLT-9	
10	A-Sw-S10	A-Sw-L10	A-SPC-10	A-BG3-10	A-Cum-10	A-MDLT-10	Tunnel Blank
Hot-Start FTP Transient Cycle (20 minutes test)							
1	FTP-Sw-S1	FTP-Sw-L1	FTP-SPC-1	FTP-BG3-1	FTP-Cum-1	FTP-MDLT-1	Tunnel Blank
2	FTP-Sw-S2	FTP-Sw-L2	FTP-SPC-2	FTP-BG3-2	FTP-Cum-2	FTP-MDLT-2	
3	FTP-Sw-S3	FTP-Sw-L3	FTP-SPC-3	FTP-BG3-3	FTP-Cum-3	FTP-MDLT-3	
4	FTP-Sw-S4	FTP-Sw-L4	FTP-SPC-4	FTP-BG3-4	FTP-Cum-4	FTP-MDLT-4	
5	FTP-Sw-S5	FTP-Sw-L5	FTP-SPC-5	FTP-BG3-5	FTP-Cum-5	FTP-MDLT-5	
6	FTP-Sw-S6	FTP-Sw-L6	FTP-SPC-6	FTP-BG3-6	FTP-Cum-6	FTP-MDLT-6	
7	FTP-Sw-S7	FTP-Sw-L7	FTP-SPC-7	FTP-BG3-7	FTP-Cum-7	FTP-MDLT-7	
8	FTP-Sw-S8	FTP-Sw-L8	FTP-SPC-8	FTP-BG3-8	FTP-Cum-8	FTP-MDLT-8	
9	FTP-Sw-S9	FTP-Sw-L9	FTP-SPC-9	FTP-BG3-9	FTP-Cum-9	FTP-MDLT-9	
10	FTP-Sw-S10	FTP-Sw-L10	FTP-SPC-10	FTP-BG3-10	FTP-Cum-10	FTP-MDLT-10	Tunnel Blank

[1] The BG3 sampling train incorporated a cyclone downstream instead of upstream of the filter holder. This was equivalent to operation without a cyclone.

TABLE 8. TEST MATRIX FOR COMPARING THE PERFORMANCE OF PARTIAL FLOW SAMPLING SYSTEMS COUPLED TO ENGINE EXHAUST

No. of Repeats	SwS	SwL	BG3	MDLT	SPC	AEI/CUMmins
Rated Speed, 100 % Load, 30 minutes w/o Bypass, 20 min with Bypass						
7	x	x	x	x	x	x
Rated Speed, 10 % Load, 30 minutes w/o Bypass, 20 min with Bypass						
7	x	x	x	x	x	x
Hot-Start FTP Transient Cycle, 20 minutes						
7	x	x	x	x	x	x
Hot-Start Non-Road Transient Cycle (NRTC), 20.5 minutes						
7	x	x	x	x	x	x

Originally, Task 7B was not a part of Phase 3, and was later added by SwRI to gain more insight of the PM composition collected by the different PFSS units. Task 7B was similar to Task 7.2 but with very limited number of experiments that were performed using quartz filters, as shown in Table 9.

TABLE 9. TEST MATRIX FOR COMPARING THE PERFORMANCE OF PARTIAL FLOW SAMPLING SYSTEMS COUPLED TO ENGINE EXHAUST AND USING QUARTZ FILTERS

No. of Repeats	SwS	SwL	BG3	MDLT	SPC	AEI/CUMmins
Rated Speed, 100 % Load, 20 minutes with Bypass						
3	x	x	x	x	x	x
Hot-Start FTP Transient Cycle, 20 minutes with Bypass						
3	x	x	x	x	x	x
Rated Speed, 100 % Load, 30 minutes without Bypass						
1	x	x	x	x	x	x

4.0 RESULTS

4.1 Effect of Secondary Dilution System Residence Time on Particulate Mass Measurement

Figure 14 shows the brake-specific PM emission as a function of different secondary dilution tunnel residence time using Teflo filters, DMM-230, and the EEPS. The engine was operated at rated speed, 100 percent load and the exhaust was treated with the CRT-DPF without Bypass. All measurement methods showed a PM increase as the residence time was increased. Using Teflo filters, the measured PM mass emission increased from about one percent of the 2007 standard with a residence time of 0.75 seconds to seven percent of the standard with a residence time of 15 seconds. The real time instruments showed a similar trend, but the absolute PM emission level was 33 to 90 percent lower than that reported using Teflo filters, depending on the residence time. The filter-based PM level seemed to have an offset at the shortest residence time, likely due to positive artifact or measurement error. The filter weight gain ranged from about 10 µg to about 50 µg during these experiments. For the purpose of these experiments with the EEPS, the total PM mass was calculated without including particles above 50 nm in diameter. Particles above 50 nm seemed to be insensitive to the residence time, as shown in Figure 15. They also seemed to be very noisy which could be due to inherent noise in certain electrometer channels. If particles above 50 nm were included in the PM reported in Figure 14, the measurement variability would have been much higher and the absolute emission level would have been about a factor of 6 to 15 higher than what was reported in Figure 14.

The EEPS size distribution, shown in Figure 15, for two different residence times showed that the mass mean diameter of nanoparticles (< 50 nm) is on the order of 20 nm at the long residence time. At the short residence, the mass distribution of nanoparticles completely disappeared. This phenomenon was observed in Phase 2 and in previous work [8, 9, 10]. It is mainly related to particle nucleation and growth of sulfuric acid and semi-volatile hydrocarbon species.

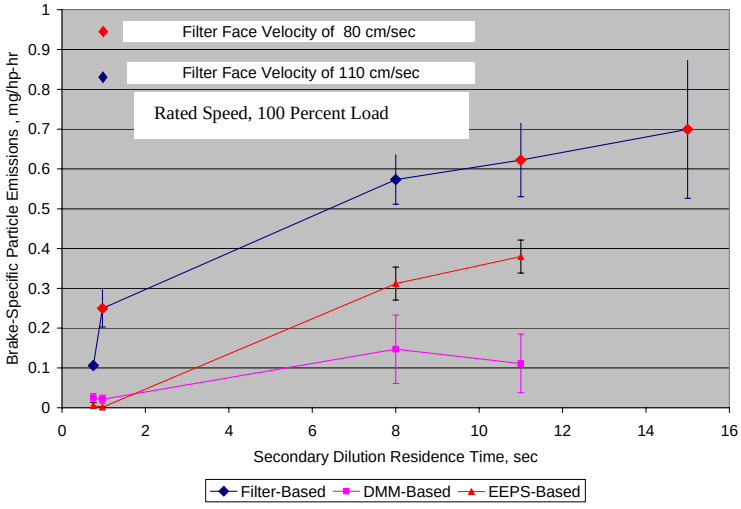


FIGURE 14. INFLUENCE OF SECONDARY DILUTION TUNNEL RESIDENCE TIME ON PARTICLE MASS EMISSIONS (AVERAGE AND STANDARD DEVIATION BASED ON FIVE REPEATS)

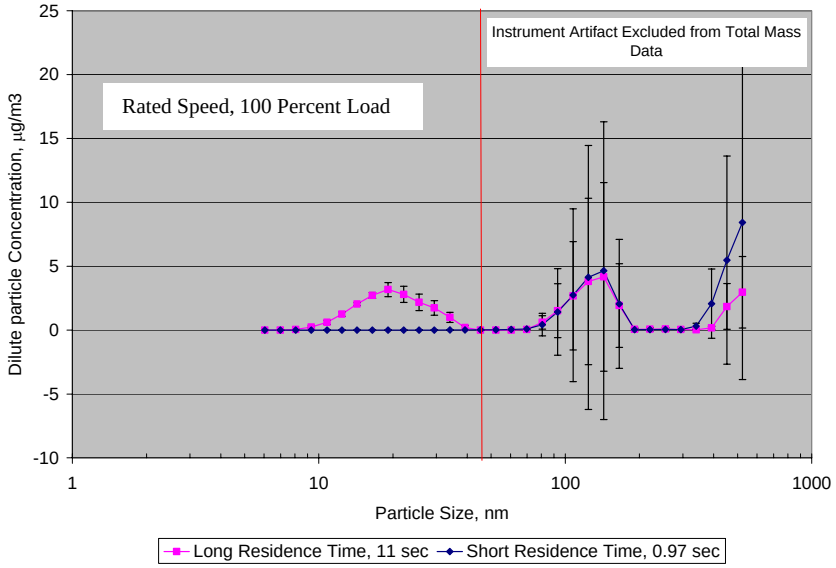


FIGURE 15. EFFECT OF RESIDENCE TIME ON PARTICLE MASS-WEIGHTED SIZE DISTRIBUTION USING EEPS (AVERAGE AND STANDARD DEVIATION BASED ON FIVE REPEATS)

The EEPS and the DMM-230 were used under similar operating conditions and residence times in both Phases 2 and 3. As shown in Figure 16, the PM emission level reported with these instruments in Phase 2 was about 6 times higher than reported in Phase 3 at a residence time of about 10 seconds. It is hypothesized that the main reason for the difference is fuel property changes. For example, the sulfur level in the fuel used in Phase 2 was 1.8 times higher than that in Phase 3, and the polynuclear aromatics were also 11 times higher. More work may be needed to investigate the effect of fuel properties on particle emissions under different residence times before a final conclusion can be reached. However, both Phase 2 and Phase 3 work indicated that there is an influence of residence time on the measurements of PM emissions, although the changes in PM emissions remained small but important compared to the 2007 PM standard.

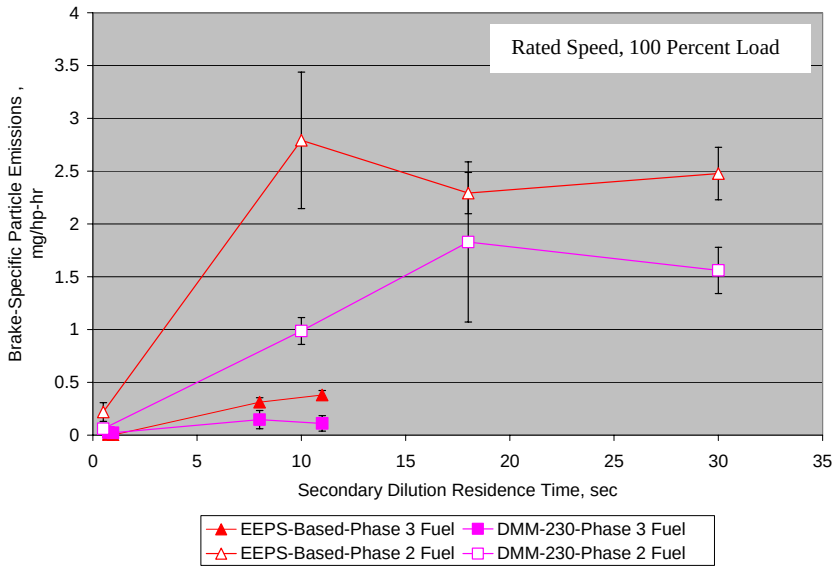
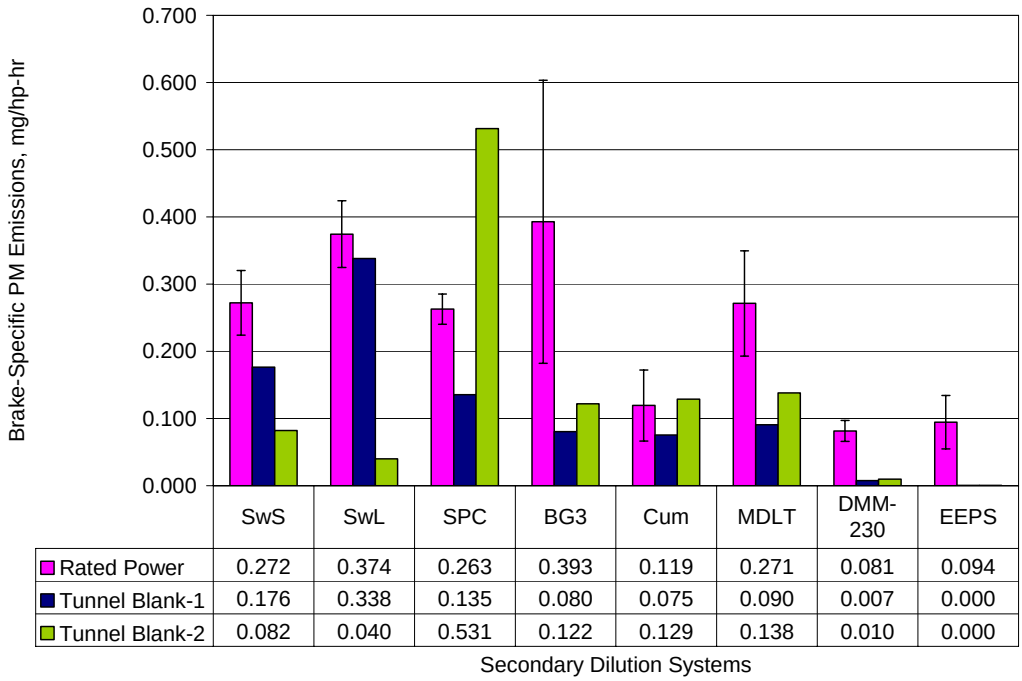


FIGURE 16. EFFECT OF SECONDARY RESIDENCE ON PM EMISSIONS USING TWO DIFFERENT FUEL PROPERTIES (AVERAGE AND STANDARD DEVIATION BASED ON FIVE REPEATS)

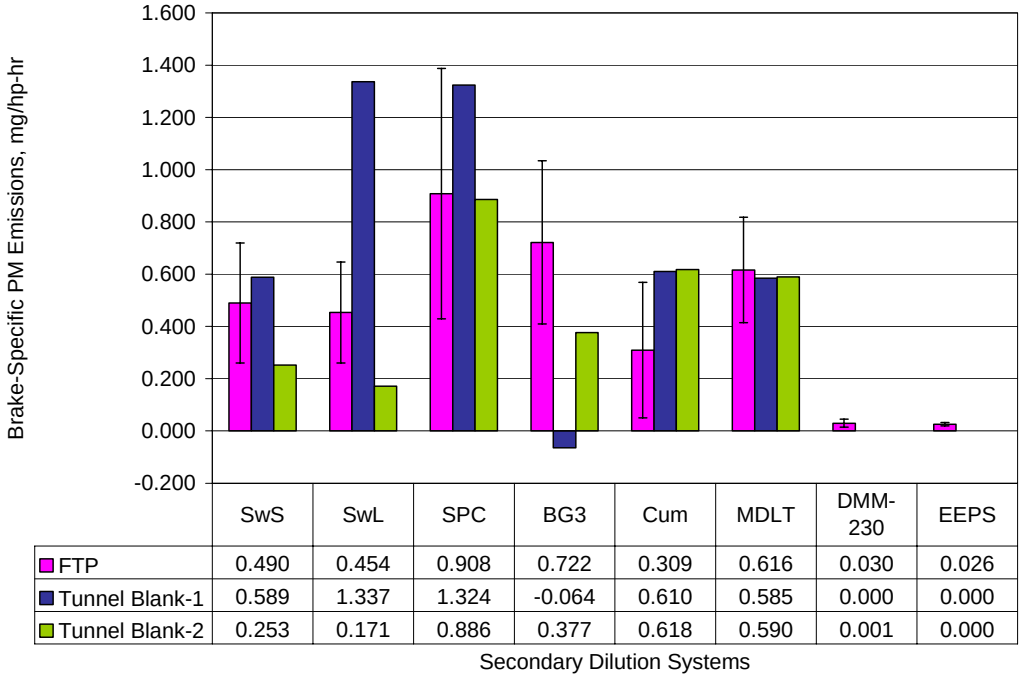
4.2 Comparison of Different Dilution Systems Used As Secondary Tunnels on Full Flow CVS

Figures 17 and 18 show the average brake-specific PM emission levels measured for the rated power condition and the hot-start FTP transient cycle, respectively, using the SwL, SwS, with three PFSS units; SPC, MDLT, and the BG-3. The EEPS and the DMM-230 measured PM in parallel to the filter measurement used with SwL. The average and standard deviations were calculated and plotted based on seven separate runs of the steady-state and for the transient engine operating conditions. The average PM emission level, regardless of the sampling system used, was at most 10 percent of the 2007 standard. The tunnel blank equivalent emission level, without engine operation, was comparable to the emission level with engine operation, suggesting that the true engine PM emissions were much lower than the average emission level reported using mass collected on a filter. The real time instruments such as the DMM-230 and EEPS were the only measurement techniques that clearly differentiated between a tunnel blank and an engine test run.



	SwS	SwL	SPC	BG3	Cum	MDLT	DMM-230	EEPS
Rated Power	0.272	0.374	0.263	0.393	0.119	0.271	0.081	0.094
Tunnel Blank-1	0.176	0.338	0.135	0.080	0.075	0.090	0.007	0.000
Tunnel Blank-2	0.082	0.040	0.531	0.122	0.129	0.138	0.010	0.000

FIGURE 17. PARTICLE MASS EMISSIONS AT ENGINE RATED POWER USING DIFFERENT SECONDARY DILUTION SYSTEMS (AVERAGE AND STANDARD DEVIATION BASED ON SEVEN REPEATS)



	SwS	SwL	SPC	BG3	Cum	MDLT	DMM-230	EEPS
FTP	0.490	0.454	0.908	0.722	0.309	0.616	0.030	0.026
Tunnel Blank-1	0.589	1.337	1.324	-0.064	0.610	0.585	0.000	0.000
Tunnel Blank-2	0.253	0.171	0.886	0.377	0.618	0.590	0.001	0.000

FIGURE 18. PARTICLE MASS EMISSIONS FOR THE FTP USING DIFFERENT SECONDARY DILUTION SYSTEMS (AVERAGE AND STANDARD DEVIATION BASED ON FIVE REPEATS)

Because the emission level was very low, less than 10 percent of the 2007 standard based on filter measurement and less than one percent based on real time particle instruments, comparable to the tunnel blank, it was beyond the scope of this project to draw a statistically valid conclusion about the performance of the various systems. They all had a similar performance.

4.3 Comparison between Partial Flow Sampling Systems and Full Flow CVS

In this section, the results relative to PFSS response time and correlation performance are reported, followed by the PM emissions performance for the CRT-DPF without and with Bypass.

4.3.1 PFSS Response Time and Correlation-Simulated Cycle

One of the fundamental issues of concern about a PFSS in the past was the ability of a PFSS to vary the sample mass flow rate extracted from the exhaust rapidly enough, better than 200 ms response time, proportional to the engine exhaust mass flow rate. This short response time requirement is to ensure that the PFSS samples the rapid changes in exhaust PM concentration during a transient engine operation without missing essential sample. All PFSS manufacturers have worked to improve the response time of their PFSS relative to the earlier studies at SwRI in 2002 [2]. Before proceeding with engine testing with the PFSS units, the response time of each PFSS was examined using a simulated transient cycle, designed to mimic the exhaust flow changes during actual transient operation by providing a surrogate voltage signal similar to that produced during actual engine operation by the engine intake air flow meter. The output signal was fed to each PFSS to examine its sample flow response time.

Figures 19, 20, 21, and 22 show the simulated transient cycle exhaust flow rate changes and the sample flow response of the PFSS units. The correlation between the two flows, including R^2 and the standard error are shown. In general, all PFSSs had an excellent correlation with an R^2 better than 99 percent, and a standard error relative to the average flow of better than 5 percent. The rise time of the PFSS was as good as the rise time of the simulated signal. The delay time was better than 200 ms, generally on the order of 100 ms. Typically, CFR Part 1065, allows the removal of 5 percent of the total data points collected for the purpose of the correlation. Although not applied for the results presented here, such practice will further improve the correlation coefficient as well as the standard error for all systems.

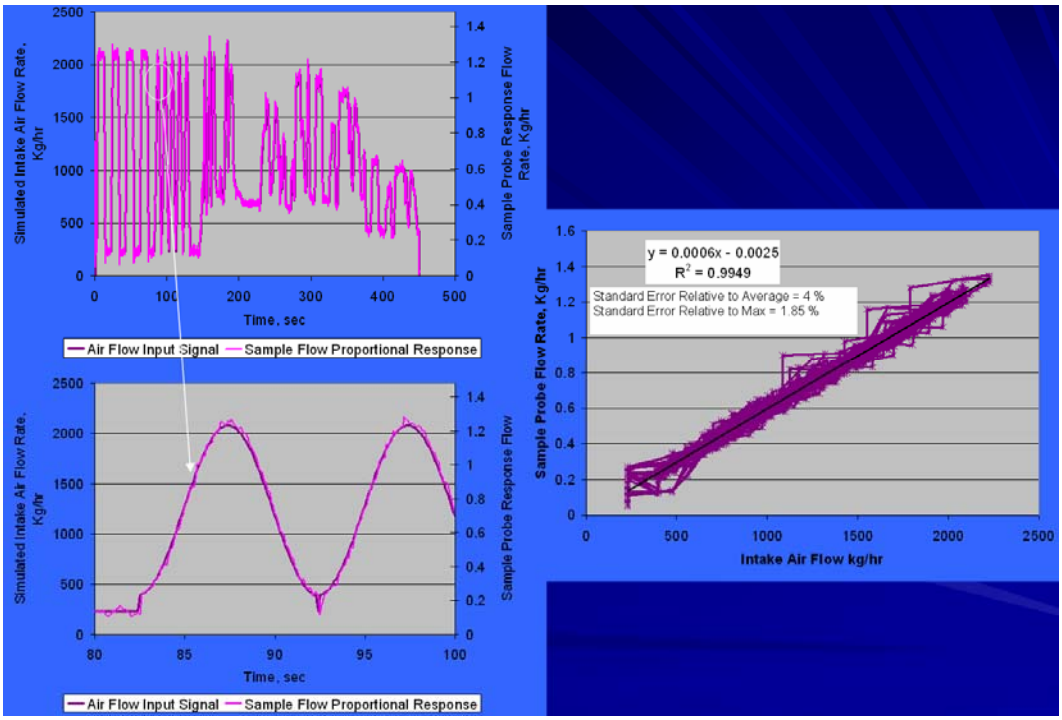


FIGURE 19. RESPONSE TIME AND CORRELATION OF THE BG3

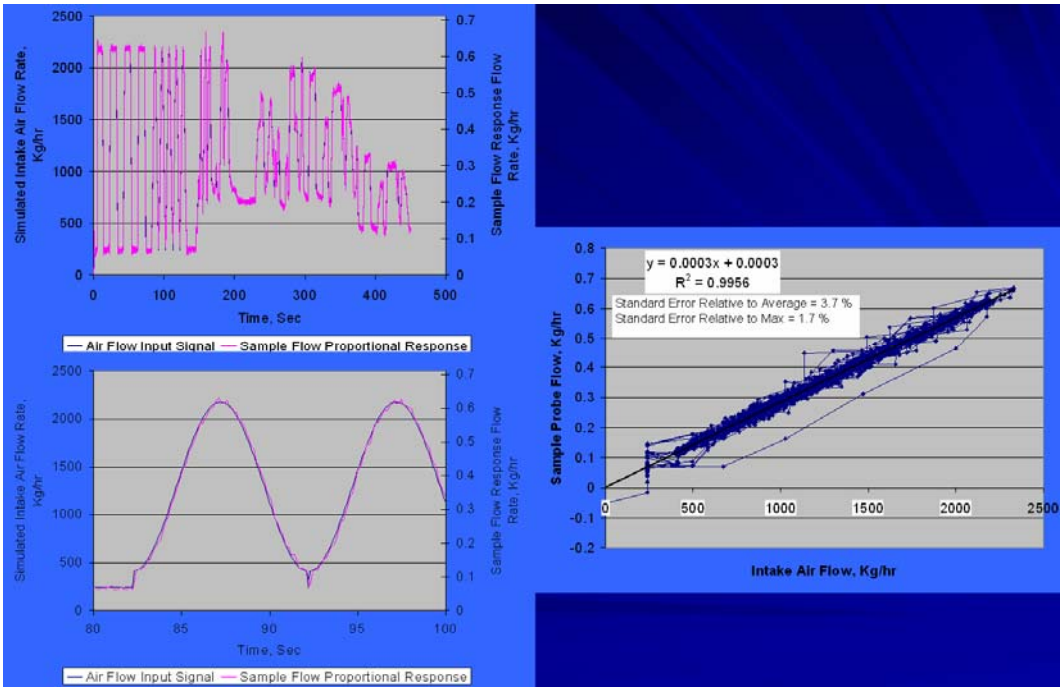


FIGURE 20. RESPONSE TIME AND CORRELATION OF THE MDLT

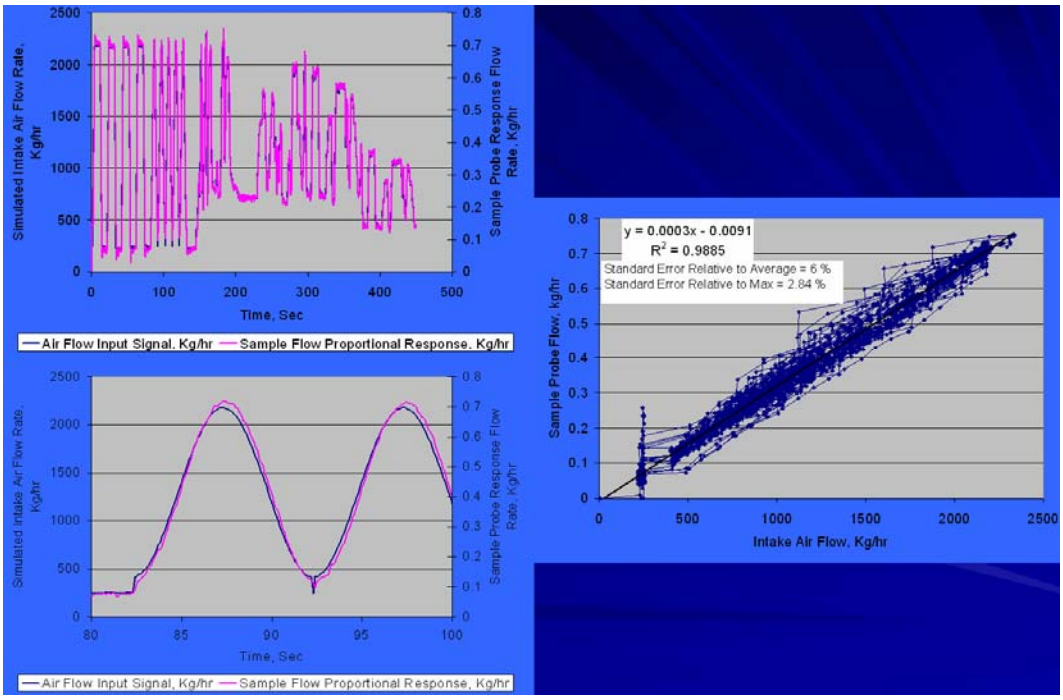


FIGURE 21. RESPONSE TIME AND CORRELATION OF THE SPC

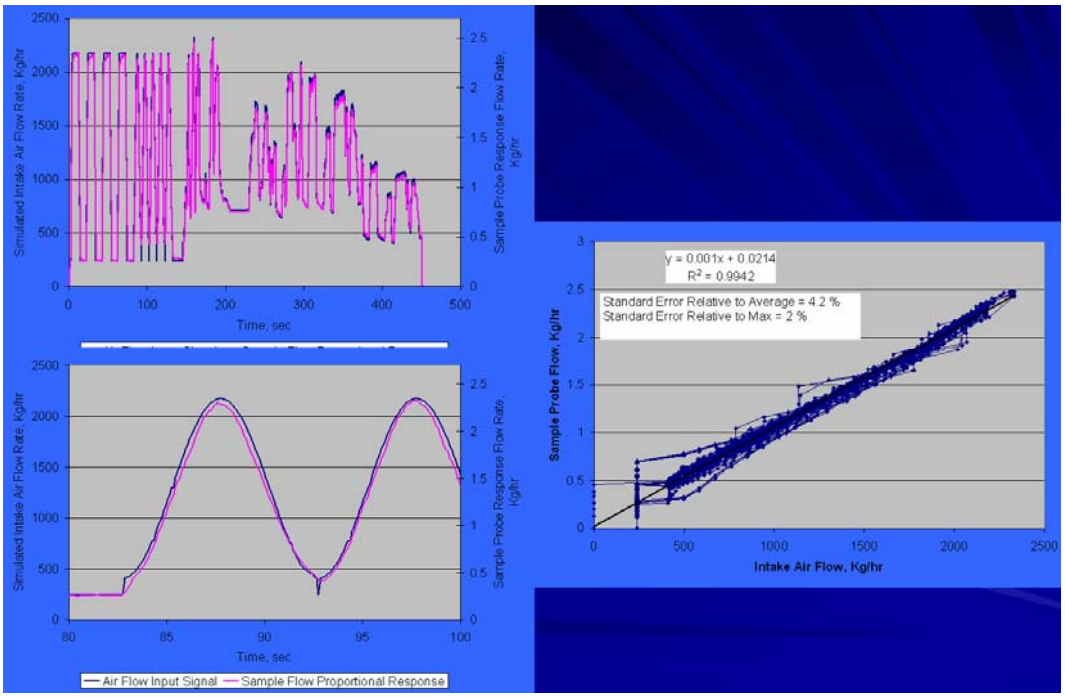


FIGURE 22. RESPONSE TIME AND CORRELATION OF THE AEI/CUM

The simulated cycle or surrogate signal was not used on the MPS. The MPS is designed to receive an exhaust feedback signal from its own exhaust flow meter, and the feedback signal involves more than a single voltage output. In addition, the MPS was not configured at the time of this work to collect the sample flow on a 10 Hz basis to determine the proper response time.

4.3.2 PFSS Correlation-Transient Cycles

Figures 23 through 27 show the correlation between the sample flow extracted from the exhaust and the intake air flow of the engine for the different PFSS units. For the MPS, the correlation was made with the directly measured exhaust flow instead of intake air flow. For the AEI/CUM, the sample flow extracted from the exhaust is normally constant because the AEI/CUM operates at a constant dilution ratio, so, the exhaust sample probe flow in Figure 24 is actually the mass flow rate through the filter because the system operates at variable filter flow rate under transient engine operation.

It is important to note here that all data points collected were used for this correlation and no data points were thrown out. Again, CFR Part 1065 allows the removal of five percent of the data points which would improve the correlation and the standard error reported in Figures 23 through 27.

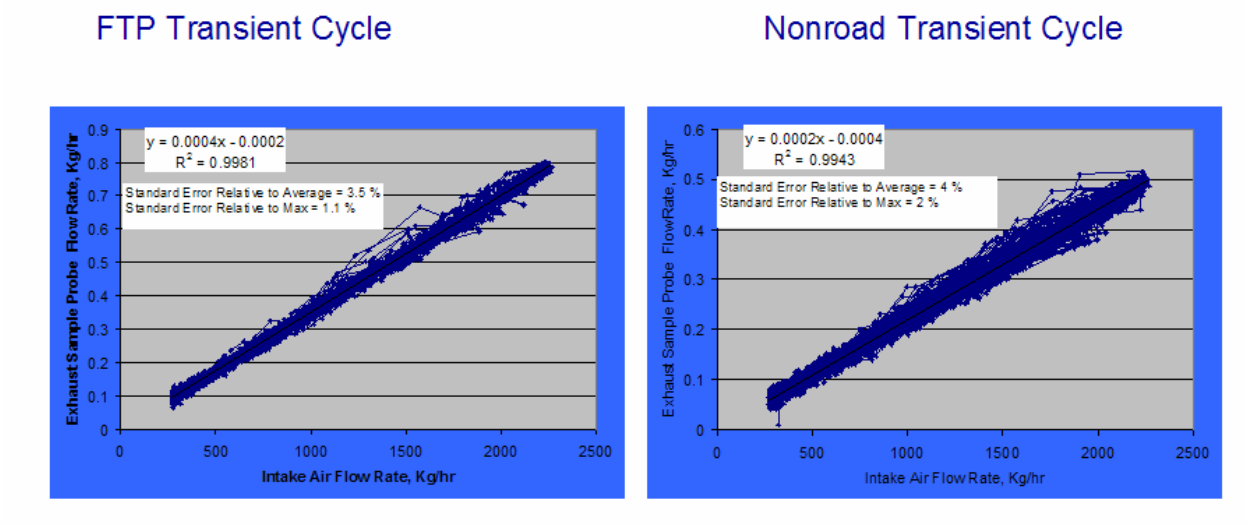


FIGURE 23. CORRELATION BETWEEN SAMPLE FLOW AND INTAKE AIR FLOW FOR THE BG3

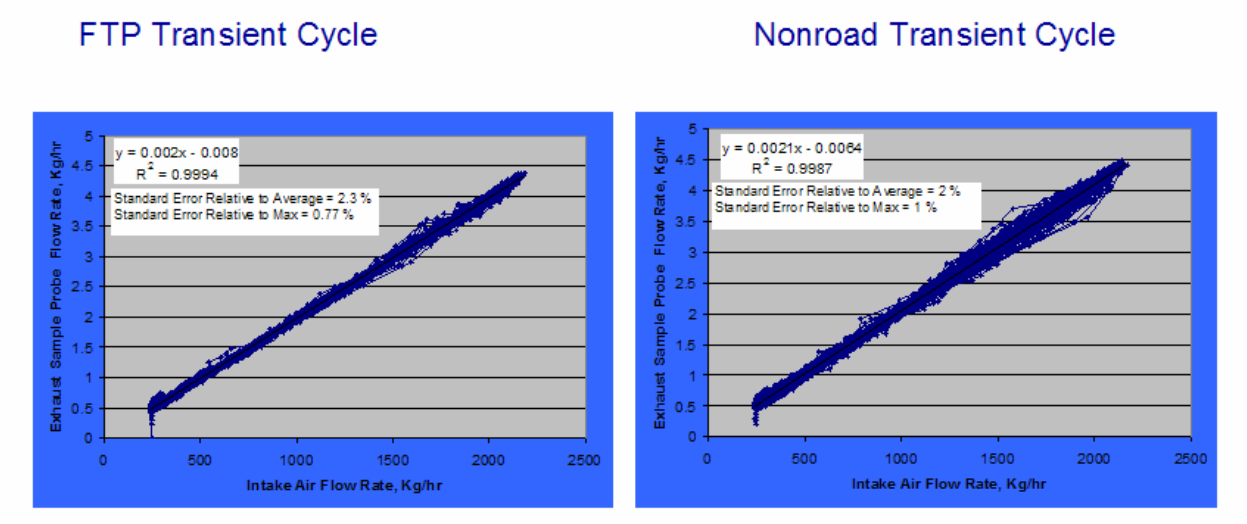


FIGURE 24. CORRELATION BETWEEN FILTER FLOW AND INTAKE AIR FLOW FOR THE AEI/CUM

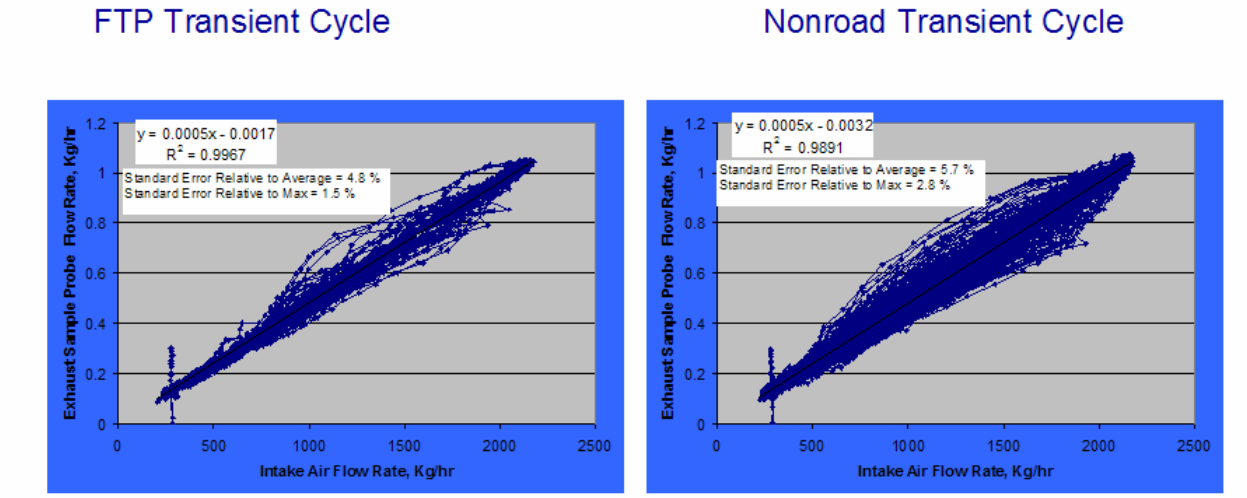


FIGURE 25. CORRELATION BETWEEN SAMPLE FLOW AND INTAKE AIR FLOW FOR THE SPC

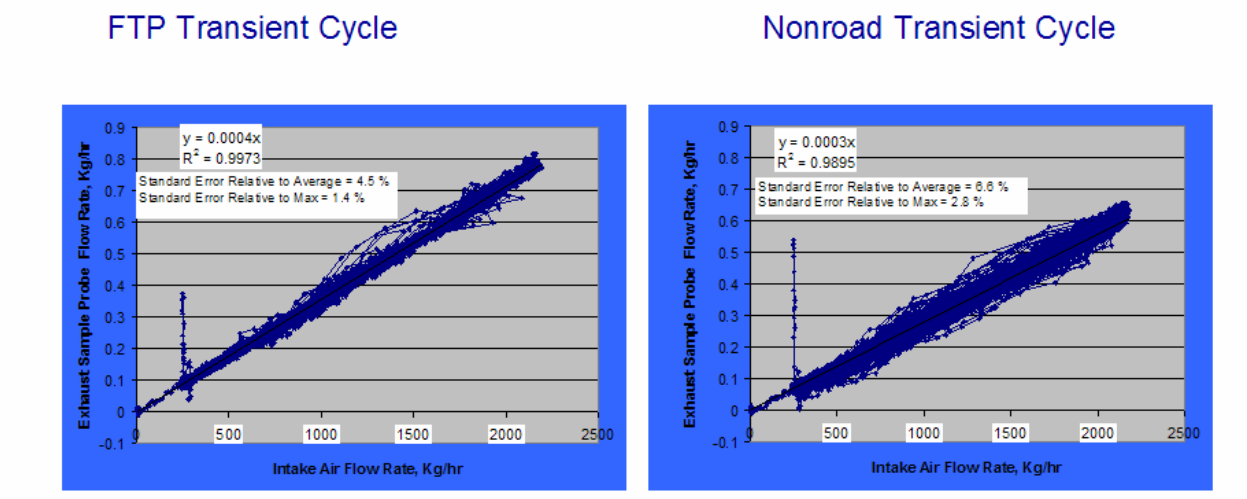


FIGURE 26. CORRELATION BETWEEN SAMPLE FLOW AND INTAKE AIR FLOW FOR THE MDLT

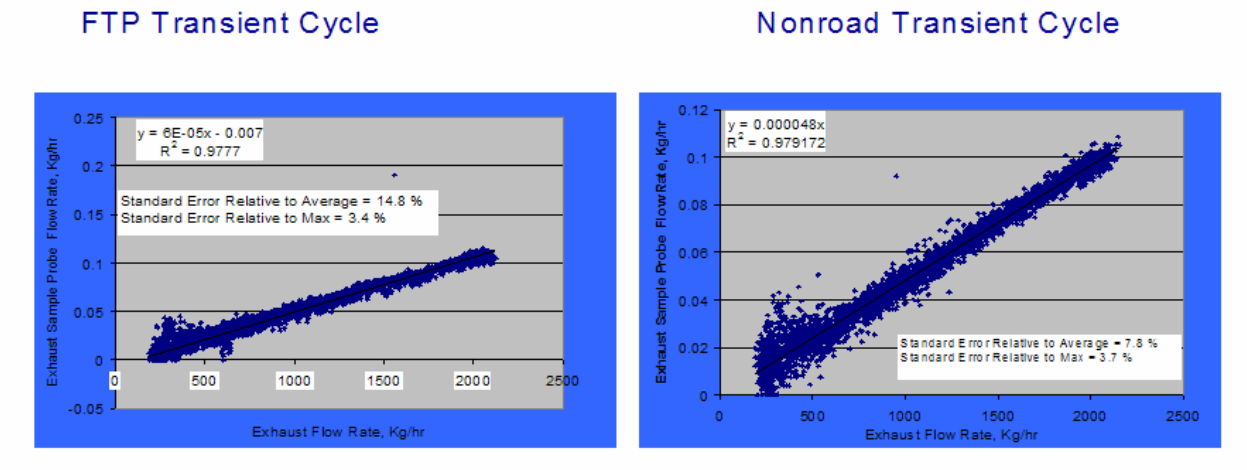


FIGURE 27. CORRELATION BETWEEN SAMPLE FLOW AND EXHAUST FLOW FOR THE MPS

In general, most systems had an excellent correlation coefficient of better than 99 percent for the FTP. For the NRTC, the BG3 and AEI/CUM had a correlation coefficient exceeding 99 percent and the SPC and the MDLT correlation coefficients were near 99 percent. The MPS had the lowest correlation coefficient of about 97 percent and the highest standard errors, about 7 percent for the FTP and 13 percent for NRTC. The MPS was a prototype system that was being used for the first time, and improvements are expected to be implemented as a result of this program.

4.3.3 CRT-DPF without Bypass

Figures 28 and 29 show the engine PM emission performance using the five different PFSS units on engine exhaust and the two different secondary dilution systems, SwS and SwL, coupled to the full flow dilution CVS tunnel. All the engine exhaust was treated by the CRT-DPF without Bypass. Generally, except for the MPS, the PM emission level reported by all systems was 15 percent or lower of the 2007 PM standard.

At rated engine speed, 100 percent load, the emission levels reported by most of the PFSS units were similar to the SwS at a level less than five percent of the 2007 PM standard. The AEI/CUM system, however, reported the lowest PM emission level at less than 0.1 percent of the standard , possibly because it was using a 47°C dilution air instead of 20°C to 30°C used by the other systems. The MPS showed the highest level at about ten percent of the 2007 PM standard.

At rated speed, 10 percent load, the PM loading on the filter was very small, only 2 to 4 µg, and the resulting low PM emission level had high variability. The MPS showed the highest PM emission level, but the filter weight gain was below 4 µg for both the 100 and the 10 percent load conditions and the results could be easily distorted by minor filter weighing errors at such low PM loadings.

For the FTP, the PM emission performance was very similar to that observed at rated speed, 100 percent load. The AEI/CUM gave the lowest PM emission level at less than 0.3 percent of the standard, and the MPS gave the highest PM emission level at about 25 percent of the standard, where the SPC, MDLT, and BG3 gave similar PM level to that of the SwS.

For the NRTC, the SwS, SPC, and MPS gave similar results at an emission level of about eight percent of the 2007 PM standard. The BG3 and AEI/CUM gave slightly lower results at five and three percent of the PM standard, respectively. The SwL and MDLT gave higher results at 15 and 12 percent of the standard, respectively.

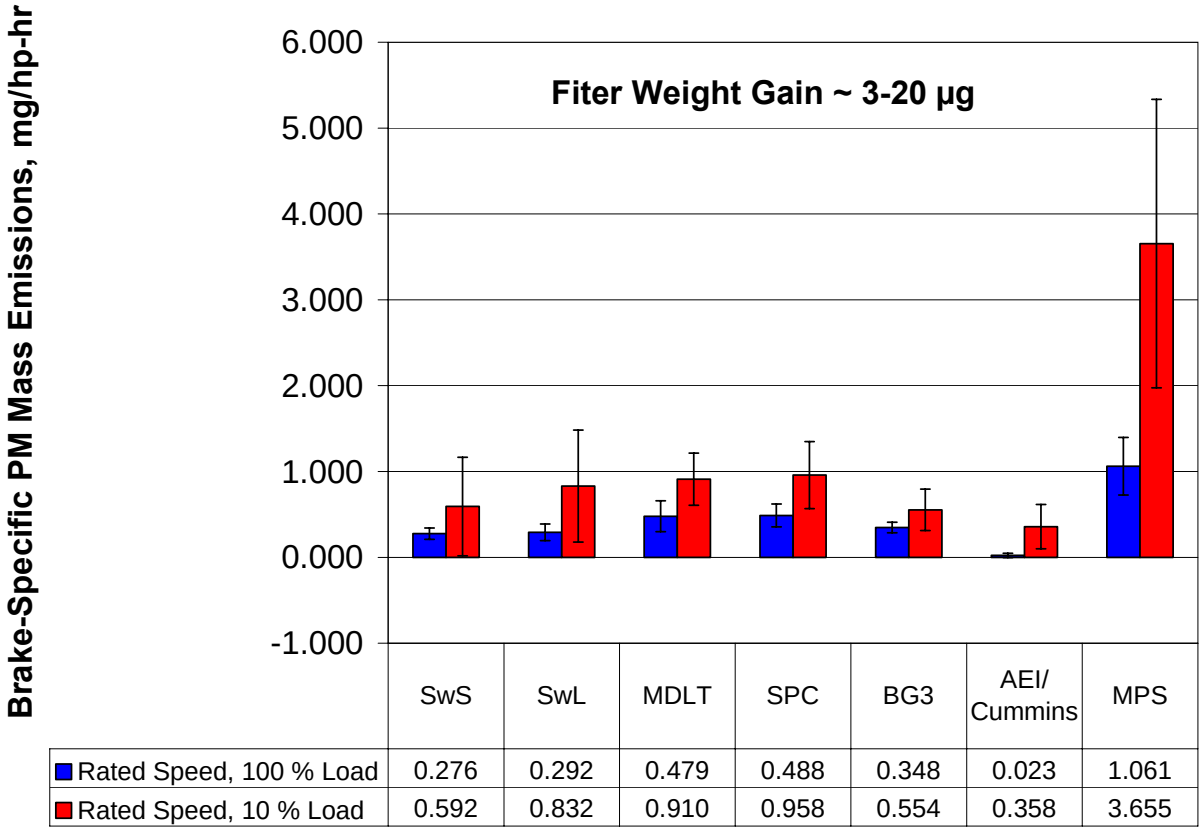
The AEI/CUM consistently gave on the order of 50 to 70 percent lower PM emission results than the rest of the systems. This was possibly due to the high dilution air temperature of 47^{o}C used with AEI/CUM. Generally, the MPS gave a factor of 3 higher PM emission results than the rest of the systems. The MPS was used in these experiments as part of its development, and several software and operational changes were performed during the course of this work. It is difficult to try to formulate a good understanding of why it showed a higher PM level than the rest of the systems because the filter weight gain throughout this work was well below 5 µg.

4.4 CRT-DPF with Bypass

Figures 30 and 31 show the PM emission results using five different PFSS units on engine exhaust and two secondary dilution systems coupled to the full flow dilution CVS tunnel. The engine exhaust configuration included the CRT-DPF with Bypass, targeting a PM emission level of about 80 percent of the 2007 PM standard.

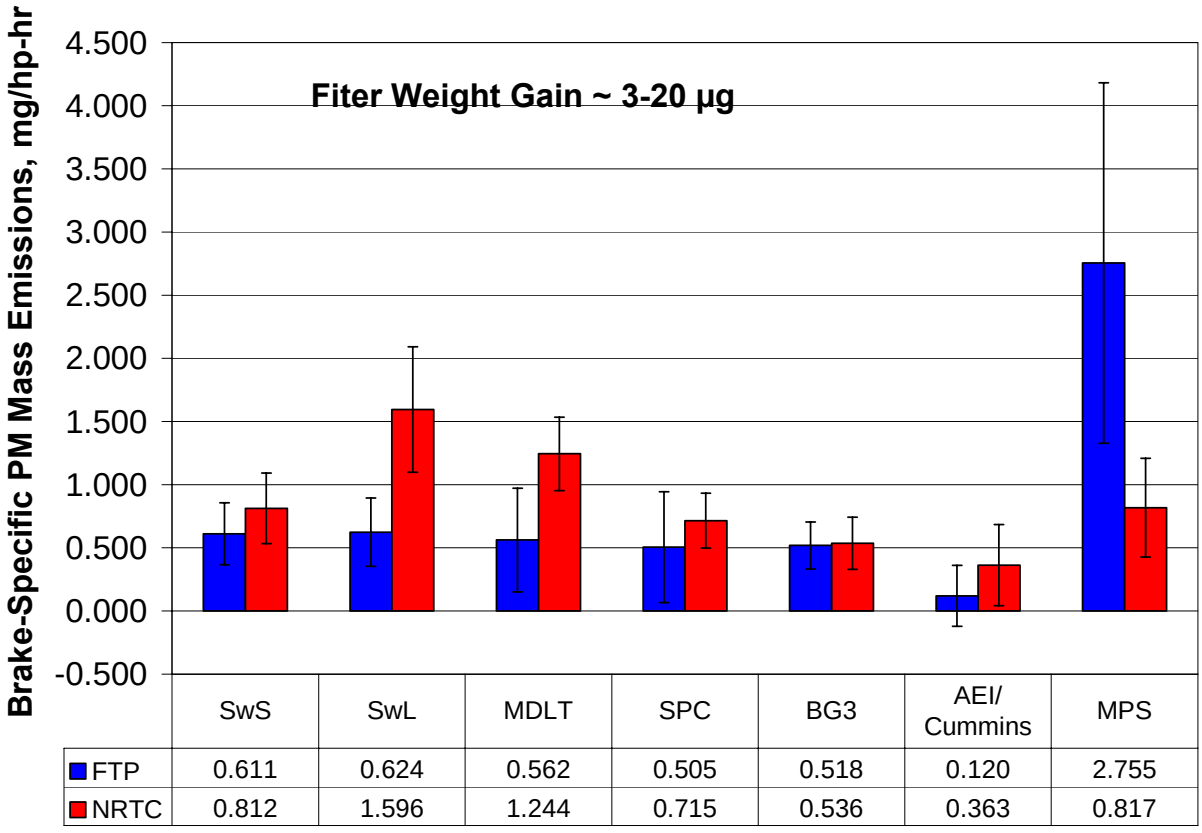
At rated engine speed, 100 percent load, Figure 30, the PM emission level reported by most of the PFSS units was similar. For the SPC, however, the PM emission level was 2.5 times higher at rated speed, 100 percent load, but 50 percent lower at rated speed, 10 percent load,

compared to the SwS. For the MPS, the PM emissions level was slightly higher at rated speed, 100 percent load, and about 25 percent lower at rated speed, 10 percent load, compared to the SwS. The MPS PM emissions at rated speed, 10 percent load had more variability than the rest of the systems. This was likely due to the low filter weight gain of about 7 µg collected on the filter, compared to the rest of the system that collected about 15 to 20 µg.



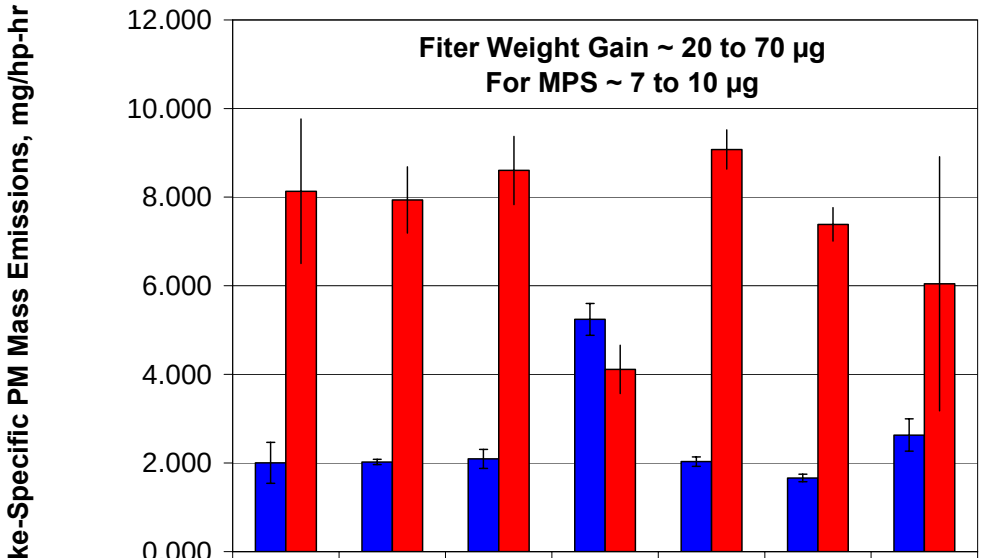
	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
Rated Speed, 100 % Load	0.276	0.292	0.479	0.488	0.348	0.023	1.061
Rated Speed, 10 % Load	0.592	0.832	0.910	0.958	0.554	0.358	3.655

FIGURE 28. PERFORMANCE OF DIFFERENT DILUTION SYSTEMS UNDER STEADY-STATE ENGINE OPERATION USING CRT-DPF WITHOUT BYPASS (AVERAGE AND STANDARD DEVIATION BASED ON SEVEN REPEATS)



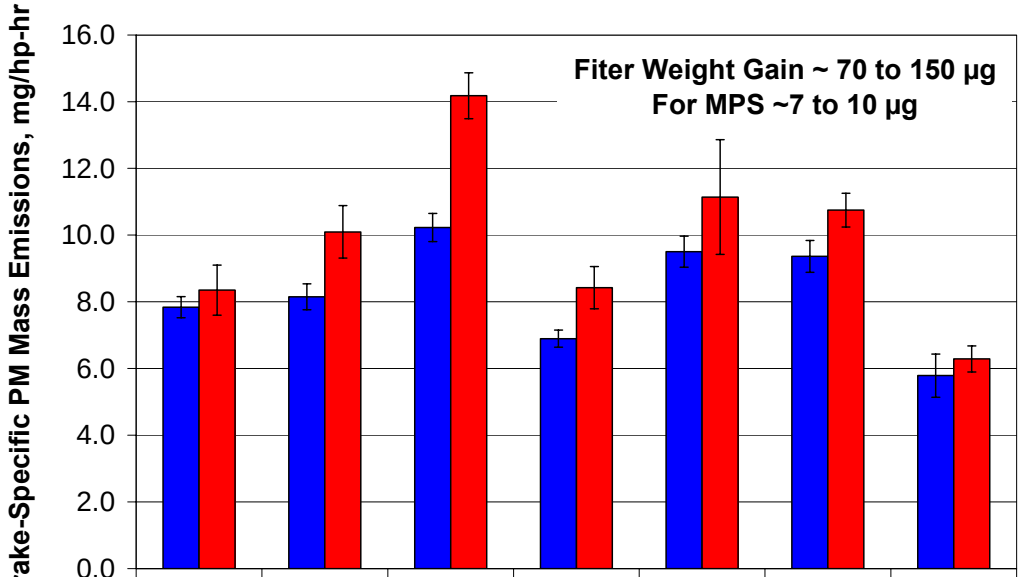
	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
FTP	0.611	0.624	0.562	0.505	0.518	0.120	2.755
NRTC	0.812	1.596	1.244	0.715	0.536	0.363	0.817

FIGURE 29. PERFORMANCE OF DIFFERENT DILUTION SYSTEMS UNDER TRANSIENT ENGINE OPERATION USING CRT-DPF WITHOUT BYPASS (AVERAGE AND STANDARD DEVIATION BASED ON SEVEN REPEATS)



	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
Rated Speed, 100 % Load	2.004	2.022	2.095	5.242	2.032	1.662	2.631
Rated Speed, 10 % Load	8.133	7.936	8.602	4.113	9.076	7.385	6.045

FIGURE 30. PERFORMANCE OF DIFFERENT DILUTION SYSTEMS UNDER STEADY-STATE ENGINE OPERATION USING CRT-DPF WITH BYPASS (AVERAGE AND STANDARD DEVIATION BASED ON SEVEN REPEATS)



	SwS	SwL	MDLT	SPC	BG3	AEI/ Cummins	MPS
FTP	7.839	8.149	10.227	6.894	9.501	9.361	5.786
NRTC	8.350	10.095	14.176	8.423	11.139	10.748	6.287

FIGURE 31. PERFORMANCE OF DIFFERENT DILUTION SYSTEMS UNDER TRANSIENT ENGINE OPERATION USING CRT-DPF WITH BYPASS (AVERAGE AND STANDARD DEVIATION BASED ON SEVEN REPEATS)

Under transient cycle operation, Figure 31, the PM emissions using the MDLT were about 30 percent higher for the FTP and 69 percent higher for the NRTC, compared to the PM emission level obtained using the SwS. The AEI/CUM gave 19 and 29 percent higher PM emissions than those reported by the SwS for the FTP and NRTC, respectively. The BG3 gave 21 and 33 percent higher PM emissions than those reported by the SwS for the FTP and NRTC, respectively. The PM emission level using the MPS for both the FTP and the NRTC was about 25 percent lower than the PM emission using SwS. For the SPC, the NRTC PM emission level was similar to the SwS and it was about 13 percent lower for the FTP. SwL performance was similar to SwS for the FTP and was about 25 percent higher for the NRTC.

Since the response time of all the PFSS units was on the order of 100 ms, and the correlation between the sample flow and the exhaust flow was excellent with an R^2 exceeding 99 percent and a standard error better than 5 percent, all the PFSS units should be eligible candidates for measuring PM from engines equivalent to the CVS. However, some puzzling results were obtained during this work. Under steady-state engine operation, all systems performed similarly, except for the SPC system which measured a lower PM emission level than the rest of the PFSS units at rated speed, 10 percent load, and substantially higher at rated speed, 100 percent load. Under transient engine operation, the MDLT, BG3, and AEI/CUM reported higher PM emission level than that using the SwS for both the FTP and the NRTC. Using the SwL and SwS for the FTP gave similar results but the SwL gave higher results for the NRTC. The MPS was lower for both the FTP and the NRTC, and the SPC was similar for the NRTC but lower for the FTP.

Due to the variation seen in PM levels for different engine operations by each system compared to the CVS (SwS), especially the large difference seen on the AVL SPC at rated speed, 100% load, there were some questions raised about the quality of the mixing between the Bypass and exhaust stream exiting the CRT-DPF. This was in spite of the fact that the flow in both the Bypass and exhaust streams were in the turbulent regime in all engine operating modes, with Reynolds numbers between 8,000 and 160,000. Further, the first PFSS sampling probe was over 12 pipe diameters downstream of the initial mixing point of the two streams. However as previously stated, sample flow results from the PFSS show that sampling proportionality was being maintained in a competent manner, suggesting that correlation to CVS should be achievable for most, if not all, of the production systems. AVL strongly recommended that additional mixing studies be performed on the exhaust system to resolve the potential mixing issue. However, the funding for the E-66 testing at SwRI had essentially been depleted.

4.5 Particulate Matter Composition Using Quartz Filters

It is important to note that only the SwS and the AEI/CUM used a primary and a backup filter. For the AEI/CUM, the backup filter weight for SOF and sulfate were subtracted from the primary filters to correct for filter artifact. The SOF artifact level was about 25 percent for the rated speed, 100 percent load, and 27 percent for the FTP. The sulfate artifact level was zero for the rated speed, 100 percent load, and 14 percent for the FTP. For the SwS and the rest of the PFSS units, the SwS backup filter was used to account for artifact collection on the primary. The SOF artifact was 42 percent and the sulfate artifact was 55 percent at the rated power condition. For the FTP, the SOF artifact was 27 percent, and the sulfate artifact was near 80 percent. It was assumed that the artifact fraction which is defined as the backup filter weight gain over the primary filter weight gain is the same for the SwS and the rest of the PFSS units, except for the

AEI/CUM.

Figure 32 shows the EC brake-specific PM emission using the different dilution systems at engine rated speed, 100 percent load. The PM emission level reported by the SPC was higher than the rest of the systems, similar to what was observed with total PM when using Teflo filters. The MPS showed a lower EC than the rest of the systems. This could be due to particle loss in the sampling system or to the lack of sensitivity of the analytical method because the mass on the filter for the MPS was about 17 µg while it was about 70 µg with the other systems. Similar results were obtained for the FTP transient cycle, Figure 33, with the MPS.

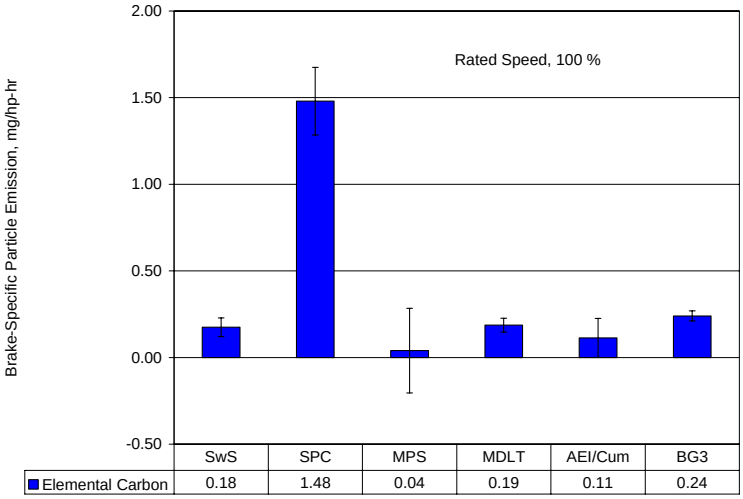


FIGURE 32. ELEMENTAL CARBON EMISSIONS UNDER STEADY-STATE ENGINE OPERATION USING DIFFERENT DILUTION SYSTEMS (AVERAGE AND STANDARD DEVIATION BASED ON THREE REPEATS)

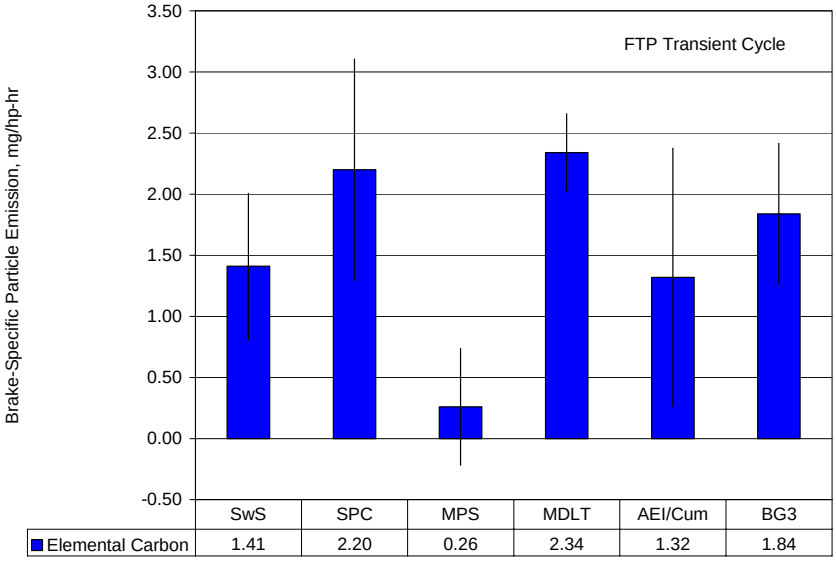
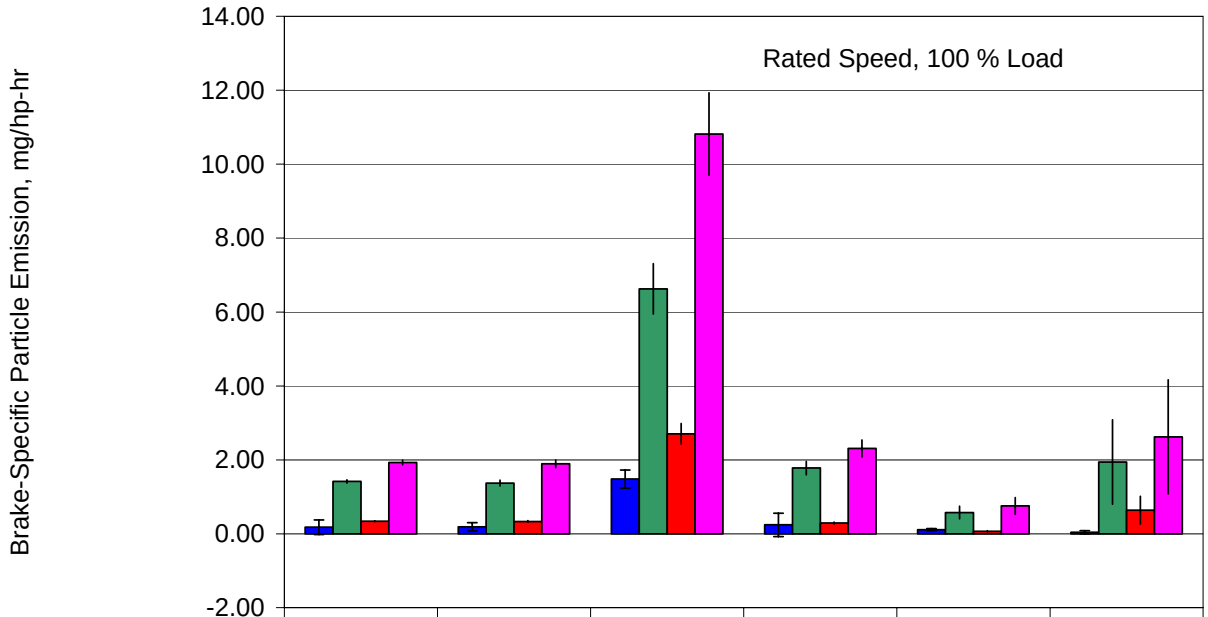


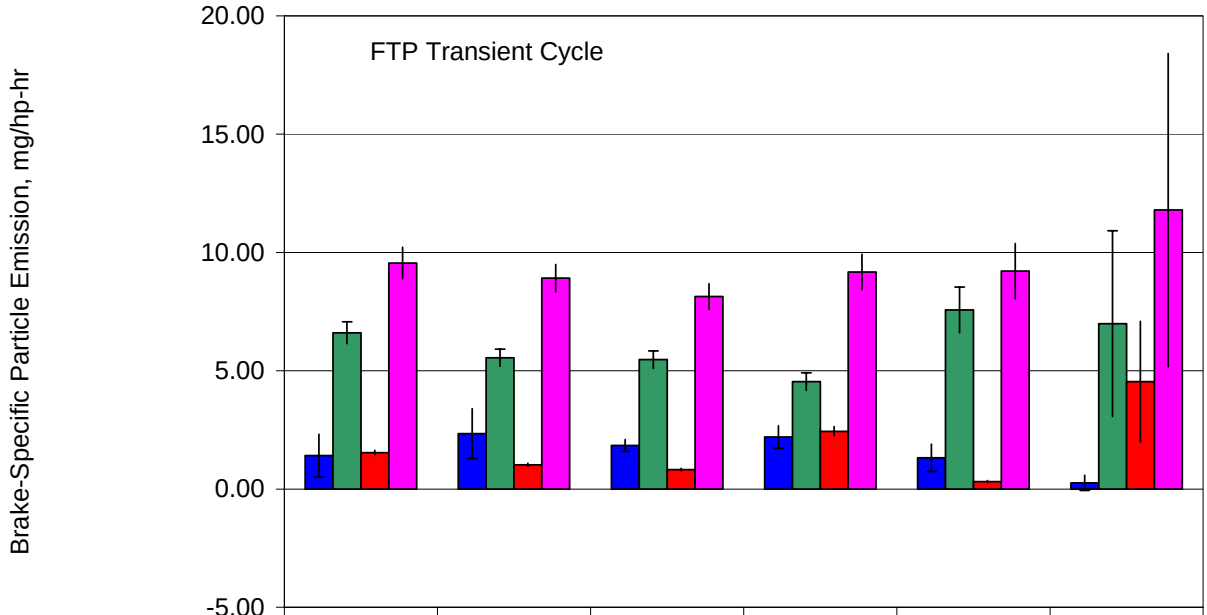
FIGURE 33. ELEMENTAL CARBON EMISSIONS UNDER TRANSIENT ENGINE OPERATION USING DIFFERENT DILUTION SYSTEMS (AVERAGE AND STANDARD DEVIATION BASED ON THREE REPEATS)

Figures 34 and 35 show the particle composition for the rated speed, 100 percent load condition and for the FTP transient cycle. The AEI/CUM system was equipped with a primary and a backup filter during filter collection. The AEI/CUM backup filter OC, EC, and sulfate mass was subtracted from the primary filters of all systems. There was about 42 percent reduction in OC, 55 percent reduction in sulfate on the primary filter due to subtraction of the backup filter. The EC on the backup filter was negligible.



	SwS	MDLT	SPC	BG3	AEI/Cum	MPS
Elemental Carbon	0.18	0.19	1.48	0.24	0.11	0.04
Organic Carbon	1.42	1.37	6.63	1.78	0.58	1.94
Sulfate	0.34	0.33	2.71	0.29	0.06	0.64
Total	1.93	1.89	10.81	2.31	0.75	2.62

FIGURE 34. PARTICLE COMPOSITION USING CRT-DPF WITH BYPASS AT RATED ENGINE POWER (AVERAGE AND STANDARD DEVIATION BASED ON THREE REPEATS)



	SwS	MDLT	BG3	SPC	AEI/Cum	MPS
Elemental Carbon	1.41	2.34	1.84	2.20	1.32	0.26
Organic Carbon	6.61	5.55	5.47	4.54	7.57	6.99
Sulfate	1.53	1.02	0.82	2.44	0.32	4.54
Total	9.55	8.91	8.13	9.18	9.21	11.79

FIGURE 35. PARTICLE COMPOSITION USING CRT-DPF WITH BYPASS FOR THE FTP TRANSIENT CYCLE (AVERAGE AND STANDARD DEVIATION BASED ON THREE REPEATS)

The SPC OC, EC, and sulfate emissions were all higher than the rest of the systems at engine rated speed, 100 percent load. This was consistent with the Teflo filter results. The increase in PM emission level was not only related to the increase of elemental carbon but also to volatile and semi-volatile PM. The AEI/CUM gave lower PM than the rest of the systems at engine rated speed, 100 percent load. This was consistent with the Teflo data. The AEI/CUM was expected to give a lower OC and sulfate than the rest of the system because of the high secondary dilution air temperature of 47°C that was used throughout all experiments. This was clearly demonstrated in Figure 34.

For the FTP transient cycle, most systems gave similar organic and sulfate emissions. The MPS results were questionable because of the low level of PM collected by the MPS due to the use of 25 mm filter instead of 47 mm filter. For the AEI/CUM, the sulfate emission level was lower than the rest of the system but the OC was about the same as the rest of the systems.

The work using the quartz filters was limited in scope. It was performed to assess the PM emissions performance in a qualitative manner. More work is needed in order to provide a more robust quantitative assessment of the performance of different systems relative to EC, OC, and sulfate PM emissions. Also, the issue of EC artifact due filter analysis with the MEXA 1370 PM was not investigated. During filter analysis, due to the high temperature (950ºC) applied on the quartz filter to desorb the OC in an inert nitrogen environment, EC artifact might form on the

filter due to pyrolysis of OC. The contribution of OC to EC has not been quantified for these experiments and remained unknown.

5.0 DISCUSSION

The results obtained with the PFSS using the CRT-DPF with Bypass was questioned by AVL pointing to the possibility of an exhaust mixing problem between the flow exiting the DPF and the flow in the Bypass leg. This was in spite of the fact that the flow in both the Bypass and exhaust streams were in the turbulent regime in all engine operating modes, with Reynolds numbers between 8,000 and 160,000. Further, the first PFSS sampling probe was over 12 pipe diameters downstream of the initial mixing point of the two streams.

In order to address the mixing question, EMA, EPA, and CARB together with SwRI agreed to fund additional work to verify experimentally whether or not there was a mixing problem.

Figures 36 and 37 show the overall experimental setup for the exhaust mixing investigation. Solid particle size distribution measurements were taken using a catalytic stripper along with a Scanning Mobility Particle Sizer (SMPS). The function of the catalytic stripper was to remove the volatile portion of PM by oxidation prior to any measurement with the SMPS. The measurements were taken in two quadrants in the exhaust pipe at Locations A and B, shown in Figure 36. The test matrix is shown in Figure 38. Three SMPS repeats were taken at each of the nine points shown along the horizontal and vertical axes of the exhaust cross section.

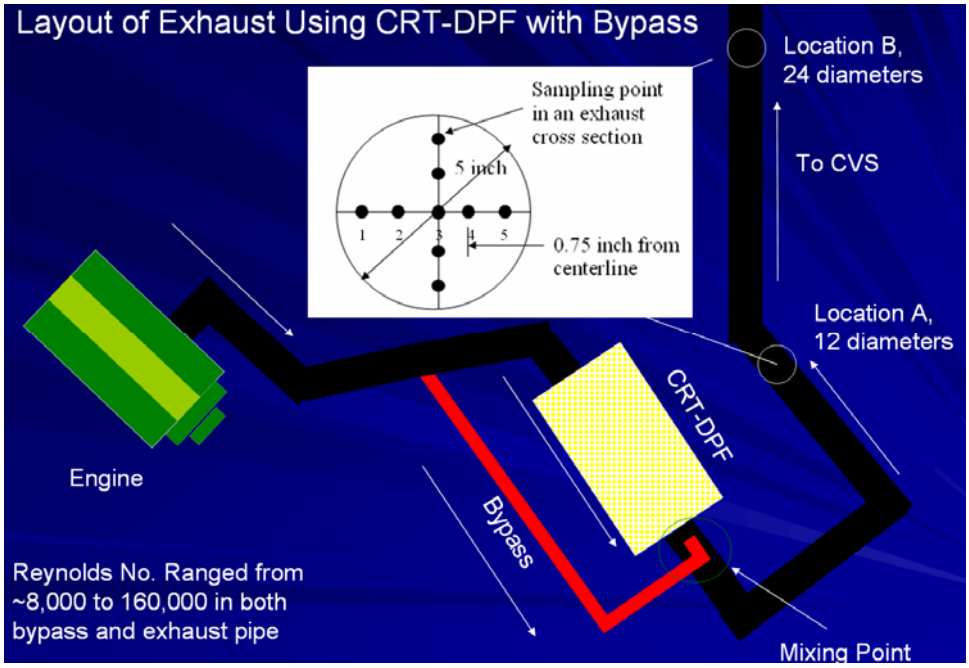


FIGURE 36. ENGINE EXPERIMENTAL SETUP FOR EXHAUST MIXING INVESTIGATION

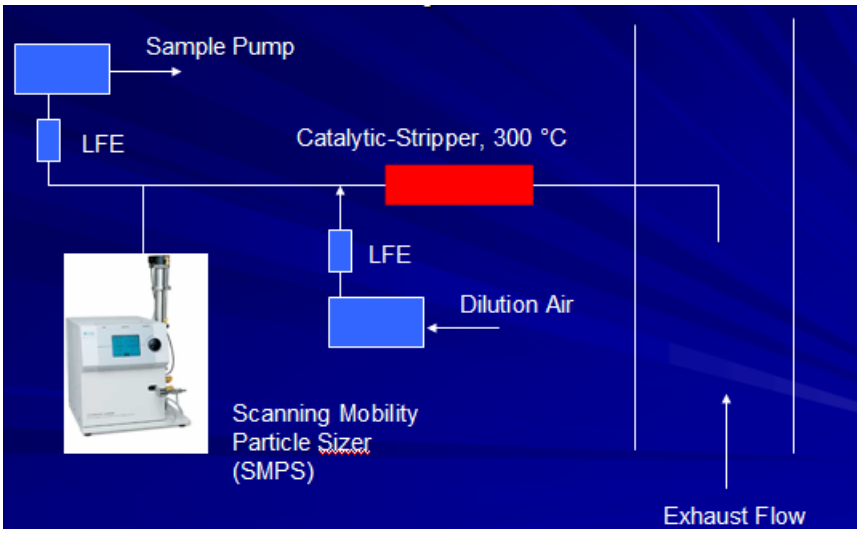


FIGURE 37. SOLID PARTICLE MEASUREMENT USING CATALYTIC STRIPPER SYSTEM AND SMPS

Test Matrix

	Location A, with Bypass	Location B, with Bypass
Rated Speed, 100 Percent Load	9 sampling points, 3 repeat each	9 sampling points, 3 repeat each
Rated Speed, 10 Percent Load	9 sampling points, 3 repeat each	9 sampling points, 3 repeat each

FIGURE 38. TEST MATRIX FOR THE MIXING INVESTIGATION

Figure 39 shows the average number concentration at different points along the vertical and horizontal axes at Locations A and B for the rated speed, 100 percent load condition. Figure 40 is similar to Figure 39, but it was plotted for particle volume concentration, which is an indication of particle mass. Figures 41 and 42 are similar to Figures 39 and 40, but show data for the rated speed, 10 percent load condition rather than the 100 percent load condition. Based on the results obtained, one can conclude from this work that the exhaust was fully mixed regardless of whether the engine was operated at rated speed, 100 or 10 percent load, and regardless of the sampling locations and sampling points along the horizontal or vertical axes of the exhaust pipe. Thus, the hypothesis made that the exhaust was not fully mixed during the PFSS work using a CRT-DPF with Bypass was not valid, and exhaust mixing was not a problem. The discrepancy in the results obtained between the CVS SwS and the AVL SPC was due to other phenomena that were not related to exhaust mixing.

Following the mixing study, AVL sponsored additional work at SwRI, outside the scope of Project E-66, to understand the reason for the difference in PM emission results between the SwS used on CVS and AVL SPC. The work was performed under steady-state engine operation, particularly at rated speed, 100 percent load, where, as shown earlier in Figure 30, the AVL SPC reported more than 2.5 times higher PM emissions than the SwRI CVS method.

Figure 43 shows the new results obtained at rated speed, 100 percent load. When both the total dilution ratio (DR) and dilution air temperature (DAT) of the SPC were matched to that of the CVS, the SPC reported PM emission went down from being 2.5 times higher than the CVS reported value to 29 percent higher, based on an average of three repeats. It is worth noting that the two systems also had a similar residence time on the order of one second.

This additional work showed that matching the dilution parameters between the CVS and the PFSS units will be important in any future work investigating the performance of the two methods. While the Project E-66 target was to compare the performance of the systems at similar dilution parameters, it was left up to each individual PFSS manufacturer to set the parameters needed to meet the filter face temperature requirement dictated by CFR Part 1065. Due to the high temperature inside the engine test cell, some PFSS units required different dilution conditions from that of the CVS in order to meet the filter face temperature requirement. This was partly why the AVL SPC was operated at a dilution ratio of 16 and a dilution air temperature of 15°C, compared with the CVS total dilution ratio of 7 and a CVS dilution air temperature of 35°C. When the dilution parameters were matched between the two systems, the PM emission performance was much closer to each other.

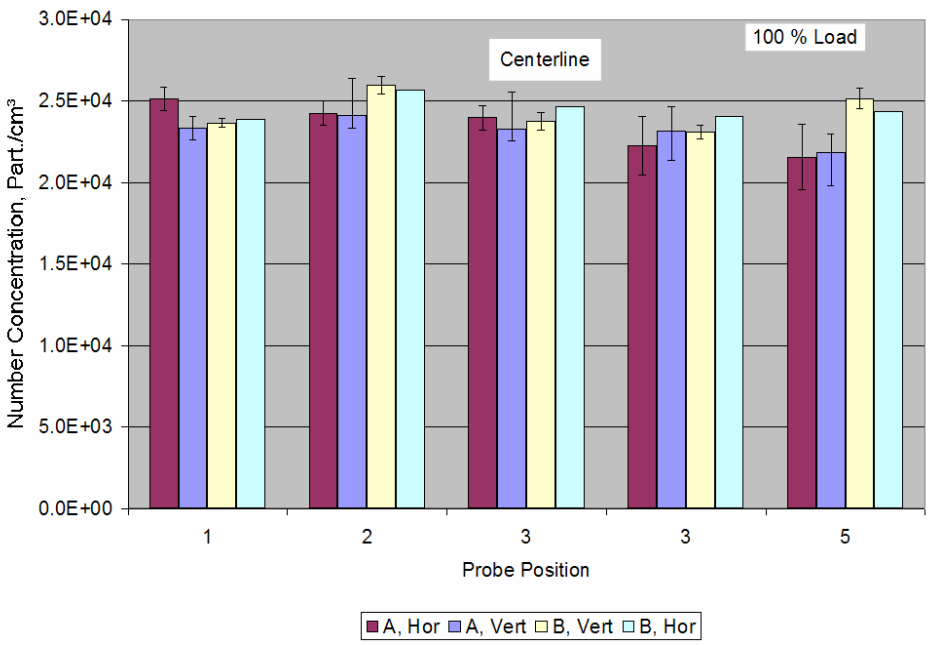


FIGURE 39. PARTICLE NUMBER CONCENTRATION ALONG THE VERTICAL AND HORIZONTAL CROSS SECTION OF AN EXHAUST PIPE AT TWO DIFFERENT LOCATIONS (RATED SPEED, 100 % LOAD)

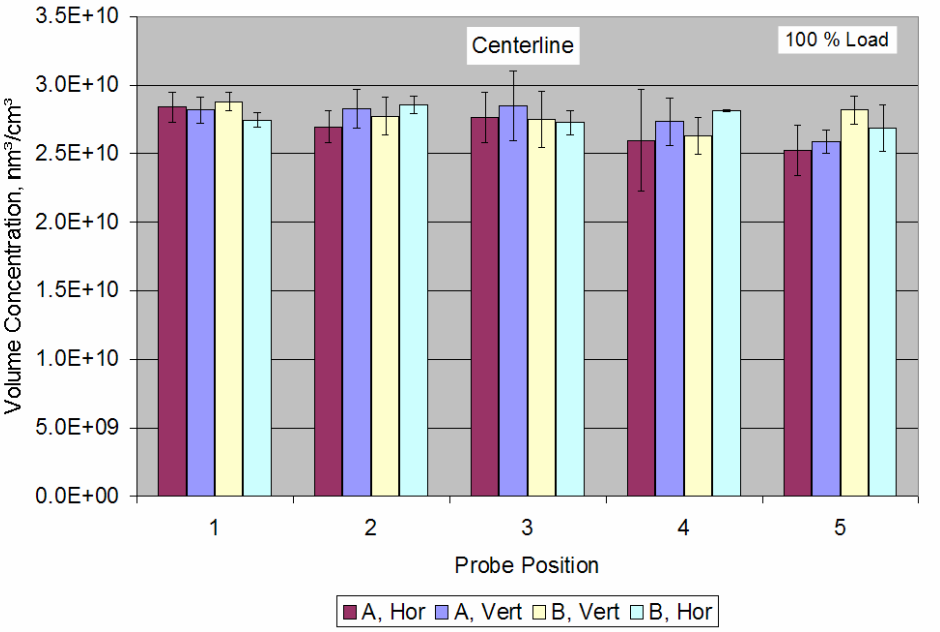


FIGURE 40. PARTICLE VOLUME CONCENTRATION ALONG THE VERTICAL AND HORIZONTAL CROSS SECTION OF AN EXHAUST PIPE AT TWO DIFFERENT LOCATIONS (RATED SPEED, 100 % LOAD)

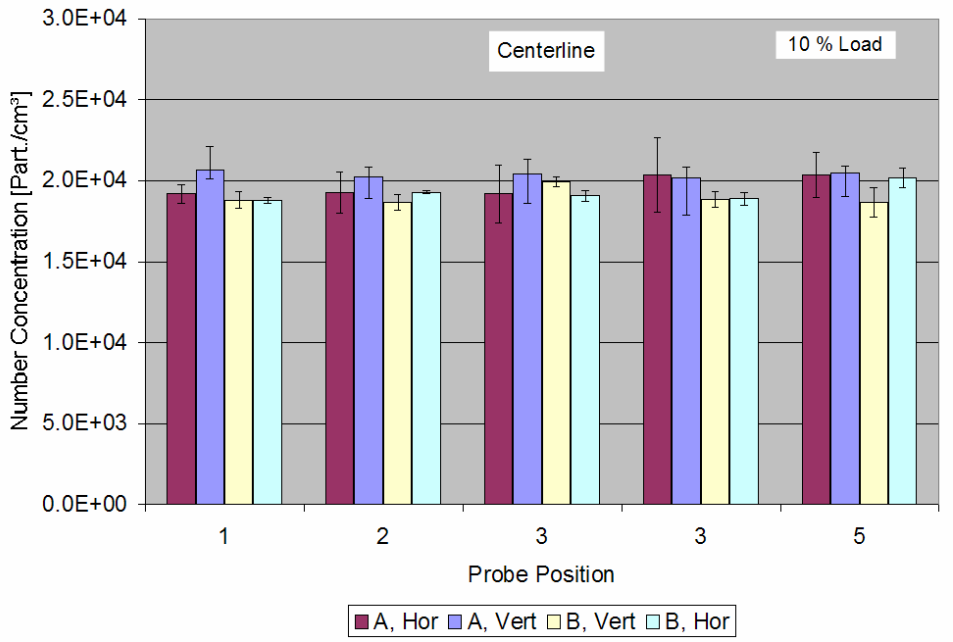


FIGURE 41. PARTICLE NUMBER CONCENTRATION ALONG THE VERTICAL AND HORIZONTAL CROSS SECTION OF AN EXHAUST PIPE AT TWO DIFFERENT LOCATIONS (RATED SPEED, 10 % LOAD)

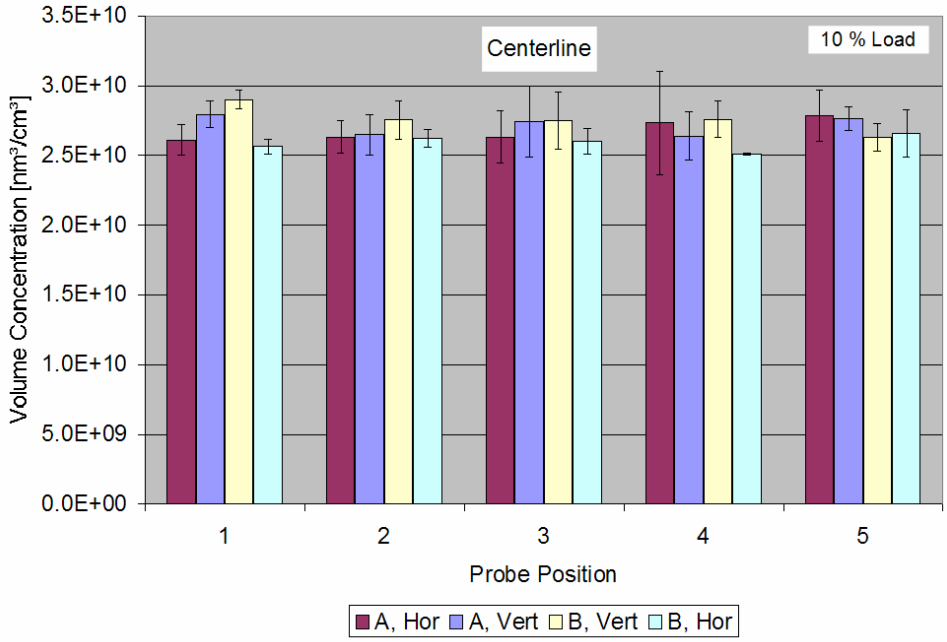


FIGURE 42. PARTICLE VOLUME CONCENTRATION ALONG THE VERTICAL AND HORIZONTAL CROSS SECTION OF AN EXHAUST PIPE AT TWO DIFFERENT LOCATIONS (RATED SPEED, 10 % LOAD)

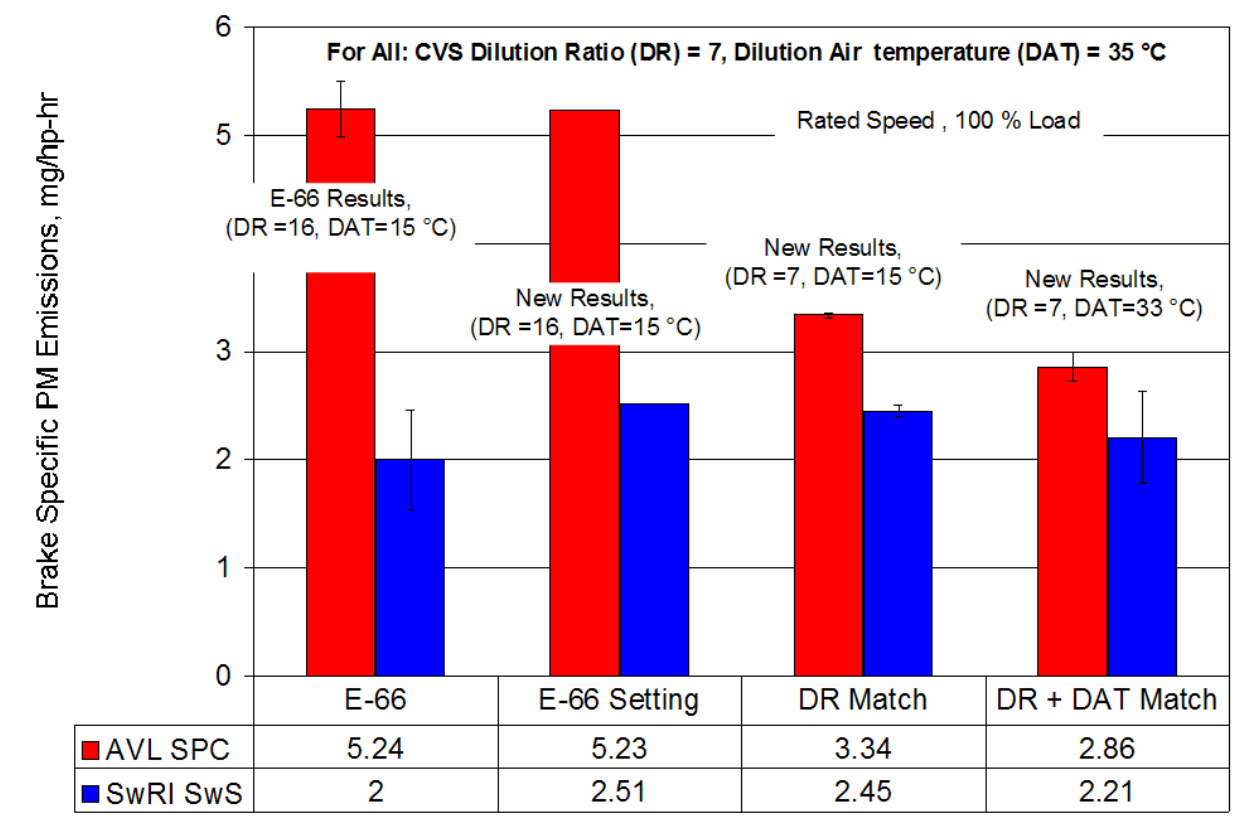


FIGURE 43. COMPARION BETWEEN AVL SPC AND SRI SWS (CVS) AT DIFFERENT DILUTION CONDITIONS

6.0 CONCLUSIONS

Several conclusions can be made from this work:

The response time of all PFSS units was better than 200 milliseconds with excellent proportionality to exhaust flow changes during transient operations. These PFSS units were the BG3, SPC, MDLT, AEI/CUM, and the MPS. The correlation coefficient was at 99 percent or better for the BG3, AEI/CUM, MDLT, and SPC; and better than 97 percent for the MPS. The standard error relative to the average was generally below five percent, except for the MPS where the standard error was about 7 percent for the FTP and 13 percent for the NRTC. It is important to note that the correlation was based on all data points collected, however, CFR Part 1065 allows for the removal of five percent of the data collected for this correlation which would improve the correlation coefficient and standard error reported above for all the PFSS units.

The BG3, SPC, MDLT, and AEI/CUM gave similar PM emission levels when used as secondary dilution systems on the full flow CVS. Their performance was similar to the performance of the short and long secondary dilution systems used by SwRI. The PM emission comparison was performed using an exhaust configuration that included a CRT-DPF without Bypass. The PM emission level was below 10 percent of the 2007 PM standard and comparable to the PM level obtained using a tunnel blank filter without engine operation.

The BG3, SPC, MDLT gave similar PM emission levels to that of the CVS when used on an engine exhaust equipped with a CRT-DPF without Bypass. The AEI/CUM reported PM emissions were 50 to 70 percent lower than those reported by the CVS. But, the MPS reported PM emissions were about three times higher. For the AEI/CUM, it is likely that the 47^{o}C dilution air temperature had resulted in lower PM collection on the filter, compared to the CVS method, which used a secondary dilution air temperature of about 27^{o}C. For the MPS, it was not clear why the reported PM emission level was higher than the one reported using the CVS method.

Different PM emission performance characteristics of the PFSS units were observed when the CRT-DPF with Bypass was used to elevate the PM emissions to 80 percent of the 2007 PM standard. This higher PM emission level is more likely to be observed when 2007 engines are required to meet both 2007 PM and NOx levels without NOx aftertreatment or when using a less efficient DPF. For steady-state engine operation at rated speed, 100 and 10 percent load, the BG3 and MDLT gave a PM emission level that was 4 to 12 percent higher than that given the full flow CVS. The AEI/CUM gave a 10 to 17 percent lower PM. But, the SPC PM emission level was about 2.5 times higher at rated speed, 100 percent load, and 50 percent lower at rated speed, 10 percent load. The MPS was about 30 percent higher at rated speed, 100 percent load, and about 25 percent lower at rated speed, 10 percent load. For the FTP and the NRTC transient cycles, different results were obtained from that observed under steady-state conditions. For the MDLT, the PM emission level was 69 and 30 percent higher than CVS for the NRTC and

the FTP, respectively. For the BG3, the PM emissions level was 33 and 21 percent higher than CVS. For the AEI/CUM, the PM emissions was 29 and 19 percent higher than CVS. For the SPC, however, the PM emissions level was within less than 1 percent from CVS for the NRTC and 12 percent lower for the FTP transient cycle. For the MPS, the PM emissions level was about 25 percent lower than CVS for both the NRTC and the FTP transient cycle.

Using the CRT-DPF with Bypass, the results from the different PFSS units were not consistent. Some systems showed good results at steady-state operation and deviated from CVS during transient operation or vice versa. It is important to note, however, that all PFSS units tested on this program were fundamentally acceptable PFSS units because of their fast response time and good correlation with exhaust flow. There must be other variables related to particle physics that need to be taken into account. For example, additional work with the SPC showed that when the residence time, dilution ratio, and dilution air temperature were matched with that of the CVS, the difference in PM emission results at rated speed, 100 percent load, narrowed significantly. Thus, future work should focus on comparing the PFSS with the CVS under very tightly defined dilution parameters. However, there should be also a recognition that the dilution process is different and they may not agree under all engine operating conditions or with changes in engine technology.

The secondary dilution system residence time affects the amount of PM mass collected on a Teflo filter during PM sampling. Longer residence led to a higher PM collection. For example, the PM emission level increased by a factor of 2.8 from 0.25 mg/hp-hr to 0.7 mg/hp-hr by increasing the residence time from 0.75 to 15 seconds. However, the PM emission level at 0.7 mg/hr-hr remained well below the 2007 PM standard, based on using Teflo filters.

Real time instruments such as the EEPS and DMM-230 showed similar trends to that of the Teflo filter when changing the residence time. They also showed a similar trend to the PM emissions observed in Phase 2 of Project E-66. However, the level of PM increase associated with longer residence time in Phase 2 was about six times higher. For example, at a residence time of about 10 seconds, the PM emissions in Phase 3 were about 0.4 mg/hp-hr relative to about 2.5 mg/hp-hr in Phase 2. The ULSD fuel used in Phase 2 had a factor of 1.8 more sulfur and a factor of 11 more of polynuclear aromatics. It is hypothesized that these fuel properties influenced the degree of change in PM emission in response to residence time. However, more work is needed to investigate the effect of 2007 diesel fuel properties on PM emissions under different residence time and other dilution variables before drawing any conclusions related to fuel effects.

For a CRT-DPF without Bypass, only the real time instruments such as the EEPS and the DMM-230 were able to give a clear distinction between a tunnel blank test and a test conducted with engine operation. Although the emission level based on the real time instruments was near one percent of the 2007 standard, the PM emission level measured by the real time instruments was nearly ten times higher than the result of a tunnel blank run.

Relative to the work with quartz filters, the results were qualitative in nature due to the low level of PM collection on the filter and the possible EC artifact formation during PM analysis using the MEXA 1370 PM:

The AVL SPC showed higher emissions at rated engine power, not only relative to EC, but also relative to OC and sulfate. The observed results particularly relative to the increase in OC and sulfate supports the data obtained when the dilution parameters between the SPC and CVS were matched. The EC results do not support the agreement obtained between the CVS and the SPC as a result of changing the dilution parameters, suggesting a potential EC artifact.

The Sensors MPS seemed to underestimate EC in comparison to all other systems. This indicates that particle losses could be a problem with this system, or the analytical technique used for EC analysis is not accurate due to the very low level of EC collected with the MPS. At any rate, a particle loss experiment will be useful to conduct with the MPS to better understand particle losses in the sample train.

The AEI/CUM that used a 47^{o}C secondary dilution air temperature seemed to minimize the collection of sulfate on the filter. This temperature may play a role in reducing the potential of sulfuric nucleation and growth because the secondary dilution system never sees a temperature below 47^{o}C during particle collection. Hence, by using a 47^{o}C dilution air temperature, one would suppress condensation and minimize the evaporation of condensable material that occurs as a result of using a dilution air temperature that is lower than the filter face temperature or the wall temperature of the sample train. It is suspected that this condensation and evaporation process may not be totally reversible and may have some amount of hysteresis resulting in inadvertently condensed material not going back into the gas phase.

6.1 Summary of Conclusions

This section is derived from the conclusions section to summarize the main conclusion points of Phase 3 of Project E-66.

- PFSS (BG3, SPC, MDLT, AEI and MPS) evaluated in Project E-66 demonstrated their ability to follow a transient test with 200 ms response.
- PFSS (BG3, SPC, MDLT and AEI) yielded similar PM results as the secondary dilution system on a CVS.
- When PM levels were only 10% of the 2007 standard, PFSS (BG3, SPC, and MDLT) yielded PM results equivalent to a CVS, while AEI results were 50-75% lower and MPS results were 3 times as high.
- Real time PM instruments tested during E-66 suggested that collecting particles on filters can result in artifact formation, even for filters less prone to artifacts.
- When PM levels were 80% of the 2007 PM standard, these PFSS units behaved differently and resulted in additional studies that explained some of the noted differences, while other differences need investigation.

- Test conditions that should be controlled if comparisons are made among different labs or different systems within the same lab include residence time, dilution ratio, dilution air temperature, filter temperature, filter material, filter face velocity, artifact formation, fuel composition and dilution system blank measurements.
- Although many investigations were included during E-66, particulate measurement is sufficiently complex that not all issues could be examined and new discoveries are being made in this area, thus interested parties should consult the particulate measurement literature to avail themselves of the latest developments.

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