PM-PEMS Measurement Allowance Determination

Final Report

United States Environmental Protection Agency

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

and

California Air Resources Board

and

Engine Manufacturers Association

Prepared by
Southwest Research Institute
SwRI Project 03.14936.12

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PM- PEMS MEASUREMENT ALLOWANCE DETERMINATION

FINAL REPORT

SwRI® Project 03.14936.12

Prepared for

U.S. Environmental Protection Agency
California Air Resources Board
Engine Manufacturers Association

June 2010

Prepared by:

Imad A. Khalek, Program Manager

Approved by:

Jeff J. White, Director

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

FOREWORD

The PM-PEMS measurement allowance program was performed by the Department of Emissions Research and Development under Mr. Jeff White, Director. Dr. Imad Khalek, Program Manager, was the Principal Investigator and Project Manager, Mr. Thomas Bougher, Research Engineer, was the Project Leader, and Mr. Daniel Preece, Research Assistant, was the laboratory technical assistant. Dr. Robert Mason, Institute Analyst, was the Principal Co-Investigator responsible for statistical analysis, and Ms. Janet Buckingham, Staff Analyst, was the Project Leader/Statistics. Other SwRI Emissions R&D staff with contribution to the project were Mr. Michael Feist, Senior Research Engineer, Mr. Richard Mechler, Senior Research Technologist, Mr. Donald Parker, Senior Technician, Mr. Jose Sosa, Principal Technician, Mr. Keith Echtle, Laboratory Assistant Manager, and Mr. Ernest Krueger, Laboratory Manager. Additional SwRI assistance during Environmental Testing was provided by Rick Pitman, Senior Engineering Technologist, Mr. Mike Negrete, Senior Technician, Mr. David Smith, Staff Technician, Mr. Herbert Walker, Senior Engineering Technologist, and Mr. Eric Dornes, Principal Engineer.

This work was performed under Environmental Protection Agency (EPA) Work Assignments 2-7, 3-7, 4-7, and 2-12, under SwRI Project Numbers 12859.07, 13749.07, 14658.07, and 14936.12, respectively. The original EPA Work Assignment Manager was Mr. Matthew Spears. After March of 2009, the EPA Work Assignment Manager became Mr. Christopher Laroo. This work started in June of 2007 and will end by June 26, 2010. Testing started in June of 2008 and ended in September of 2009.

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Dr. Andrew Reading, Dr. David Booker, Dr. Atul Shah, Mr. Carl Ensfield, Mr. Timothy Bottomley, and Mr. Kevin Bouma, from Sensors

A measurement allowance steering committee (SC) composed of EMA, EPA, CARB, and PM-PEMS manufacturer members met on a regular basis throughout the entire project to discuss the progress made and make recommendations. The SC has contributed significantly to this project. SwRI acknowledges the following SC members for their active participation:

Mr. Rey Agama, Caterpillar
Dr. Michael Akard, Horiba
Dr. Dipak Bishnu, CARB
Dr. David Booker, Sensors
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Mr. John Kegebein, John Deere
Mr. Thomas Kramer, Navistar
Mr. Christopher Laroo, EPA
Mr. Hector Maldonado, CARB
Mr. William Martin, Cummins
Dr. Shirish Shimpi, Cummins
Mr. William Silvis, AVL
Ms. Carol Smith, Isuzu
Mr. Matthew Spears, EPA
Mr. Steven Trevitz, Volvo Powertrain
Dr. Qiang Wei, Horiba

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ACRONYMS

ACES	Advanced Collaborative Emissions Study
BCI	Bulk Current Injection
BS	Brake-Specific
BSFC	Brake-Specific Fuel Consumption
BSPM	Brake-specific Particulate Matter
CARB	California Air Resources Board
CE-CERT	Bourns College of Engineering Center for Environmental Research & Technology
CF	Correction Factor
CFR	Code of Federal Regulations
COV	Coefficient of Variation
CVS	Constant Volume Sampling
DCS	Diffusion Charge Sensor
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DR	Dilution Ratio
EAD	Electrical Aerosol Detector (TSI, Inc.)
EATS	Exhaust after-treatment system
ECM	Engine Control Module
EE	Electrical Enclosure
EEPS	Engine Exhaust Particle Sizer (TSI, Inc.)
EFM	Electronic Flow Meter
EGR	Exhaust Gas Recirculation
EMA	Engine Manufacturers Association
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
ESD	Electrostatic Discharge
HDIUT	Heavy-Duty In-Use Testing
HE	Heated Enclosure
HEPA	High Efficiency Particulate Air
LFE	Laminar Flow Element
MA	Measurement Allowance
MAD	Median Absolute Deviation
ME	Mechanical Enclosure
MEL	Mobile Emissions Laboratory
MSS	Micro Soot Sensor (AVL)
NMHC	Non-Methane Hydrocarbons
NO_X	The Oxides of Nitrogen ($NO + NO_2$)\
NTE	Not-to-exceed
OBS	On-board systems
OC/EC	Organic Carbon/Elemental Carbon
PEMS	Portable Emission Measurement System
PM	Particulate Matter
PPMD	Portable Particulate Measurement Device (Sensors, Inc.)

ACRONYMS (CONT'D)

PSD	Power Spectral Density
QCM	Quartz Crystal Microbalance
RFI	Radio Frequency Interference
RMS	Root Mean Square
SAE	Society of Automotive Engineers
SS	Steady State
SwRI	Southwest Research Institute
TPA	Tail Pipe Adaptor
TRPM	Transient Response Particulate Matter
ULSD	Ultra-Low Sulfur Diesel
VGT	Variable Geometry Turbocharger

EXECUTIVE SUMMARY

The United States Environmental Protection Agency (EPA), Engine Manufacturers Association (EMA) and California Air Resources Board (CARB) agreed to pursue an experimental data driven program to establish a measurement allowance (MA) for in-use particulate matter (PM) testing using PM portable emissions measurement systems (PM-PEMS). The MA is a brake-specific PM emissions error associated with using in-use PM-PEMS equipment compared to the laboratory reference filter method. If the MA error is a positive value above zero, after the EPA rounding method, as described in the Code of Federal Title 40, Part 1065 [1], it will increase the EPA in-use not-to-exceed (NTE) standard by the rounded value. If the error is negative or zero, it will not contribute to any changes to the in-use standard.

The measurement allowance steering committee (SC) accepted the following PM-PEMS to be part of the MA program:

- Sensors Portable Particulate Measuring Device (PPMD). This is a PM-PEMS that uses proportional dilution and a series of 8 quartz crystal microbalances to measure total (solid plus volatile) PM. The total PM is measured as a single flow-weighted value for an NTE event.

- Horiba Transient Particulate Matter (TRPM). This is a PM-PEMS that uses proportional dilution, a real time electrical aerosol detector, and an integrated filter sample to report total PM. The total PM is measured as a single flow-weighted value for a NTE event. This instrument can report real time total PM, but was not used as such on this program.

- AVL micro-soot sensor (MSS). This is an instrument that uses constant dilution and a photo acoustic detector to measure soot or the elemental carbon portion of PM. Soot is measured in real time during an NTE event.

The SC agreed that only the PPMD by Sensors and TRPM by Horiba would be used for the official determination and validation of the measurement allowance generated because both are designated as complete PEMS and both measure total (solid plus volatile) PM, as required by US EPA to be valid PM-PEMS. The SC also agreed that only the PM-PEMS that produces the lowest positive 95th percentile measurement allowance, based on Sensors or Horiba only, would be chosen for in-use validation by CE-CERT due to funding limitation. The third instrument, the MSS by AVL, was not a complete PM-PEMS and was always used in conjunction with the PPMD on this program, based on an agreement reached between Sensors and AVL. The SC agreed that the MSS would not be considered as an option for official measurement allowance determination, unless both the PPMD and the TRPM failed validation.

The PM-PEMS-MA project included four main elements:

- Laboratory steady-state (SS) and transient engine NTE testing using PM-PEMS and CVS filter measurement during SS testing only. The SS testing was used to capture bias, compared to the CVS, and the transient was used to capture precision only since there is no reference method to measure PM during a short NTE event. A 2007 heavy-duty diesel Mack MP7, from Volvo Powertrain, was used to conduct the engine experiments. The engine was configured with a bypass around the diesel particle filter (DPF) to provide PM concentration levels similar to those expected at the NTE threshold limits between 0.02 g/hp-hr and 0.03 g/hp-hr.

- Environmental testing such as the effect of shock and vibration, pressure, temperature and relative humidity, and electric noise on PM-PEMS precision.

- Monte Carlo simulation to determine a brake-specific measurement allowance value using error surfaces generated from the PM-PEMS laboratory and environmental testing, and from error surfaces generated during the gaseous PEMS program

    - A total of 141 Reference NTEs were provided by EMA as an input to the model for calculating ideal brake specific emissions, prior to the Monte Carlo simulation

- Model validation using data generated from in-use PM-PEMS testing by CE-CERT.

Three methods are used to determine in-use NTE brake-specific PM emissions:

- Method 1 f($\overline{PM}$, torque$_i$, speed$_i$, exhaust-flow$_i$)
- Method 2 f($\overline{PM}$, torque$_i$, speed$_i$, exhaust- flow$_i$, G-flow$_i$, fuel$_{ECMi}$)
- Method 3 f(PM$_i$, torque$_i$, speed$_i$, and fuel$_{ECMi}$, G-flow$_i$)

Where $\overline{PM}$ is a flow-weighted PM measurement, i is instantaneous, ECM is engine control module, and G-flow is gas-based fuel flow. All methods require ECM broadcasted torque and speed. In addition, Method 1 requires measured exhaust flow but not fuel flow; Method 2 requires measured exhaust flow, ECM broadcasted fuel flow, and G-flow; Method 3 is similar to Method 2, but it does not require measured exhaust flow. Besides real time PM measurement, all methods can use a single flow-weighted PM measurement for an NTE event, except Method 3, where real time PM measurement is required. Thus, Method 1 and Method 2 were applied to all three PM-PEMS, but Method 3 was only applied to the AVL MSS.

Compared to the Horiba TRPM, the Sensors PPMD, as shown in Table ES-1, produced the lowest positive 95th percentile measurement allowance of 0.00605 g/hp-hr for an NTE threshold level of 0.02 g/hp-hr, using calculation Method 2. The Horiba TRPM produced a measurement allowance value of 0.0100 g/hp-hr. Thus, the PPMD was selected by the SC for in-use testing by CE-CERT for Monte Carlo model validation. Although not accepted as a PM-PEMS, the AVL MSS produced the lowest measurement allowance of essentially zero. The SC agreed to include the AVL MSS during in-use validation because it was used in conjunction with the PPMD during the laboratory portion of the testing.

TABLE ES-1. MEASRUEMENT ALLOWANCE BASED ON 0.02 G/HP-HR THRESHOLD

Measurement Errors at NTE Threshold, g/hp-hr			
PEMS	**Method 1**	**Method 2**	**Method 3**
AVL	0.0001	-0.0005	-0.0005
Horiba	0.0109	0.0100	n/a
Sensors	0.0069	0.0061	n/a

Figures ES-1 and ES-2 show examples of validation plots for Sensors PPMD using Method 1 and AVL MSS using Method 3. The dots on each of the two figures represent the in-use delta BSPM between PEMS and CE-CERT 47 mm filter measurements on the y-axis versus CE-CERT BSPM on the x-axis (Ideal BSPM determined by the filter measurement). Similarly, the lines represents the 5th and 95th percentile errors produced by Monte-Carlo simulation based on laboratory testing versus a reference NTE BSPM value on the x-axis (Ideal BSPM using 47 mm measurements). To pass model validation, ≤ 10% of the in-use NTE delta brake-specific PM (BSPM) between the PEMS and the CE-CERT (dots on Figures ES1 and ES2) must reside outside the 95th percentile and 5th percentile lines.

The Sensors PPMD failed validation using Method 1 and Method 2, as shown in Table ES-2. For Method 1, 32 percent of the data were below the 5th percentile, and for Method 2, 34 percent of the data were below the 5th percentile. The failure was mainly due to negative bias. The exact cause for negative bias is unknown, and funding limitation did not permit further investigations to resolve this issue under the scope of the MA program.

The AVL MSS passed validation using Method 3, as shown in Table ES-3, where 9.89 percent of the data were outside the 5th and 95th percentiles, with the majority of the failed points being above the 95th percentile. Method 2 failed validation by one percentage point, and Method 1 failed validation by having 18 percent of the data outside the 5th and 95th percentiles, with the majority of failed points being above the 95th percentile.

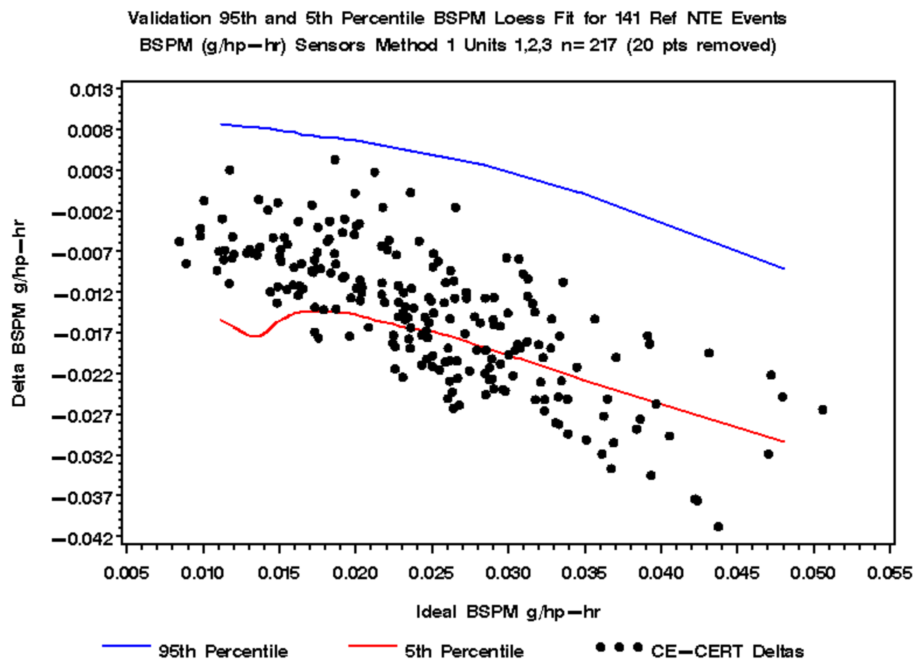


FIGURE ES-1. IN-USE VALIDATION PLOT FOR SENSORS PPMD USING METHOD 1. (Y AXIS IS THE DIFFERENCE BETWEEN PEMS AND IDEAL BSPM. IDEAL BSPM IS THE LABORATORY CVS BSPM FOR THE 5TH AND 95TH AND THE CE-CERT BSPM FOR THE DOTS)

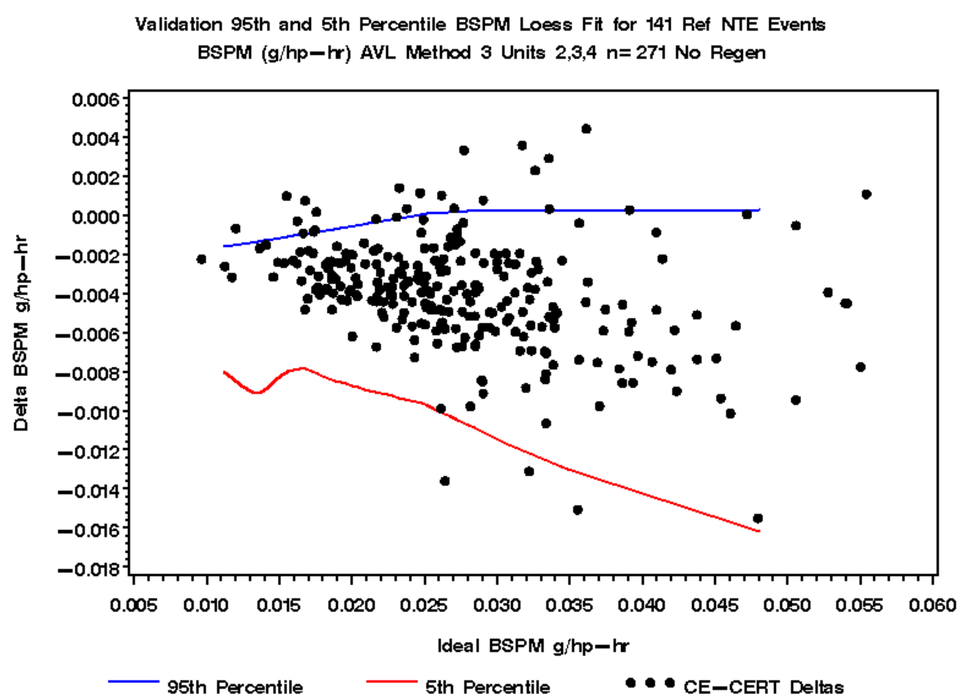


FIGURE ES-2. IN-USE VALIDATION PLOT FOR AVL MSS USING METHOD 3. (Y AXIS IS THE DIFFERENCE BETWEEN PEMS AND IDEAL BSPM. IDEAL BSPM IS THE LABORATORY CVS BSPM FOR THE 5TH AND 95TH AND THE CE-CERT BSPM FOR THE DOTS)

TABLE ES-2. SENSORS PPMD VALIDATION RESULTS

	Method 1	Method 2
Total No. CE-CERT Points	217	217
No. CE-CERT Points within Ideal BSPM Range	210	210
No. CE-CERT Points above 95th Percentile	0	1
No. CE-CERT Points below 5th Percentile	68	70
No. CE-CERT Points between 5th and 95th Percentiles	142	139
% CE-CERT points that did not validate	32.38	33.81

TABLE ES-3. AVL MSS VALIDATION RESULTS

	Method 1	Method 2	Method 3
Total No. CE-CERT Points	271	271	271
No. CE-CERT Points within Ideal BSPM Range	263	263	263
No. CE-CERT Points above 95th Percentile	47	28	23
No. CE-CERT Points below 5th Percentile	2	2	3
No. CE-CERT Points between 5th and 95th Percentiles	222	233	237
% CE-CERT points that did not validate	18.08	11.41	9.89

Due to the lack of additional funding, the measurement allowance program was concluded by the SC without being able to solve the lack of validations issue with the Sensors PPMD, or perform additional CE-CERT testing with the Horiba TRPM to determine if it validates the model. The AVL MSS passed the validation criteria using Method 3. However, the MSS as used in this program is not accepted as a PM-PEMS by EPA, and the measurement allowance generated based on the performance of this instrument is not an official part of the measurement allowance.

The final official measurement allowance accepted by the SC was based on the Sensors PPMD. Further investigation of why the PPMD did not validate the model is being investigated outside the MA program, and the details are expected to be part of the CE-CERT Final Report on PM-PEMS In-Use Validation Testing.

1.0 INTRODUCTION

The U.S. EPA, EMA, and CARB agreed to pursue an experimental data driven program to determine PEMS bias and precision measurement errors expected in in-use NTE testing and compliance before enforcement. The idea is to combine these errors into a measurement allowance which will be used with the EPA in-use regulatory standard. The combination, in-use standard plus measurement allowance, will allow for a larger threshold due to instrument and measurement uncertainties that the engine manufacturers must comply with. The gaseous PEMS measurement allowance program was completed by SwRI in April of 2007, and this work focuses on the PM-PEMS measurement allowance, as set forth in Test Plan and meeting minutes, shown in Appendices A and B, respectively.

To determine all bias and precision errors associated with in-use PM-PEMS measurement would take a very extensive set of experimental data and engines to cover all engine steady-state and transient NTE operations, as well as, different environmental conditions and configurations that may influence the measurement. Instead of focusing on a wide matrix of experimental data, the SC approach was to:

a) Perform repeats on a series of six laboratory NTE steady-state laboratory tests using the CVS PM filter method and the PM-PEMS, and establish a bias error surface for each of the PEMS tested.
b) Perform repeats on a series of laboratory NTE transient cycles containing thirty 32 seconds NTE events, and use the PM-PEMS measurement to produce precision error surface for each of the PEMS tested.
c) Perform a series of environmental tests that includes electromagnetic and radio frequency interferences, shock and vibration, pressure, and temperature and humidity, and produce an error surface, if any, for each PEMS associated with each parameter.
d) Use torque and fuel flow error surfaces provided by the engine manufacturers.
e) Use other error surfaces established during the gaseous measurement allowance program.
f) Use Monte-Carlo simulation based on a set of 141 Ideal brake-specific PM (BSPM) reference NTE events to predict the error distribution at each reference NTE.
g) Use the 95th percentile and 5th percentile of the error distribution at each Ideal BSPM reference NTE level as the upper and low boundary of the deltas between PM-PEMS BSPM and Ideal BSPM..
h) Perform actual in-use testing with the PM-PEMS using the CE-CERT trailer to determine whether or not the data generated in-use validates the model.

A total of nine PM-PEMS, three from each manufacturer, were used on this program. The PM-PEMS, shown in Table 1, included the Sensors PPMD, Horiba TRPM, and AVL MSS. Each set of three PM-PEMS, one PM-PEMS from each manufacturer, was tested simultaneously in parallel using a series of steady-state and transient NTE engine experiments. After the completion of steady-state testing and transient testing, one PM-PEMS from each manufacturer was used on a series of environmental test conditions that included electromagnetic and radio frequency interferences, shock and vibration, atmospheric pressure, and temperature and humidity.

TABLE 1. PM-PEMS USED ALONG WITH SERIAL NUMBER

PEMS Name	PEMS Serial Number
Horiba 1	10107-01
Horiba 2	10107-02
Horiba 3	10107-03
Sensors 1	E08-PD03
Sensors 2	G08-PD02
Sensors 3	A08-PD03
AVL 1	346
AVL 2	472
AVL 3	273

To validate the model, a series of in-use tests with the PM-PEMS was performed by CE-CERT using the CE-CERT emissions trailer. Details about this testing will be provided in a separate report by CE-CERT on PM-PEMS In-Use Validation Testing.

This report describes:

- Model approach used to perform the modeling portion of this work.
- Engine experiments with the PM-PEMS including steady-state and transient NTE PM results
- Environmental setup and PM results
- Measurement allowance produced by the model for each of the three PM-PEMS provided by each manufacturer
- Model validation using the PM-PEMS selected for in-use testing

2.0 MODELING APPROACH

2.1 Purpose of Model

This program was designed to generate BSPM measurement allowances based on rigorous statistical methods applied to a large body of data. At the same time, it was desirable to exclude outlier data caused by extreme measurement errors which were not considered representative of normal in-use operations. A direct approach could have been to test PEMS against some kind of mobile laboratory reference (such as the CE-CERT Mobile Emission Laboratory) on a large number of vehicles, and quantify errors directly. However, such an approach would have been expensive in terms of both time and funding.

Given these factors, the Steering Committee ultimately elected to use a simulation approach in order to generate the BSPM measurement allowances, similar to what was done in the gaseous in-use emissions testing program [2]. In this approach, the Steering Committee defined all of the expected sources of PEMS measurement errors based on existing in-use testing expertise and understanding of how the PEMS functioned. Priority was given to the Horiba's and Sensors' PEMS in the design of experiments. Each of these errors was quantified using a series of controlled laboratory experiments, each designed to isolate errors related to a single error source. The results of each experiment would essentially be an empirical model of a given source of measurement error. In this report, these error models are referred to as error surfaces. It is important to note that each of these error surfaces represents an incremental error of PEMS measurement, as compared to an associated laboratory reference measurement.

2.2 Model Improvement

Several improvements to the execution of the Monte Carlo simulation model were implemented to improve the efficiency and post-processing of the simulation runs. Eight macros were written to perform various tasks and are summarized in the section below.

<u>Macro 1:</u> Controls batch processing and allows the ability to run several simulations back-to-back (batch mode). Reads each reference NTE event data, number of trials, and the number of reference NTE events in the batch run. Calls other macros.

<u>Macro 2:</u> Clears and deletes extra rows in error model (see Appendix C for a detailed description). Calculates ideal PM emissions for each calculation method.

<u>Macro 3:</u> Checks error surfaces turned 'off' in simulation run and clears unused error surface charts and Excel tabs for calculation speedup (see Appendix D) for a detailed description).

<u>Macro 4:</u> Controls Crystal Ball run preferences, runs Crystal Ball simulation for the given NTE Event, and controls Crystal Ball creation of Report and Extract data files. No longer stores each trial i_c value (40,000 – 65,000 values). Reduced the number of sensitivity charts created. Only stores BS emissions in g/hp-hr units. This reduced EXTRACT and REPORT files from 133 MB to 17 MB per NTE event (≈ 87% reduction).

Macro 5: Reads EXTRACT file, controls calculation of 5th, 50th and 95th percentiles from full model and calls Macro 6.

Macro 6: Computes 5th, 50th and 95th percentile delta BS emissions and confidence limits from order statistics from the Full model. These values are used in the measurement allowance plots and to check for convergence.

Macro 7: Reads Extract file Validation data, computes 5th, 50th and 95th percentiles for the Validation model (calls Macro 6).

Macro 8: Reads REPORT file, selects and formats sensitivity data for Assumption sensitivities greater than 5 percent or less than -5 percent contribution to variance and stores in sensitivity file. Creates sensitivity file with "important" error surfaces.

The development of the macros resulted in substantial improvements in the simulation run-time and post-processing of the extract files. The estimated reduction in model simulation run-time and post processing was approximately 80 to 85 percent of the time used in the gaseous PEMS program. The developed macros eliminated the need to manually post-process the files as had been done in the gaseous PEMS program. The batch processing allowed up to 20 reference NTE events to be simulated in a single Excel run. The size of the EXTRACT and REPORT files was greatly reduced by only storing needed variables and delta PM emissions.

2.3 Monte Carlo Simulation Approach

The error surfaces representing incremental errors of PEMS measurement were programmed into a computer model which employed Monte Carlo random sampling methods to simulate the combined effects of all of these sources of error on the final measured brake-specific value. An ideal reference NTE data set (see Section 2.5) for a given test event was run through the Model, and all the various errors were applied to that data set in a randomly chosen manner. Brake-specific PM emission values were then calculated for both the ideal and error-applied data sets, which were compared to yield a final measurement error (see Appendix C and D). The process was repeated thousands of times, with many different ideal data sets, to generate a large, robust data set which was evaluated to determine a final set of combined measurement errors. These final errors, referred to in this report as deltas, were generated for the PM pollutant for each calculation method and three PEMS model units from each of the three manufacturers, for a final set of seven deltas; Methods 1-3 for the AVL PEMS unit, Methods 1-2 for the Horiba PEMS unit and Methods 1-2 for the Sensors PEMS unit. A complete description of the Monte Carlo methodology and of the model is given in Section 2.5 of this report.

2.4 Calculation Methods

Calculations must be performed on the recorded data to determine brake-specific PM emission values in accordance with methods outlined in 40 CFR Part 1065 Subparts G and J. The symbolic notation given in the formulas shown later in this section is fully described in 40 CFR Part 1065 Subpart K [1].

40 CFR Part 1065 allows for the use of any of three different calculation methods in order to determine brake-specific emission values from in-use test data. The basic calculation of brake-specific emissions requires three main inputs as follows:

$$BS\ Emissions = \frac{Mass}{Work} = \frac{Concentration\ x\ Flowrate}{Power}$$

The three calculation methods vary somewhat in the means used to determine either the Flow component or the Work component of this calculation. Each of the three methods is summarized below. Because each method relies on different inputs, it is possible that each method of calculation will react differently to various measurement errors. Therefore, measurement allowances must be examined independently for each method. However, according to the Test Plan, see Appendix A and B, methodology, only one of the three calculation methods would be selected to generate the final measurement allowances. The selection methodology is outlined later in this introduction under the Measurement Allowance Generation section.

2.4.1 Calculation Method 1 – "Exhaust Flow-Torque-Speed" Method

Calculation Method 1 is analogous to the method used by most dynamometer laboratories, and relies on direct input of both exhaust flow and torque. In the case of exhaust flow, this is the flow rate measured by the same form of exhaust flow meter. The Sensors and AVL PEMS relied on the Sensors exhaust flow meter (EFM) while the Horiba PEMS had a tail pipe adapter (TPA) it employed for exhaust flow measurement. Work is not measured directly, but is instead calculated using ECM broadcast engine speed and ECM broadcast engine torque. While engine speed is directly measured by the engine ECM, ECM broadcast torque is an estimate based on a variety of other parameters; torque cannot be directly verified during in-use testing. A simplified formula for this method is:

$$Method\ 1 = \frac{\sum mass}{\sum work}$$

The more complete formula used for Method 1 is as follows:

For all PM PEMS:

$\overline{m_{PM}}$ is a flow weighted particulate matter exhaust concentration in g/mol

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i(rpm)*T_i(N\cdot m)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

Where for AVL:

$\overline{m_{PM}}$ is computed numerically as follows,

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\sum_{i=1}^{N}\left[mPM_i\left(\frac{g}{mol}\right)*\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}$$

It should be noted that calculation Method 1 is directly dependent on the accuracy of both the exhaust flow meter and the torque estimation, as well as on the measurement of PM concentration.

2.4.2 Calculation Method 2 – "Exhaust and Fuel Flow-Torque-Speed" Method

This calculation is designated solely for in-use testing, and is designed to minimize the effect of errors related to the accuracy of the exhaust flow measurement. The Method 2 calculation adjusts the exhaust flow measurement by a ratio of the CO_2-based fuel flow to the ECM reported fuel flow. This means that although the flow meter must be linear, it does not necessarily have to be accurate. In addition, Method 2 depends on the ECM broadcast torque and speed, and on the ratio of fuel flow calculated from the carbon balance using gaseous measurement over the fuel flow broadcast by the ECM. A simplified version of this method can be expressed as:

$$Method\ 2=\frac{\sum mass}{\sum\left[\frac{CO_2\ fuel}{ECM\ fuel}\times Work\right]}$$

The more complete formula for Method 2 using PM as an example is:

For all PM PEMS:

$\overline{m}_{PM}$ is a flow weighted particulate matter exhaust concentration in g/mol

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\frac{M_C}{w_{fuel}}*\sum_{i=1}^{N}\left[\frac{\dot{n}_i\left(\frac{mol}{s}\right)*\left[xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}\right]*\Delta t}{\left[\frac{\dot{m}_{fueli}\left(\frac{g}{s}\right)}{\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159}{60*1000*3600}}\right]}\right]}$$

Where for AVL:

$\overline{m}_{PM}$ is computed numerically as follows,

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\sum_{i=1}^{N}\left[mPM_i\left(\frac{g}{mol}\right)*\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}$$

It should be noted that, as mentioned earlier, Method 2 is not subject to accuracy errors for the exhaust flow measurement, although that measurement must still be linear for the method to function properly.

2.4.3 Calculation Method 3 – "Fuel Flow-Torque-Speed" Method

Method 3 does not use direct measurement of exhaust flow, but relies on a carbon balance and ECM broadcast fuel rate to determine mass. The work term for Method 3 is determined identically to the work term for Method 1; using the ECM broadcast values for engine speed and torque to calculate work. Method 3 entirely circumvents the use of an exhaust flow meter, but for the HDIUT program, EPA must approve the use of Method 1 for a given test and manufacturer. A simplified version of Method 1 may be expressed as:

$$Method\ 3=\frac{\sum\left[mass\ \times\ \frac{ECM\ fuel}{CO_2\ fuel}\right]}{\sum Work}$$

The more complete formula for Method 3 is:

For AVL Only:

$$e_{PM}\left(g/kW\cdot hr\right)=$$

$$\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

Where:

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\left(mPM_i\left(g/mol\right)\right)*\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}{\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}$$

It should be noted that Method 3 is not subject to exhaust flow measurement accuracy errors, but also that this method is wholly dependent on ECM broadcast values for both mass and work determination.

2.5 Reference NTE Events

The reference data set to which all the simulated errors were applied represented engine operations over a wide range of laboratory NTE events. Parameters in the reference data set were scaled in order to exercise the model through a more appropriate range of parameters (i.e. concentrations, flows, ambient conditions, etc.). In this scaling process, care was taken to maintain the dynamic characteristics of the reference data set.

The Monte Carlo simulation model was run on a set of 141 reference NTE events that were used during the gaseous MA program [2]. Only the events that have different speed and torque combinations were used; five engine manufacturers provided a total of 97 events; 10 reference NTE events came from each of the three engines tested in the lab during the gaseous MA transient testing; and 14 events came from the pre-pilot CE-CERT data. Because no PM data exist for these reference events, the PM concentration used to calculate the Reference NTE PM emissions was developed by SwRI based on the Volvo engine used in this study. A simple model was developed to predict the PM concentration based on speed and torque using 80 different steady-state PM concentrations that were measured with the MSS using the desired exhaust bypass configuration. Additional adjustment to the model using the rate of change in torque was added to better predict short NTE transient events. The model was further adjusted to produce a brake-specific emissions distribution for the reference NTE events centered around 0.02 g/hp-hr, as shown in Figure 1.

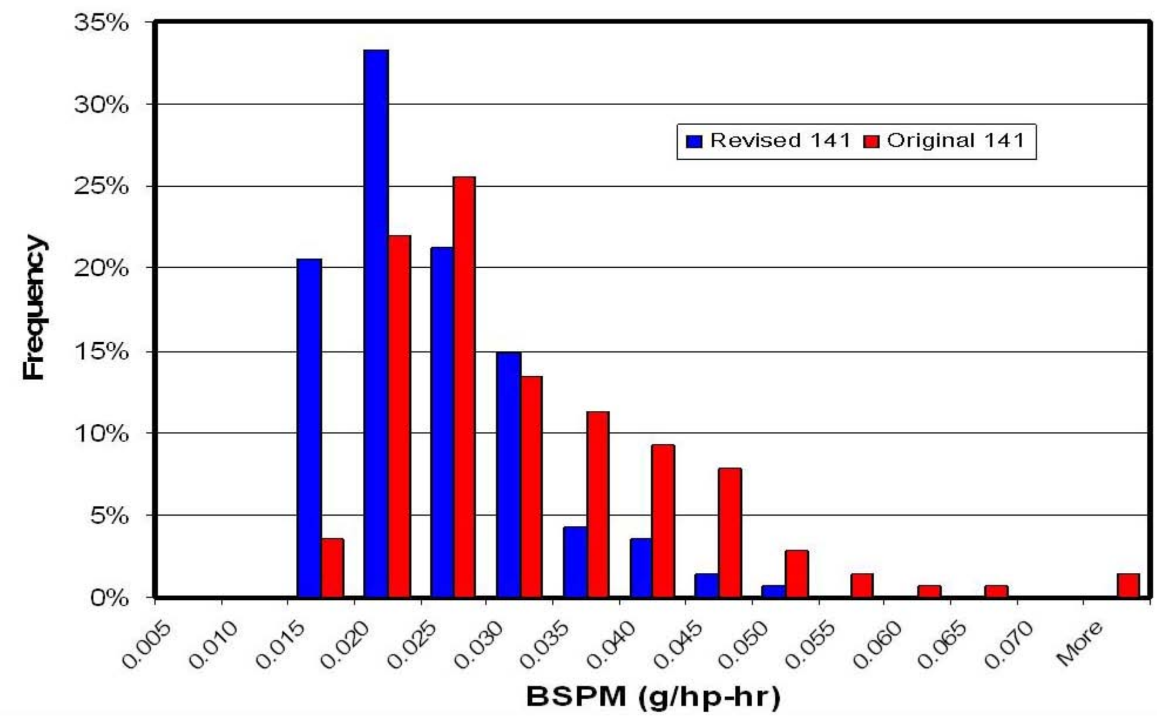


FIGURE 1. METHOD 1 IDEAL BSPM VALUES FOR REFERENCE NTE EVENTS

NTE brake-specific emissions results were calculated for PM using each of the three agreed-upon NTE calculation methods. The three different BS emissions calculation methods referred to in this test plan are:

1. Method No.1: Exhaust Flow-Torque-Speed Method
2. Method No. 2: Exhaust and Fuel Flow-Torque-Speed Method
3. Method No. 3: Fuel Flow-Torque-Speed Method

Table 2 lists the number of NTE events obtained from each data source and the BSPM emissions calculated using Method 1. These emissions have been computed with no error values added to the input parameters. For this report, emissions with no errors added will be labeled the “ideal” emissions. In contrast, the emissions with errors added through the Monte Carlo simulation will be labeled emissions “with errors.”

TABLE 2. REFERENCE NTE EVENTS AND IDEAL BSPM EMISSIONS

Source	Number of NTE Events	BSPM Min	BSPM max
International	19	0.01146	0.03069
DDC	18	0.01303	0.03463
Caterpillar	20	0.01097	0.01789
Cummins	20	0.01561	0.03253
Volvo	20	0.01541	0.02701
Engine No. 1	10	0.01215	0.04066
Engine No. 2	10	0.01675	0.04872
Engine No. 3	10	0.01099	0.03669

When the ideal brake-specific emission values were calculated for the various reference NTE events, it was noted that these ideal emission values were frequently different from one calculation method to another. While it was recognized that this was a realistic outcome, the Steering Committee felt that these discrepancies might introduce an unintended bias into the results of the Monte Carlo simulation. Therefore, the Steering Committee directed SwRI to adjust the NTE reference event data in order to align the brake-specific emission levels from all the calculation methods.

The Method 1 result was not changed, therefore torque, speed, and exhaust flow remained unchanged as well. The CO_2 concentration was adjusted to make the Method 2 result equal to the one from Method 1. This was done by using a single multiplier on all CO_2 values for the NTE event in question. Lastly the fuel rate values and alignments were adjusted to bring Method 3 in line with Method 1 and 2.

The distribution of the ideal BSPM emissions data for the 141 reference NTE events was presented to the Steering Committee. It was noted that very few reference NTE events were at or below the BSPM threshold (0.02 g/hp-hr). Thus, the reference NTE events were adjusted to produce more events with ideal BSPM values below 0.02 g/hp-hr. The original and revised ideal BSPM distributions are depicted in Figure 1. Note that the BSPM emission data has values spread above and below the corresponding NTE threshold.

Table 3 provides a summary of some descriptive statistics for the reference NTE data set for BSPM emissions.

TABLE 3. DESCRIPTIVE STATISTICS FOR BSPM EMISSIONS FOR 141 REFERENCE NTE EVENTS

Descriptive Statistic	BSPM g/hp-hr
Minimum	0.010974
Maximum	0.048717
Mean	0.020753
Median	0.019101
Standard Deviation	0.006932

The parameter data provided in each reference NTE event was on a second-by-second basis with a minimum of 30 seconds and a maximum of 300 seconds. The input parameters required for the BSPM emissions calculation methods and the Monte Carlo simulation are listed in Table 4. An Excel file with a specific input format structure was used to standardize the format of the input files. Since the total hydrocarbons (THC) was selected as an input parameter, NMHC was computed as THC*0.98.

TABLE 4. INPUT PARAMETERS FOR REFERENCE NTE EVENTS

Variable Number	Input Variable	Units	Description
1	NTE Event Number	integer	All reference NTE events must be identified by an NTE number (e.g., 001).
2	NTE Source	alphanumeric	The source of the NTE event is the company, organization and/or lab that created the event data.
3	Engine Make	alphanumeric	Engine Make
4	Engine Model	alphanumeric	Engine Model
5	Engine Displacement	L	Engine Displacement (L)
6	Date	mm/dd/yyyy	The day the NTE event data was created (mm/dd/yyyy).
7	Time Stamp	hh:mm:ss.s	Time in seconds. Each reference NTE must contain second-by-second data only.
8	Wet CO2	%	CO2 (%)
9	Wet CO	%	CO (%)
10	Wet kNO	ppm	NO (ppm) with intake air-humidity correction
11	Wet kNO2	ppm	NO2 (ppm) with intake air-humidity correction
12	Wet THC	ppm	THC (ppm)
13	Exhaust Flow Rate	scfm	Exhaust flow rate (scfm)
14	Flowmeter Diameter	3, 4, or 5 (inches)	To compute the % of PEMS flowmeter maximum flowrate we will need to know what size flowmeter was used for each NTE event.
			Enter either 3, 4, or 5 to represent the following flowmeters and maximum flow rates:
			3 = 3 inch EFM with maximum flow rate = 600 scfm
			4 = 4 inch EFM with maximum flow rate = 1100 scfm
			5 = 5 inch EFM with maximum flow rate = 1700 scfm
15	Speed	rpm	Engine speed (rpm)
16	Low Speed, nlo	rpm	To compute the % of normalized speed we will need nlo and nhi for the engine computed as follows: nlo (rpm) = lowest speed below max power at which 50% max power occurs
17	High Speed, nhi	rpm	nhi (rpm) = highest speed above max power at which 70% max power occurs
18	Fuel Rate	L/sec	Fuel rate (L/sec)
19	Max Fuel Rate	L/sec	To compute the % of maximum fuel rate we will need the max fuel rate of the engine for each NTE event.
			Max fuel rate (L/sec)
20	Derived Torque	N·m	Torque (N·m)
21	Peak Torque	N·m	To compute the % of maximum torque we will need the peak torque of the engine for each NTE event
			Peak torque (N·m)
22	Flow-weighted Average PM Concentration for Methods 1 & 2	µg/mol	Flow-weighted average PM concentration, flow-weighted by the exhaust flow. Values were calculated based on a predictive model developed using transient and steady-state experimental data.
23	Flow-weighted Average PM Concentration for Method 3	µg/mol	Flow-weighted average PM concentration, flow-weighted by the exhaust flow. Values were calculated based on a predictive model developed using transient and steady-state experimental data.

2.6 Error Surface Generation

During the discussions held at several Steering Committee meetings, 33 error surfaces were identified and considered for inclusion in the Monte Carlo simulation model. 25 of these error surfaces were the same surfaces used in the gaseous emissions in-use testing program. [2] Of the remaining eight error surfaces, two were discarded (Delta PM EMI/RFI and Delta PM Vibration). because the PM generator was not used during these tests (see Section 5) The six new error surfaces for the PM program were PM Steady-State (SS), PM Transient, PM Atmospheric Pressure, PM Ambient Temperature, Torque Engine Manufacturers and Fuel Rate Engine Manufacturers. This resulted in a final total of 31 error surfaces that were incorporated into the Model. These individual error surfaces encompassed a wide variety of error sources. In addition, all error surfaces distributions used in this program included a range of sampled data between the 1st and 99th percentile to expand the range of sample data in the Monte Carlo simulation. This was done at the request of the SC since sampling for the gaseous program covered only the range between the 5th and 95th.

Table 5 lists the error surfaces examined during the study with the surfaces excluded by the Steering Committee designated in italics. All remaining ones were implemented in the simulation model. Each error surface was assigned a number for easy identification.

For each of the measurement errors defined in Table 5, an error surface was created and used in the Monte Carlo simulation. Each error surface represented an additive error—or a subtractive error if the sign was negative—relative to the reference parameter value to which it was applied. Figures 2 through 4 show an example of how these error surfaces were created for every measurement error. Details on the construction of each error surface used in the simulation are provided in Section 0. The example illustrated in Figure 2 through 4 represents the error surface for steady-state bias and precision PM concentration errors for an individual PEMS unit

2.6.1 PEMS vs. Laboratory Nominal Results

Figure 2 was constructed from raw data acquired from steady-state engine lab tests with the PEMS conducting repeat testing at various concentration levels (PM µg/mol). The plot pools all bias and precision errors for the PEMS tested for all steady-state modes. A nominal target of 10 repeat measurements of PM was taken on each PEMS unit for each value of the corresponding average lab PM values (i.e., lab nominal value). The 10 PEMS measurements were plotted against the corresponding measurements using laboratory equipment. Shown in Figure 2 are the 5th, 50th, and 95th percentiles corresponding to the distribution of these 180 observations (30 observations at each of the six concentration levels) using the PEMS at each average PM concentration level (note that the distribution of data at each PM level may not represent a normal distribution). Since the 50th percentiles do not lie on the dashed (diagonal) line of perfect agreement, the data suggest that there is a bias error between the PEMS and lab results. In essence this graph summarizes the statistical distribution measured by the PEMS at each concentration level sampled. The example plot in Figure 2 shows only 6 discrete average PM concentration levels (ranging from 10-60 µg/mol). However, the actual number of discrete concentration levels was determined using the total number of operating conditions actually run for all the tests on the engine. In the section on *Steady-State Repeat Engine Testing and Error Surfaces* it is reported that 6 operating modes conditions from an initial number of 80 operating conditions were selected for construction of the steady-state PM error surface. From these 6 operating modes several discrete PM concentration levels were defined which were used in the error surface plots for the Monte Carlo simulation.

TABLE 5. ERROR SURFACES FOR MONTE CARLO SIMULATION

Measurement Error Surfaces and Deltas Used in BSPM Calculations				
Component	**#**	**Test Source**	**Error Surface**	**Description**
1. Delta PM	1	Engine Dyno	Delta PM SS	AVL, Horiba and Sensors
	2	Engine Dyno	Delta PM Transient	AVL, Horiba and Sensors
	3	*Environ*	*Delta PM EMI/RFI*	*Deleted by Steering Committee*
	4	Environ	Delta PM Atmospheric Pressure	AVL
	5	Environ	Delta PM Ambient Temperature	AVL
	6	*Environ*	*Delta PM Vibration*	*Deleted by Steering Committee*
2. Delta CO	7	Engine Dyno	Delta CO SS	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	10	Environ	Delta CO Atmospheric Pressure	Same as Gaseous Study
	11	Environ	Delta CO Ambient Temperature	Same as Gaseous Study
3. Delta NMHC	13	Engine Dyno	Delta NMHC SS	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
NMHC = 0.98*THC	14	Engine Dyno	Delta NMHC Transient	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	16	Environ	Delta NMHC Atmospheric Pressure	Same as Gaseous Study
	17	Environ	Delta NMHC Ambient Temperature	Same as Gaseous Study
	19	Environ	Delta Ambient NMHC	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
4. Delta Exhaust Flow	20	Engine Dyno	Delta Exhaust Flow SS	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	21	Engine Dyno	Delta Exhaust Flow Transient	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	22	Engine Dyno	Delta Exhaust Flow Pulsation	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	23	Engine Dyno	Delta Exhaust Flow Swirl	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	25	Environ	Delta Exhaust EMI/RFI	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	27	Environ	Delta Exhaust Temperature	Same as Gaseous Study
	28	Environ	Delta Exhaust Pressure	Same as Gaseous Study
5. Delta Torque	29	Engine Dyno	Delta Dynamic Torque	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	30	Engine Dyno	Delta Torque DOE Testing (Interacting Parameters Test)	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	31	Engine Dyno	Delta Torque Warm-up (Interacting Parameters Test)	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	32	Engine Dyno	Delta Torque Humidity/Fuel (Independent Parameters Test)	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	34	Engine Dyno	Delta Torque Interpolation	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	35	Engine Manuf	Delta Torque Engine Manuf	New
6. Delta Fuel Rate	42	Engine Manuf	Delta Fuel Engine Manuf	New
7. Delta Speed	43	Engine Dyno	Delta Dynamic Speed	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
8. Delta Fuel Rate	44	Engine Dyno	Delta Dynamic Fuel Rate	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
9. Delta CO_2	45	Engine Dyno	Delta CO_2 SS	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	46	Engine Dyno	Delta CO_2 Transient	Same as Gaseous Study but moved 5th% to 1st% and 95th% to 99th%
	49	Environ	Delta CO_2 Ambient Temperature	Same as Gaseous Study

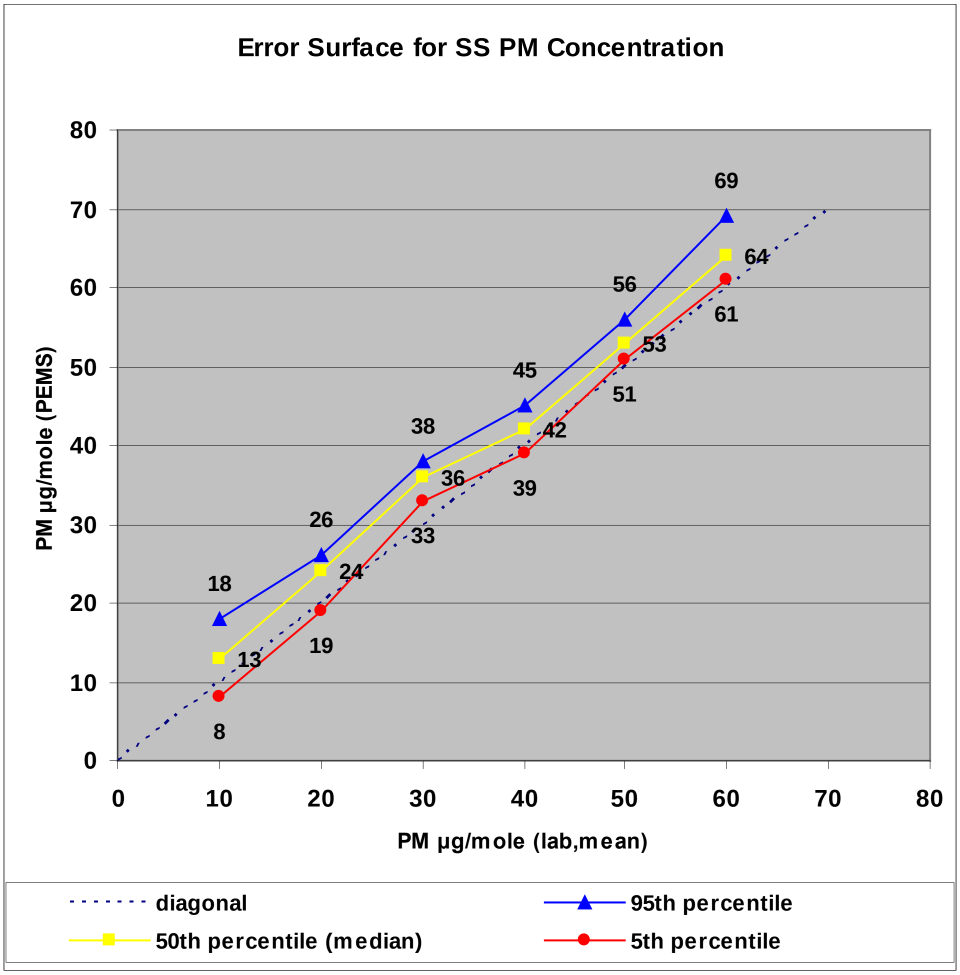


FIGURE 2. ERROR SURFACE CONSTRUCTION: PEMS VS. LABORATORY RESULTS

2.6.2 (PEMS – Laboratory) Deltas vs. Lab

Figure 3 illustrates the "error band" measured during testing. This plot was created by first subtracting the individual "lab nominal" PM value from the corresponding individual PEMS PM measurement for each test run. The sampling system used to obtain the "lab nominal" or "lab reference" PM values is described in Section 4.2.1. The difference between the PEMS PM and the lab reference was defined as the "delta" error. Second, these "PEMS - Laboratory" delta errors were pooled at each average lab nominal PM value to obtain the 5th, 50th, and 95th percentile values displayed in Figure 3. Therefore, the plot represents the average PM lab nominal at 6 discrete concentration levels versus the percentiles of the delta errors computed from the PEMS and laboratory individual test results.

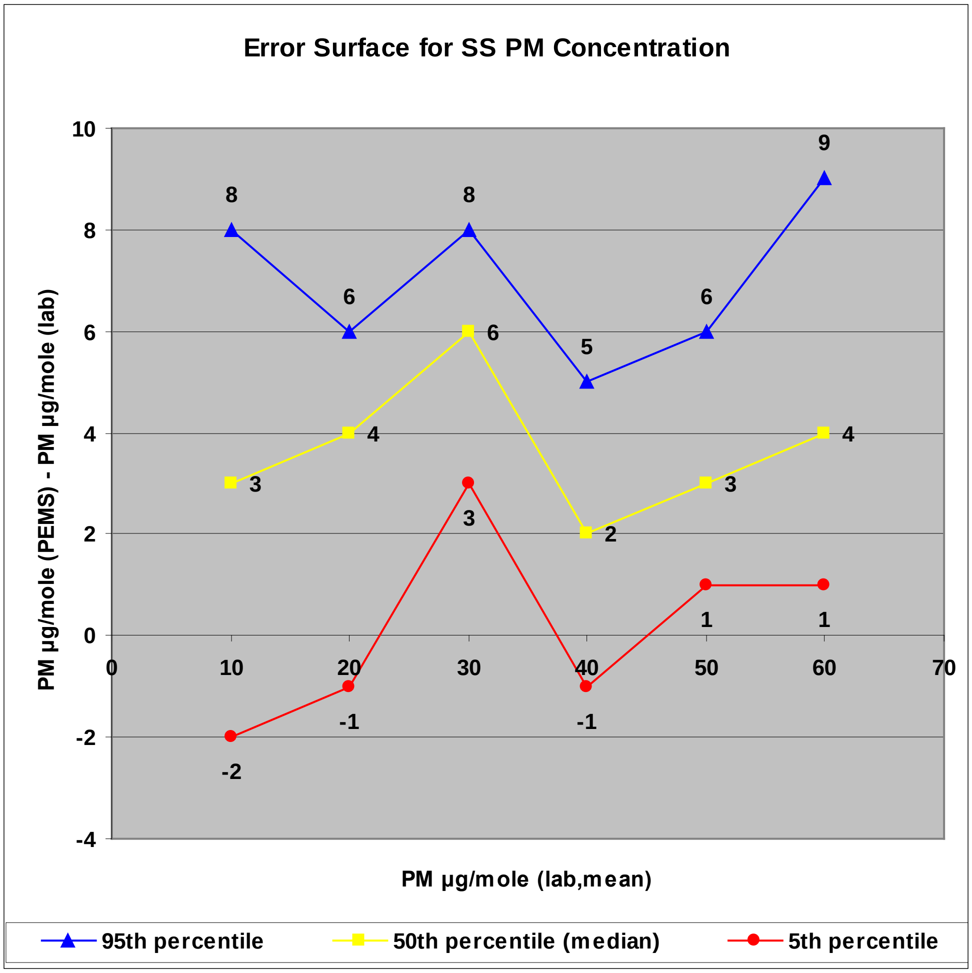


FIGURE 3. ERROR SURFACE CONSTRUCTION: (PEMS - LAB) VS. LABORATORY RESULTS

2.6.3 Variability Index vs. (PEMS – Laboratory) Deltas and Lab Nominal

This step normalized the plot in Figure 3 using what is called a "variability index (i_c)". This index represented the value randomly drawn by the Monte Carlo simulation in order to select a given error level. For the 5th and 95th percentile of the truncated normal it was allowed to vary from –1 to +1, respectively. The likelihood of "i_c" being any value between –1 through +1 was specified by a "probability density function (PDF)" assigned to i_c. In the case of this example, i_c was assumed to vary according to a standard normal (i.e, bell-shaped) distribution during the Monte Carlo simulations. This was because it was believed that the distribution of PM errors due to steady-state bias and precision would be centered about the 50th percentile of the full range of conditions measured. Each set of data for each lab "setpoint" average (i.e., lab nominal value) in Figure 3 was normalized by aligning the corresponding 5th percentile error from Figure 3 with i_c = -1, the 50th percentile error with i_c = 0, and the 95th percentile error with i_c = +1. These values were then plotted in Figure 4, where the y-axis is the variability index, the x-axis is the average lab nominal PM value, and the z-axis is the delta PM value. Notice that, when using this normalization approach, the 5th, 50th, and 95th percentile values remain equivalent between Figure 3 and Figure 4. This development of the error surfaces from the lab data was the procedure used in the gaseous emissions in-use testing program.

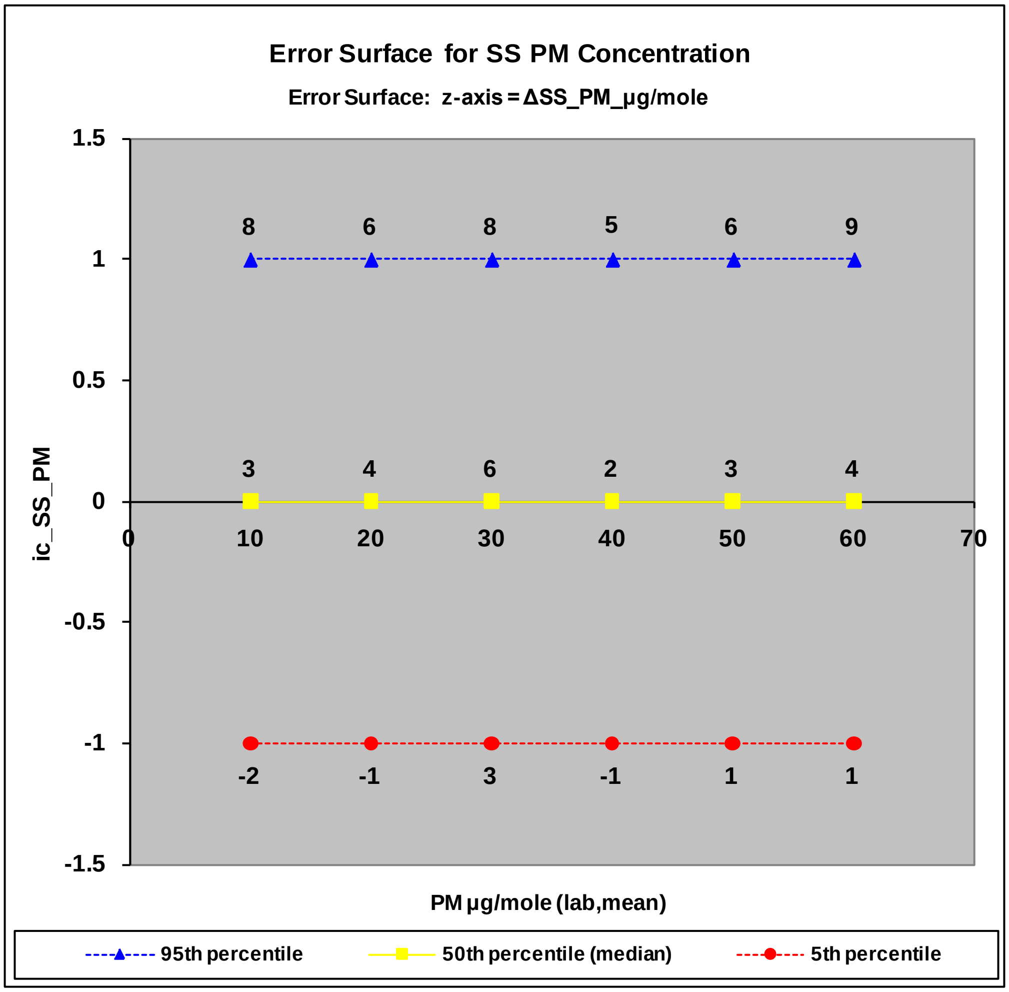


FIGURE 4. ERROR SURFACE CONSTRUCTION: ERROR AT VARIABILITY INDEX FOR 5TH AND 95TH PERCENTILES VS. LABORATORY RESULTS

For the PM measurement allowance program it was decided by the Steering Committee to expand the tails of the truncated normal distribution in the error surface formation in order to allow larger PM deltas to be sampled during the Monte Carlo simulation. Instead of truncating the lower tail at the 5^{th} percentile, it was moved to the 1^{st} percentile. Likewise on the upper tail, the 95^{th} percentile was moved to the 99^{th} percentile. Since the original truncated normal distribution was defined by a mean = 0 and a standard deviation = 0.60795, the resulting indices corresponding to the 1^{st} and 99^{th} percentiles are -1.4143 and +1.1413, respectively, as illustrated in Figure 5.

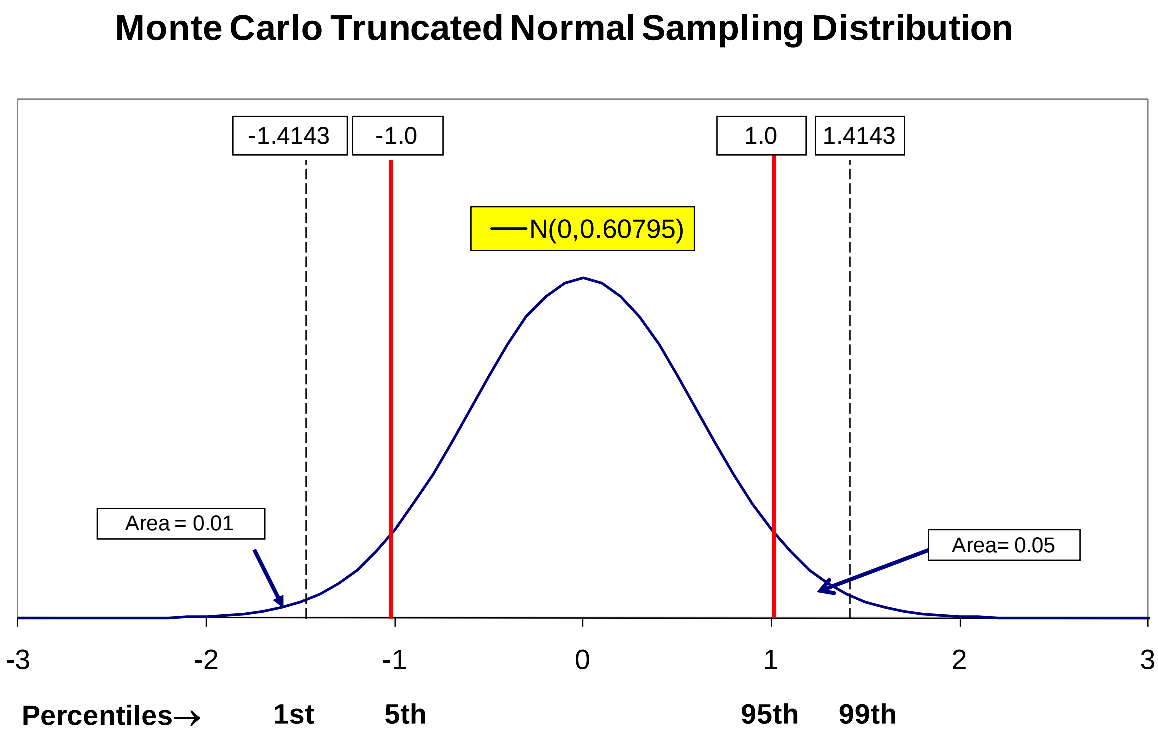


FIGURE 5. TRUNCATED NORMAL DISTRIBUTION PERCENTILES

Finally, the 5th and 95th percentile (PEMS – LAB) delta values at each lab nominal value were used to compute the corresponding values of the truncated normal for the 1st and 99th percentiles. To redefine the error surface delta at the 1st percentile, the standard deviation for the normal distribution below the 50th percentile is defined as follows:

$$Standard\ Deviation_{\ 1st} = \frac{Delta\ Value_{50^{th}} - \ Delta\ Value_{5^{th}}}{1.6449}$$

Using the mean = 50th percentile delta and the standard deviation computed above, the 1st percentile can be found using the Excel NORMINV function: NORMINV(0.01,mean,standard deviation$_{1st}$). Similarly, to redefine the error surface delta at the 99th percentile, the standard deviation for the normal distribution above the 50th percentile is defined as follows:

$$Standard\ Deviation_{\ 99th} = \frac{Delta\ Value_{95^{th}} - \ Delta\ Value_{50^{th}}}{1.6449}$$

Using the mean = 50th percentile delta and the standard deviation computed above, the 99th percentile can be found using the Excel NORMINV function: NORMINV(0.99,mean,standard deviation$_{99th}$). Taking the data for the error surface in Figure 4 and redefining it to include the 1st and 99th percentile truncated normal values results in the error surface displayed in Figure 6. All the error surfaces carried over from the gaseous program that were sampled using a truncated normal were redefined at the 1st and 99th percentiles. Those error surfaces that were sampled using the uniform distribution remained unchanged. Error surfaces such as the one presented in Figure 6 are the error deltas the Monte Carlo simulation program used during calculation of the BSPM emissions "with errors".

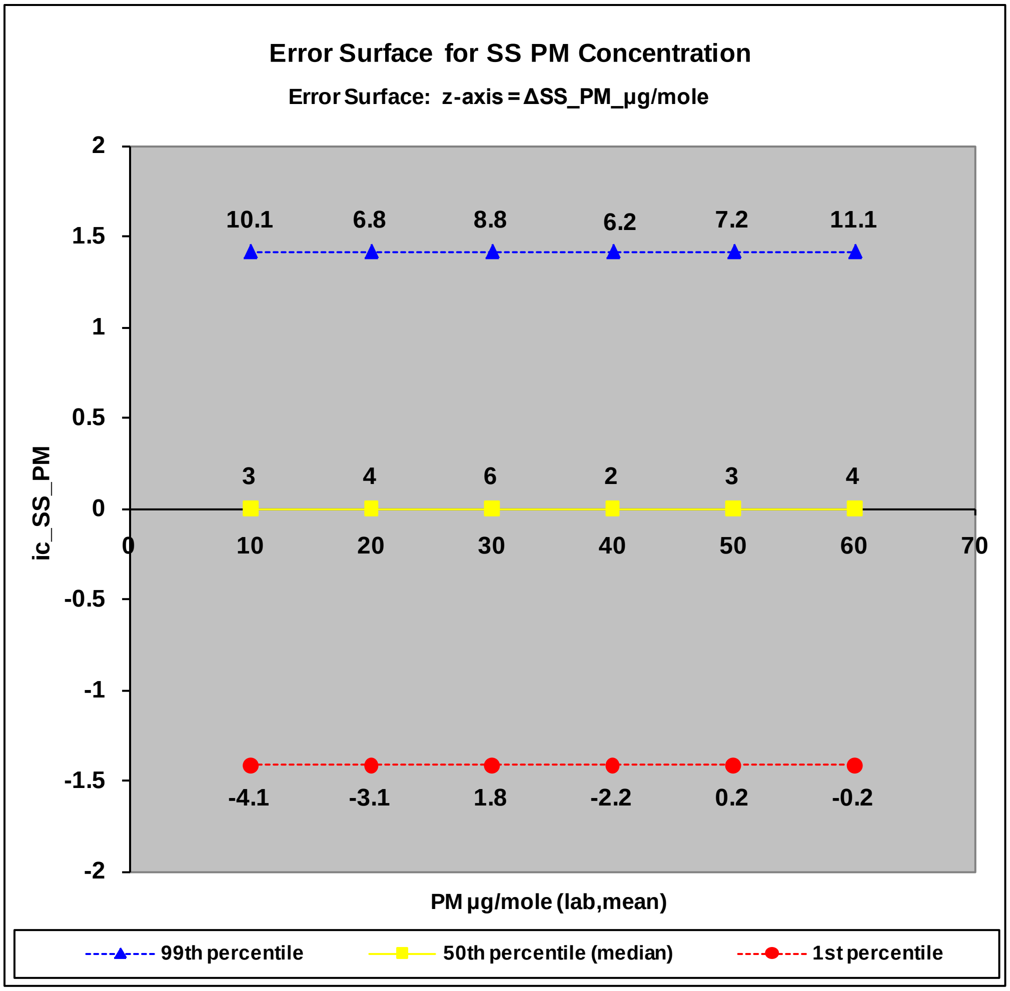


FIGURE 6. ERROR SURFACE CONSTRUCTION: ERROR AT VARIABILITY INDEX FOR 1ST AND 99TH PERCENTILES VS. LABORATORY RESULTS

2.7 Error Surface Sampling and Interpolation

The error model used two different PDF to sample the error surfaces, depending upon which experimental parameter the surface represented. To sample error surfaces that were generated from the lab test results (Section on *Engine Dynamometer Laboratory Testing*), and the applicable environmental test results, the model used a truncated standard normal PDF because these tests were designed to evenly cover the full, but finite, range of engine operation and ambient conditions. To sample error surfaces that were generated from the pressure and temperature environmental test results (Section on *Environmental Chamber Testing*), the model used a uniform PDF because these tests were already designed to cover the typical range and frequency of the respective conditions. Both of these sampling distributions are depicted in Figure 7.

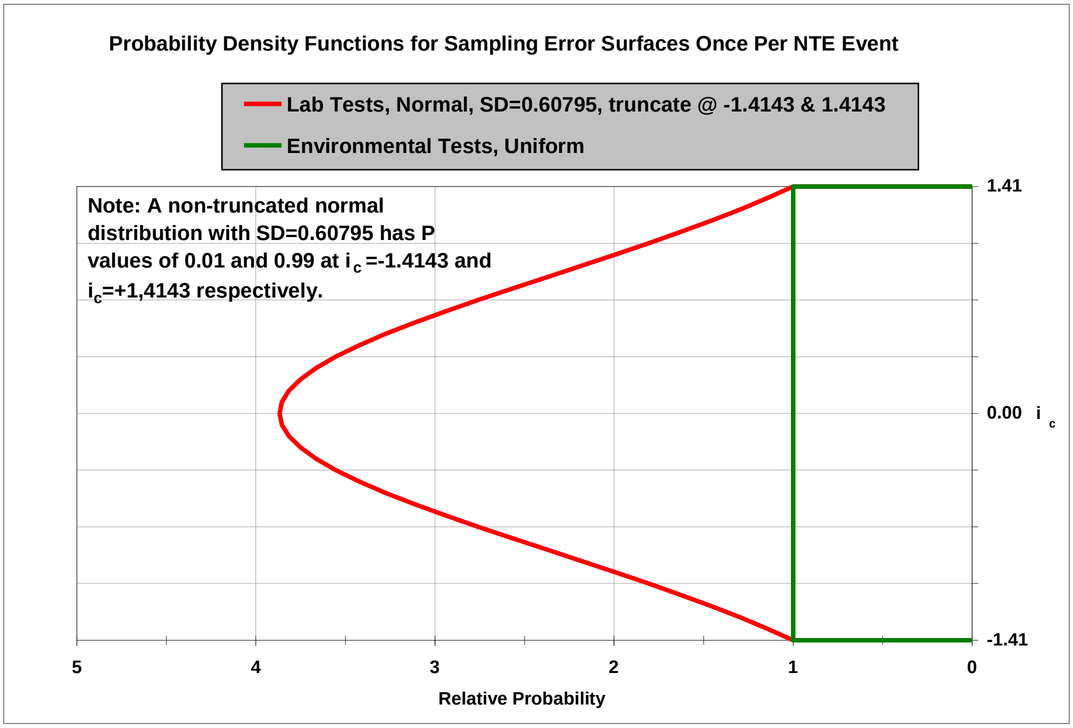


FIGURE 7. TRUNCATED STANDARD NORMAL AT 1ST AND 99TH PERCENTILES AND UNIFORM PROBABILITY DENSITY FUNCTIONS

When using the truncated standard normal PDF (see Figure 7), the Monte Carlo model sampled normal deviates that ranged between -1.4143 and +1.4143. These were used as the i_c values defined in the section on *Error Surfaces*. Similarly, the pressure and temperature environmental tests used a uniform PDF to sample test time, from which calculated errors were used. All temperature error surfaces related to the four emissions were sampled uniformly from 1 to 1080 minutes while the error surfaces related to the pressure were sampled uniformly from 1 to 720 minutes. Exhaust flow error surface for temperature was sampled uniformly from 1 to 478 minutes while the exhaust flow for pressure was sampled uniformly from 1 to 360 minutes. The errors from all the other tests were aligned with the truncated standard normal PDF such that each of the 50th percentile error values at each of the tested signal magnitudes was centered at the median (i.e., 0 value) of the PDF, and the 1st and 99th percentile error values at each of the tested signal magnitudes were aligned with the extreme negative (i_c = -1.4143) and positive (i_c = +1.4143) edges of the PDF, respectively.

Each error surface was sampled along its i_c axis (y-axis) once per trial for a reference NTE event simulation. Hence, every error surface had a separate randomly selected i_c for each trial. Since each reference NTE event contained second-by-second parameter data, except for PM for the Sensors PPMD and Horiba TRPM PEMS, the error surface was sampled at a given i_c on the y-axis and at the several selected parameter values on the x-axis that corresponded to each second of the reference NTE event. The sampled error value was determined for the given second and parameter along the error axis (z-axis) at the intersection of the i_c value and the parameter value from the reference NTE event. This was accomplished by taking each second in the reference NTE event and finding the two adjacent x-axis values from the error surface between which to linearly interpolate to obtain the error surface x-value. Each second in the reference NTE event was linearly interpolated with the same i_c value for a particular trial at the error surface x-value. If any of the sampled lab nominal values (PM, NMHC, CO, Speed, Fuel Rate, etc.) exceeded the upper or lower limits of the parameter error surface, the value of the closest endpoint of the error surface was assigned to them.

Figure 8 depicts an example of the error surface sampling using a steady-state PM error surface containing 10 lab nominal PM x-axis values. For this particular trial, the randomly selected i_c is -0.5. The example reference NTE event is noted by the symbol '*' and it plotted at i_c = -0.5 for each second in the NTE event.

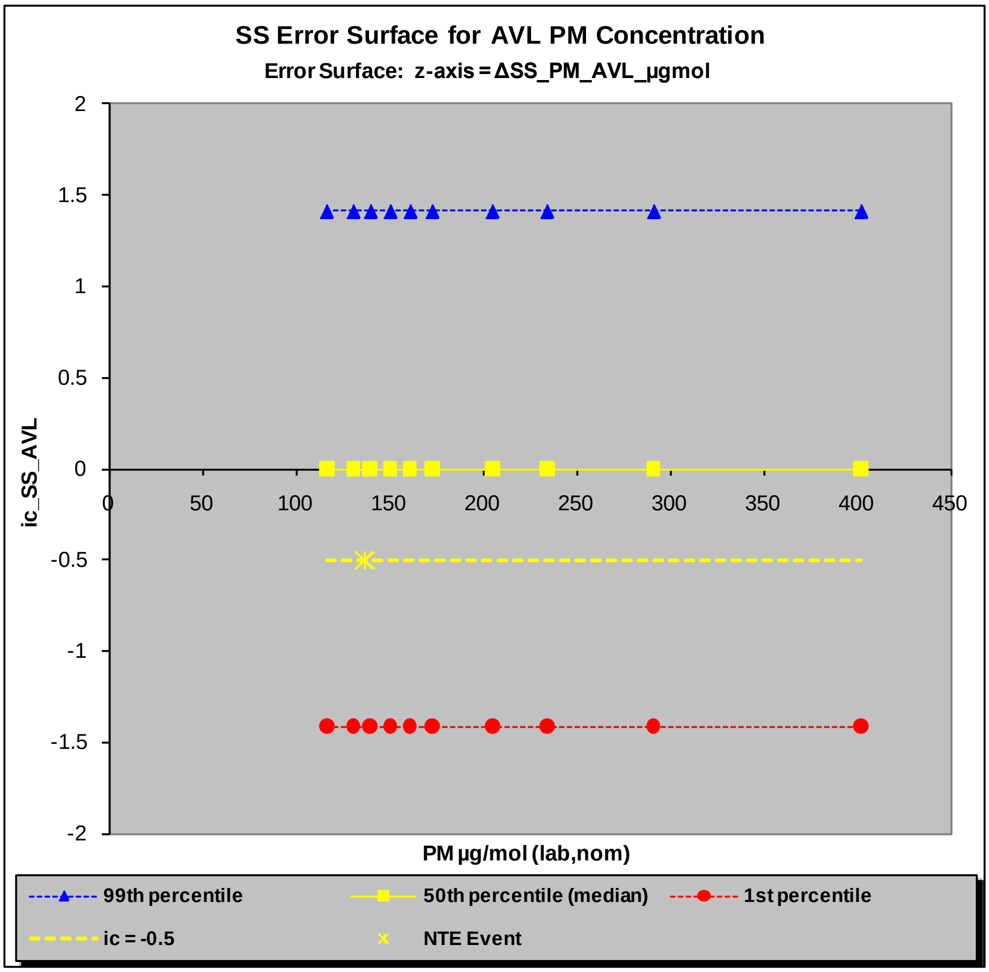


FIGURE 8. STEADY-STATE PM ERROR SURFACE FOR AVL WITH EXAMPLE SAMPLING FOR A REFERENCE NTE EVENT

2.8 Brake-Specific Emissions Calculations

Errors from Sections 4, 5, and 6 were combined by adding all of the sampled errors once per trial for each reference NTE event simulation. For example, in order to assess the errors in PM concentration by calculation Method #1, several error surfaces were sampled and added to the corresponding parameter in the Method #1 calculation and the resulting BSPM "with errors" was computed. The errors used in this calculation for the Horiba and Sensors are the following (note that the corresponding error surface numbers are provided in the subscripts):

$PM_{\mu g/mol}$ 'with errors' = $PM_{\mu g/mol\_reference} + \Delta PM_{\mu g/mol\_1} + \Delta PM_{\mu g/mol\_2}$

Exhaust Flow $_{\%}$ 'with errors' = Exhaust Flow $_{\%\ reference}$ + Δ Exhaust Flow $_{\%\ 20}$ Δ Exhaust Flow$_{_\%\ 21}$ + Δ Exhaust Flow $_{\%\ 22}$ + Δ Exhaust Flow $_{\%\ 23}$ + Δ Exhaust Flow $_{\%\ 25}$ + Δ Exhaust Flow $_{\%\ 27}$ + Δ Exhaust Flow $_{\%\ 28}$

Torque $_{\%}$ 'with errors' = Torque $_{\%\ reference}$ + Δ Torque $_{\%\ 29}$ + Δ Torque $_{\%\ 30}$ + Δ Torque $_{\%\ 31}$ + Δ Torque $_{\%\ 32}$ + Δ Torque $_{\%\ 34}$ + Δ Torque $_{\%\ 35}$

Speed $_{\%}$ 'with errors' = Speed $_{\%\ reference}$ + Δ Speed $_{\%\ 43}$

where,

$\Delta_{1,2}$ = PM concentration errors due to steady-state and transient errors,
$\Delta_{20,21}$ = exhaust flow errors due to steady-state and transient errors,
$\Delta_{22,23}$ = exhaust flow errors due to pulsation and swirl,
Δ_{25} = exhaust flow errors due to ambient temperature,
$\Delta_{27,28}$ = exhaust flow errors due to temperature and pressure,
Δ_{29} = torque errors due to dynamic torque,
$\Delta_{30,31}$ = torque errors due to DOE and warm-up,
Δ_{32} = torque errors due to interacting parameters humidity and fuel,
$\Delta_{34,35}$ = torque errors due to interpolation and engine manufacturers,
Δ_{43} = speed errors due to dynamic speed

Using the formulas for the calculation methods, the BSPM for Method #1 was computed without errors ("ideal") and then with all the errors applied as outlined above. Table 6 lists all error surfaces used by each calculation method for the PM emissions.

TABLE 6. ERROR SURFACES USED FOR COMPUTING BRAKE-SPECIFIC PM EMISSIONS BY THREE CALCULATION METHODS

Component	#	Error Surface	Method 1	Method 2	Method 3
1. Delta PM	1	Delta PM SS	✓	✓	✓
	2	Delta PM Transient	✓	✓	✓
	4	Delta PM Atmospheric Pressure	✓	✓	✓
	5	Delta PM Ambient Temperature	✓	✓	✓
2. Delta CO	7	Delta CO SS		✓	✓
	10	Delta CO Atmospheric Pressure		✓	✓
	11	Delta CO Ambient Temperature		✓	✓
3. Delta NMHC	13	Delta NMHC SS		✓	✓
NMHC = 0.98*THC	14	Delta NMHC Transient		✓	✓
	16	Delta NMHC Atmospheric Pressure		✓	✓
	17	Delta NMHC Ambient Temperature		✓	✓
	19	Delta Ambient NMHC		✓	✓
4. Delta Exhaust Flow	20	Delta Exhaust Flow SS	✓	✓	
	21	Delta Exhaust Flow Transient	✓	✓	
	22	Delta Exhaust Flow Pulsation	✓	✓	
	23	Delta Exhaust Flow Swirl	✓	✓	
	25	Delta Exhaust EMI/RFI	✓	✓	
	27	Delta Exhaust Temperature	✓	✓	
	28	Delta Exhaust Pressure	✓	✓	
5. Delta Torque	29	Delta Dynamic Torque	✓		✓
	30	Delta Torque DOE Testing (Interacting Parameters Test)	✓		✓
	31	Delta Torque Warm-up (Interacting Parameters Test)	✓		✓
	32	Delta Torque Humidity/Fuel (Independent Parameters Test)	✓		✓
	34	Delta Torque Interpolation	✓		✓
	35	Delta Torque Engine Manuf	✓		✓
6. Delta Fuel Rate	42	Delta Fuel Engine Manuf			✓
7. Delta Speed	43	Delta Dynamic Speed	✓		✓
8. Delta Fuel Rate	44	Delta Dynamic Fuel Rate			✓
9. Delta CO_2	45	Delta CO_2 SS		✓	✓
	46	Delta CO_2 Transient		✓	✓
	49	Delta CO_2 Ambient Temperature		✓	✓

2.9 Convergence and Number of Trials

Since the Test Plan did not include a provision for convergence criteria, the Steering Committee was tasked to develop a convergence method. The main goal was to define how many simulation trials at a given reference NTE event were required to estimate the 95th percentile BSPM emission differences with a given precision. Although the Crystal Ball software contained precision control options, the method used to compute a confidence interval on percentiles was based on an analytical boot strapping method which was not adequately documented. Thus, an independent convergence method was proposed and accepted by the Steering Committee.

A nonparametric statistical technique [3] was proposed which defined a 90% confidence interval for the 95th percentile of the BSPM emissions differences for an individual reference NTE simulation. If the width of the 90% confidence interval was less than 1% of the BSPM emissions threshold, then convergence was met. The following steps define the convergence method:

1. Run the Monte Carlo simulation for *N* trials.
2. Order the BS emissions differences from smallest to largest.
3. Identify the trial number at the lower end of the 90% confidence interval
$$n_{lower} = 0.95 * N - 1.645\sqrt{0.95 * 0.05 * N}$$
4. Identify the trial number at the upper end of the 90% confidence interval
$$n_{upper} = 0.95 * N + 1.645\sqrt{0.95 * 0.05 * N}$$
5. Compute (BSPM difference value at n_{upper}) – (BSPM difference value at n_{lower}).
6. If the result in (5) < 1% of the BSPM emissions NTE threshold then convergence is met.
7. The BSPM threshold was defined as 0.02 g/hp-hr. Thus, 1% of the threshold was 0.0002 g/hp-hr.

The Steering Committee agreed to the proposed convergence criteria outlined above. During the initial simulation runs for 20 reference NTE events, convergence was not met at the 1 percent criteria level until 60,000 trials were run. This only applied to the AVL PEMS unit at each of the three calculation methods. The Horiba and Sensors units only reached convergence at the 1 percent criteria for approximately half of the 20 reference NTE events simulations. Upon examination of the distributions of the delta BSPM emissions generated from the simulations, some of the distributions were positively skewed which would make convergence very difficult at the 1 percent level. This information was presented to the Steering Committee wherein a decision was made to relax the convergence level to 2 percent or higher, depending on the outcomes of the simulations.

In summary, the 141 reference NTE events were run at 40,000 trials and convergence was checked. If the width of the confidence interval on the 95th percentile delta BSPM emission was approaching 2 percent of the threshold, then the simulation was continued for up to 65,000 trials.

2.10 Simulation Output

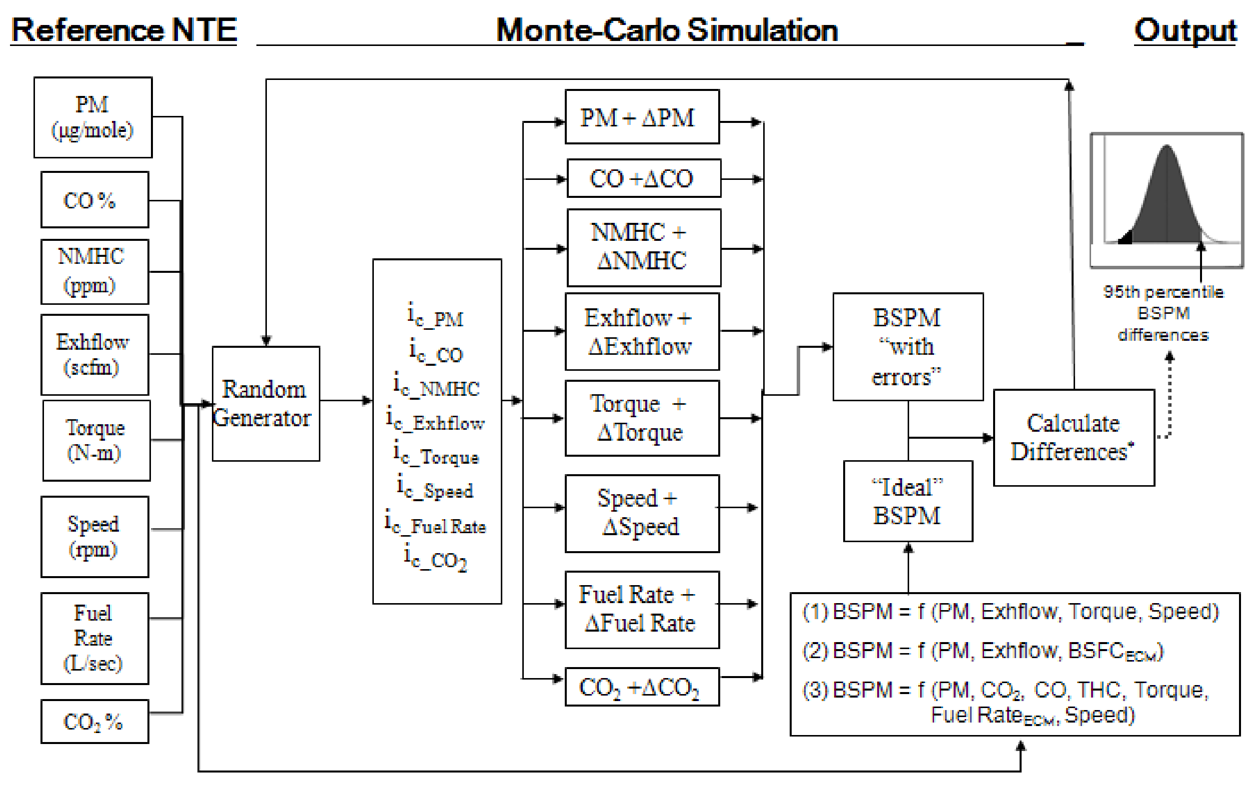
During the simulation of a reference NTE event, differences between the BSPM emissions "with errors" and the ideal BSPM emissions were obtained by each of the three PEMS model units and each of the three applicable calculation methods. These differences were computed thousands of times (once per trial) until the model converged. Then the 95th percentile difference value was determined for each reference NTE event's distributions of BS differences for the PM emissions for all three PEMS units and applicable calculation methods.

The output from the Crystal Ball simulation for each reference NTE event was saved in two separate Excel files: an EXTRACT and a REPORT file. The EXTRACT file contained descriptive statistics on all differences computed for BSPM emissions by all three calculation methods, percentiles (0%, 5%, 10%,…95%, 100%) of the differences in BSPM emissions, sensitivity data for all error surfaces, and differences in BSPM emissions computed at each trial in the simulation.

The REPORT file contained a summary of the differences in the BSPM emissions for all three PEMS units and applicable calculation methods including descriptive statistics, the number of trials, a frequency histogram of the differences in BSPM emissions, and percentiles (0%, 5%, 10%,…95%, 100%) of the differences in BSPM emissions. Also included were descriptive statistics on each i_c distribution sampled for each error surface. Lastly, sensitivity charts for the differences in BSPM emissions for the three PEMS unit and applicable calculation methods were stored. These charts provided information on how much each error surface influenced the differences computed between the BSPM emissions "with errors" and the ideal BSPM emissions. A more detailed description of the Crystal Ball output files can be found in Appendix C.

2.11 Step-by-Step Simulation Example

In order to clarify the simulation process, the following step-by-step summary is provided. This example assumes that a single reference NTE event was simulated for the BSPM difference computations. Figure 9 provides an overview of the simulation process.



* Differences = BSPM "with errors" – "Ideal" BSPM

FIGURE 9. OVERVIEW OF MONTE CARLO SIMULATION FOR BSPM

Step 1 - Enter the reference NTE input parameters into the Monte Carlo (MC) simulation model. These include the emissions concentrations, exhaust flow, torque, speed and fuel rate data used in all three calculation methods.

Step 2 - Compute the "ideal" BSPM by all three PEMS model unit and applicable calculation methods from the reference NTE event.

Step 3 - Set-up the Monte Carlo simulation parameters in Crystal Ball. An Excel spreadsheet model was developed for use with Oracle® Crystal Ball MC software for error analysis of brake-specific emissions. Crystal Ball is graphically-oriented forecasting and simulation software that runs on Microsoft® Windows and Excel. The simulations run in this program used Crystal Ball Version 11.1.1 and were run on PCs configured with a Pentium 4 CPU, 3.39 GHz, 3.50 GB RAM, 232 GB hard drive and Windows XP operating system. Microsoft® Excel 2003 SP was the spreadsheet software.

The options exercised in running Crystal Ball included the following:

- Number of trials = 40,000
  - If convergence was not met at the 2% criteria then # trials = 65,000
- Monte Carlo sampling method with random initial seeds
- Normal speed run mode
- Suppress chart windows (fastest run time)

The Excel spreadsheet is in a modular structure following the specified model outline, and it makes provisions for the three identified calculation modules. Input cells to the model are clearly identified to facilitate any revisions that may become necessary for users who want to exercise the model with other Monte Carlo software such as @Risk or newer versions of Crystal Ball. The spreadsheet was tested with controlled test cases of simplified input distributions with the Crystal Ball add-on to confirm correct model implementation in accordance with this test plan. At least one typical analysis was run as an additional confirmation, and two independent checks were made on the ideal emissions by other SwRI staff. A complete description of the spreadsheet computations is contained in Appendix D.

Step 4 - Execute a single MC trial by randomly generating a separate i_c for each error surface used in the three calculations.

Step 5 - For each second in the reference NTE event, interpolate the Δ error for all error surfaces at the input parameter values and the randomly generated i_c. Figure 10 illustrates all the error surfaces available and where the corresponding Δ errors are added. The numbers in parentheses represent the error surface number in the Monte Carlo simulation.

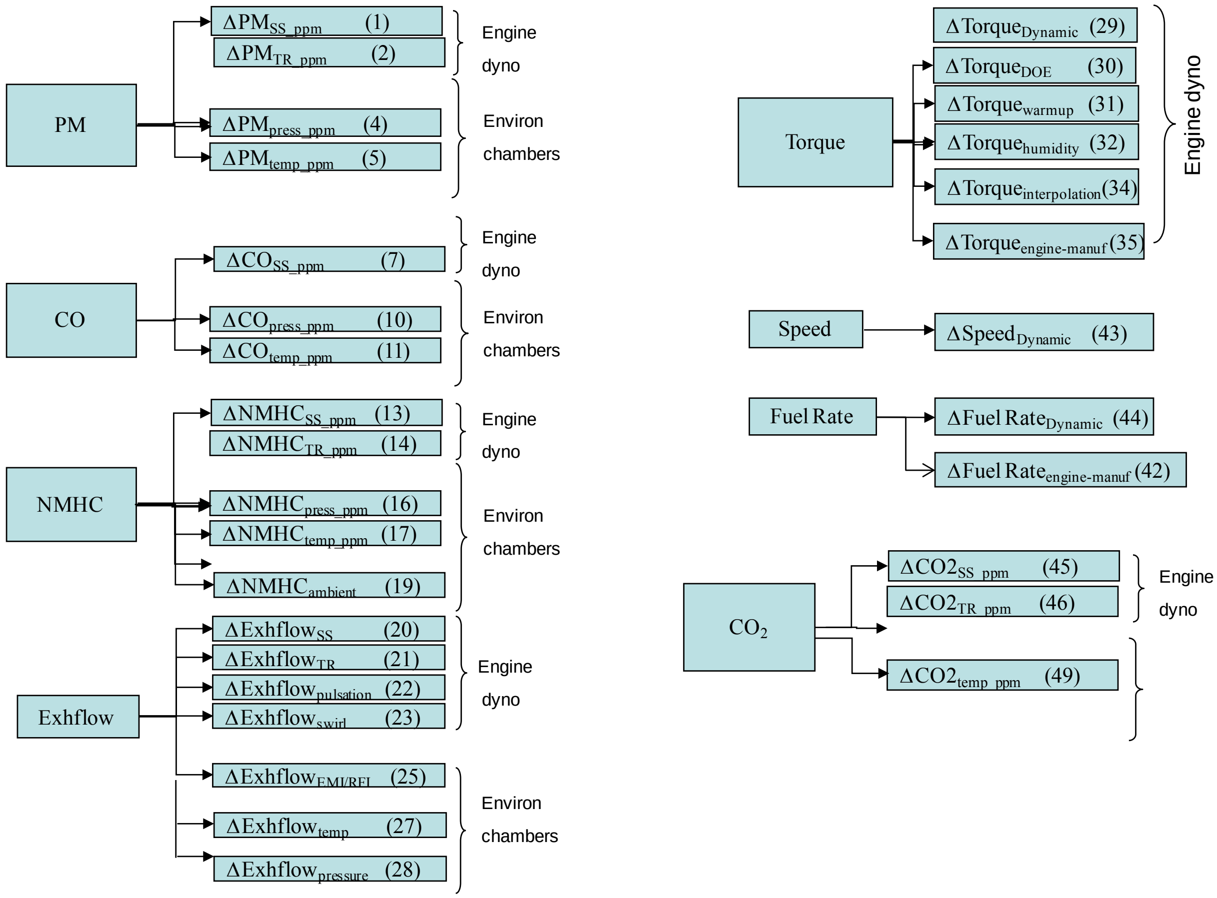


FIGURE 10. ERROR SURFACES INCLUDED IN MONTE CARLO SIMULATION

Step 6 - Compute one BSPM "with errors" for the given MC trial by adding all the Δ error values to the reference NTE data and then calculating the BSPM by all three PEMS units and applicable calculation methods.

Step 7 - Compute BSPM difference for the current trial:

BSPM emission "with errors" – "Ideal" BSPM emission

Step 8 - Repeat Steps 4-7 until the number of trials is met.

Step 9 - Check the differences in BSPM for all three PEMS units and applicable calculation methods to be certain that the convergence criteria are met. If convergence is met for all three calculation methods, continue to Step 10. Otherwise, return to Step 4 and run the Monte Carlo simulation for an additional 25,000 trials until the total number of trials is 65,000.

Step 10 - Select the 95th percentile from the distribution of BSPM differences for each of the three PEMS units and applicable calculation methods. Store the ideal BSPM and the 95th percentile BSPM differences for computing the measurement allowance.

Step 11 - Repeat Steps 1-10 for each reference NTE event.

2.12 Measurement Allowance Generation

The generation of a set of measurement allowances represented the final outcome of this program. The Test Plan provided a methodology by which all of the data from the millions of Model simulation runs would be collected and analyzed statistically, in order to generate a set of potential measurement allowances for each PEMS model unit, one for each of the calculation methods. The Test Plan then outlined a specific method by which the final set of allowances would be chosen from among deltas generated for each of the three calculation methods. The assumption made by the Test Plan, was that the final outcome of all previous efforts would be a set of validated potential measurement allowance values for each PEMS unit. Each potential allowance was expressed as a percentage of its associated BSPM NTE threshold. These measurement allowances were computed by a regression method or a median method as described below.

2.12.1 Regression Method

This method involved determining the correlation between the 95th percentile differences versus the ideal emission values for the reference NTE dataset. For each combination of PEMS units and calculation method, a least squares linear regression of the 95th percentile differences versus the ideal emissions results was computed. If the R^2 value from the regression model was greater than 0.85 and the SEE (standard error of the estimate or root-mean-squared-error) was less than 5 percent of the median ideal BS emissions, then the linear regression equation was used to determine the measurement allowance for that PEMS unit and calculation method. To determine the measurement allowance, the NTE threshold was used to predict the measurement allowance from the regression model. The measurement allowance was then expressed as a percentage of the NTE BSPM threshold value (0.02 g/hp-hr).

2.12.2 Median Method

If the linear regression did not pass the aforementioned criteria for the R^2 and SEE statistics, then the median value of the 95th percentile differences from the 141 reference NTE events was used as the single measurement allowance for a combination of emissions and calculation method. The measurement allowance was then expressed as a percentage of the NTE threshold value.

After all 95th percentile distributions were evaluated, there were seven measurement allowances corresponding to the combinations of the three PEMS units and the applicable calculation methods.

Next, the calculation method with the minimum normalized PM value will be chosen and the corresponding normalized PM value will be selected as the best measurement allowance for PM, assuming it validates. This PM measurement allowance would be the very last value added to the actual brake-specific NTE PM threshold for a given engine, based on actual family emissions limit, mileage, model year, etc. Note that if any measurement allowance was determined to have a value less than zero, then that measurement allowance was set equal to zero.

The BSPM NTE threshold used for this program was 0.02 g/hp-hr. This NTE threshold was determined by EPA and approved by the Steering Committee during the generation of the Test Plan.

These threshold values are of critical importance to the program, as they provide the basis for the scaling of measurement allowances, the assessment of model convergence, and a variety of other calculations performed during this program. The general philosophy of the Test Plan was to determine measurement allowances based on errors at these emission levels, especially in the case of any errors that scaled with emission level.

The anticipated outcome from the model runs, analysis, and validation efforts can be represented as a table similar to the one shown in Table 7. The table illustrates both the model outcome, and the process for selecting the final measurement allowance values for the AVL PEMS.

TABLE 7. EXAMPLE OF SELECTION OF MEASUREMENT ALLOWANCE AT 0.02 G/HP-HR NTE THRESHOLD FOR THE AVL PEMS

	Allowance at Respective NTE threshold (%)		
Calc. Method →	Method 1 Exhaust Flow Torque-Speed	Method 2 Exhaust and Fuel Flow Torque-Speed	Method 3 Fuel Flow Torque- Speed
BSPM	38 %	**18 %**	20 %
Selected Method →	Exhaust and Fuel Flow Torque-Speed Method		

The intent of the final selection process was to choose the smallest of the three normalized PM values for the final measurement allowance. At that point, the percentages given for the chosen calculation method would be applied to the BSPM NTE threshold value in order to generate the final additive, brake-specific measurement allowances.

An implicit assumption of the process, as described in the Test Plan, was that the values produced by the model for all three calculation methods would be successfully validated. In the event that this did not occur, it would be necessary for the Steering Committee to determine a valid alternate course of action, in order to determine the final measurement allowance values. The final model run and the selection and generation of measurement allowances are described fully in Section 0 of this report, including the final allowances approved by the Steering Committee.

2.13 Model Validation

For reasons discussed earlier, the measurement allowances were generated using a Monte Carlo computer model. As with all simulations, it is vital that such a model be validated through comparison with real experimental data. In this case, the Measurement Allowance model needed to be validated against a data set generated through actual in-use field testing. Because the model generates an incremental error in comparison to a Laboratory Reference, a suitable in-use reference measurement was needed for comparison to the PEMS measurements. The Steering

Committee determined that the CE-CERT Mobile Emission Laboratory, operated by the University of California-Riverside, would be an appropriate reference for validation of the model-based in-field testing.

To ensure that the validation was not disturbed by some inherent bias between the SwRI Reference Laboratory and the CE-CERT MEL validation reference, a correlation exercise was performed between the two laboratories, prior to the start of on-road validation efforts. The CE-CERT MEL was brought to SwRI's laboratory facilities in San Antonio, Texas, and a side-by-side correlation test was run. During this test, exhaust from the same test engine was alternately routed to the measurements systems of both SwRI and CE-CERT. This was done repeatedly over the course of three days of testing. The data was then supplied to the Steering Committee, in order to allow for a determination to be made that correlation between the facilities was acceptable for the purposes of validation of the model.

After the correlation exercise was completed, a 2007 test truck with a Cummins engine was procured by CE-CERT for use in this validation exercise. In addition, two Sensors PEMS used at SwRI during the program were also delivered to CE-CERT. A third PEMS unit of the same type was provided by Sensors. The steering committee allowed Sensors to provide a similar model with some small hardware upgrades for testing. CE-CERT then conducted a series of on-road test runs over various driving routes in California, which were designed to take the test truck through a wide range of environmental and ambient conditions. During these tests, simultaneous measurements were made with the PEMS and the MEL in order to generate a validation data set. This formed the primary validation set for the model.

Because the CE-CERT MEL does not readily incorporate a means of direct torque measurement on a vehicle, the on-road validation data set could not be used to validate model errors associated with broadcast torque.

The difference between the PEMS results and the CE-CERT trailer results will be compared to the measurement allowance limits predicted by the Monte Carlo Model and defined by the LOESS fit.

Validation will be based on the following procedure. For each reference NTE event, the Monte Carlo model will be used to generate the 5th and 95th percentiles of the simulated distribution of the brake-specific PM emission differences. In order to obtain simulations representing similar conditions to those obtained on-road, some error surfaces may need to be suppressed in the simulations since not all of them may be applicable to the on-road conditions. The choice of which error surfaces to suppress would need to be made by the Steering Committee.

Next, the 5th and 95th delta percentiles obtained from the above simulations will be separately fit to a line or curve using two chosen methods: a linear regression procedure and a local regression (loess) technique [4]. Depending on which of the resulting two fits is best for each set of data (i.e., either for the 5th percentile deltas or the 95th percentile deltas), the resulting line or curve will be used as one of the lower or upper limits for the on-road data.

To determine the best fit for a given set of delta percentiles (i.e., 5th or 95th), a simple regression line initially will be fit to the data. If a least squares linear regression of the 5th or 95th percentile deltas versus the ideal PM emission has an r^2 greater than 0.85 and an *SEE* less than 5 percent of the median ideal PM emissions, then the regression line will be used. If this set of criteria is not met, then a loess fit will be used. Since a loess regression requires the selection of a smoothing parameter [5] to smooth the data, the chosen smoothness parameter should balance the residual sum of squares against the smoothness of the fit.

The on-road delta errors, obtained from the results of collecting data on several NTE events during on-road operations, will be plotted on a graph containing the 5th and 95th percentile delta limits determined from the regression fits chosen above. The graph will consist of a plot of delta PM versus ideal PM. The number of on-road points outside these limits will be determined and expressed as a percentage of the total number on on-road data points. If this number does not exceed 10% of the total number of on-road data, the simulation data will be considered to be valid.

An example of a validation plot is given in Figure 11 and Figure 12. The plots shown correspond to gaseous emissions concentration data that were collected in the prior PEMS study. Figure 11 contains the 5th and 95th validation limits for NO_X data determined by fitting a linear regression model to the simulated data for both limits. Figure 12 contains the 5th and 95th validation limits for NO_X data determined by fitting a loess model to the simulated data for both limits.

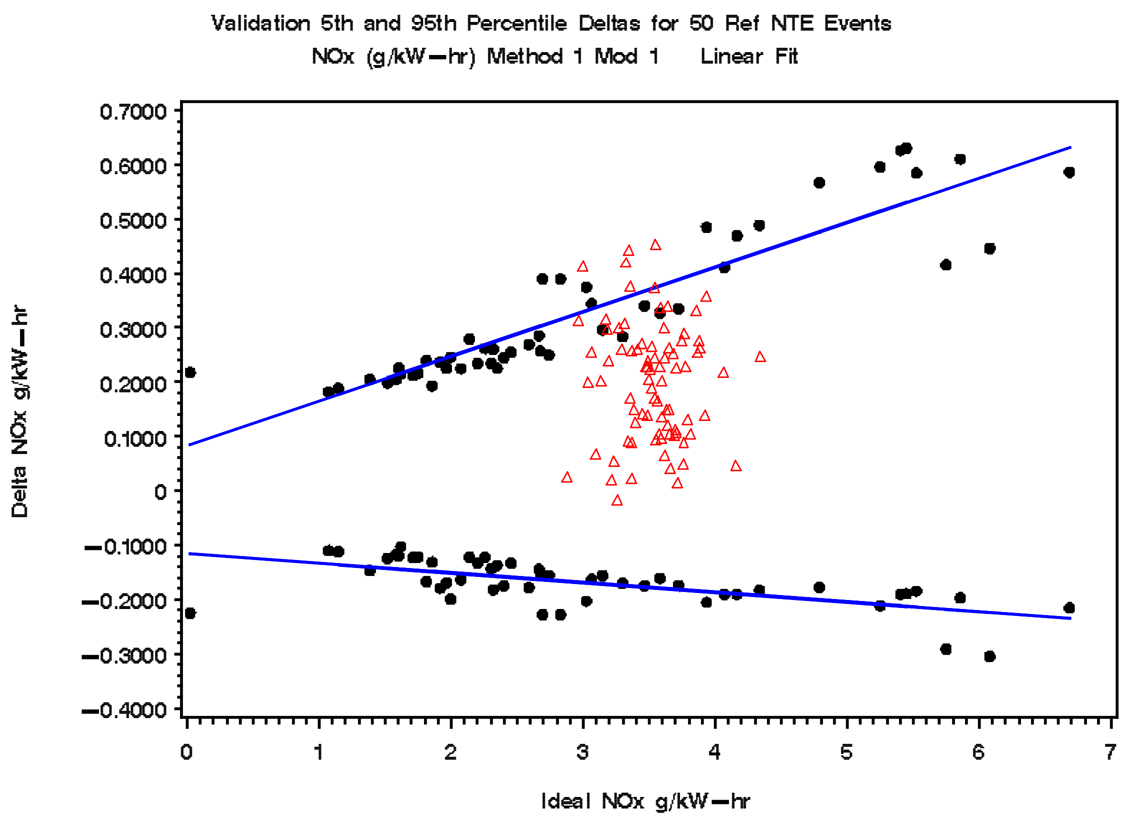


FIGURE 11. LINEAR REGRESSION FIT TO 5TH AND 95TH PERCENTILE DELTAS

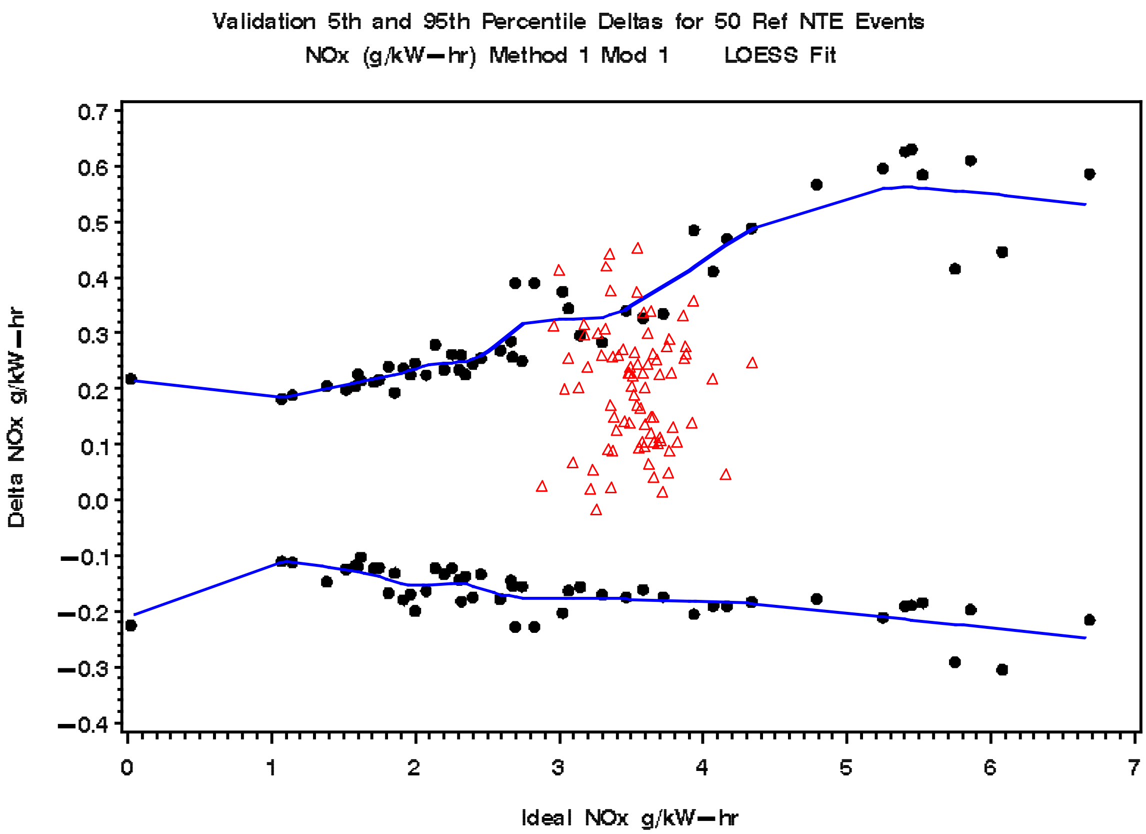


FIGURE 12. LOESS REGRESSION FIT TO 5TH AND 95TH PERCENTILE DELTAS

Validation of the model was assessed independently for the PM pollutant for each of the three PEMS model units, and for each of the applicable three calculation methods. A full description of the validation efforts, including the data analysis methodology and the results of PM validation for each PEMS unit by all three calculation methods is given in Section 2.4, with the exception of the CE-CERT on road validation testing.

3.0 PART 1065 PEMS AND LABORATORY AUDIT

Prior to the start of official testing both the laboratory system and each PEMS underwent an extensive audit in accordance with CFR Part 1065. Table 8 summarizes the audits that were performed on each type of system along with the CFR reference for each of the verifications.

TABLE 8. LINEARITY VERIFICATION RESULTS FOR INTAKE AIR FLOW AND FUEL FLOW

Fuel Flow				
Description	$\lvert x_{min}(a_1-1)+a_o \rvert$	a_1	**SEE**	R^2
Measured	-0.02	1.00	0.14	1.000
Criteria	0.55	0.98-1.02	1.10	0.990
Pass / Fail	Pass	Pass	Pass	Pass
Intake Air Flow				
Description	$\lvert x_{min}(a_1-1)+a_o \rvert$	a_1	**SEE**	R^2
Measured	0.00	1.00	1.22	1.000
Criteria	15.68	0.98-1.02	31.36	0.990
Pass / Fail	Pass	Pass	Pass	Pass

3.1 1065 Lab Audit

The most important audits performed on the laboratory system were those directly related to the PM concentration measurement accuracy, namely the linearity of flows and the PM balance. The intake air flow and fuel flow were verified for linearity, while the CVS and PM sampling flows were verified using a propane recovery check. The linearity verifications were performed in accordance with 40 CFR Part 1065.307 although they were performed within 180 days rather than 370. The propane checks were performed weekly during official testing in accordance with 40 CFR Part 1065.341. The maximum allowable interval for the propane check is 35 days. Table 8 shows the initial linearity verifications for fuel and intake air flow.

One additional verification was performed for the fuel and intake air flow with similar results. Two different nominal flow rates were used for the PM secondary dilution system, one for steady state testing and another for transient testing. A total nominal flow of 3.6 m^3/hr (2.0 scfm) was used to target a filter face velocity of 100 cm/s during steady state testing. Because the filter measurement was unofficial the total flow was reduced during transient testing to prevent overloading the filter. A nominal total flow rate of 2.4 m^3/hr was used during transient testing. The propane recovery check was performed at a total secondary flow of either 3.6 or 2.4 m^3/hr depending on whether the testing at the time was steady state or transient. Table 9 shows a summary of the propane recovery results. The percent difference is between the calculated propane concentration based on a known flow of propane and the measured propane concentration from a hydrocarbon analyzer. The pass limit for the CVS system is plus or minus two percent and plus or minus five percent for the secondary sampling system.

TABLE 9. CVS PROPANE RECOVERY CHECK SUMMARY

Test Date	CVS Blower, m³/hr	Secondary Dilution, m³/hr	Secondary Total, m³/hr	Secondary Sample Diff, %	CVS Diff, %
10/29/08	3,941	1.75	3.53	-1.16	0.75
11/05/08	3,855	1.73	3.64	1.02	1.67
11/14/08	3,887	1.72	3.65	1.17	1.66
12/01/08	3,921	1.73	3.81	-1.1	0.37
12/08/08	3,931	1.72	3.75	0.06	1.33
12/18/08	3,955	1.75	3.62	-2.15	1.4
01/05/09	3,832	1.31	2.63	-1.89	-0.61
01/12/09	3,875	0.97	2.36	-2.72	-0.64
01/20/09	3,928	0.97	2.36	-2.98	-0.17
02/11/09	3,899	1.00	2.28	-0.05	-1.35
02/18/09	3,896	1.00	2.46	1.13	0.74
02/25/09	3,841	1.00	2.31	2.04	0.77
03/06/09	3,905	1.90	3.72	1.86	1.19
03/16/09	3,893	1.92	3.72	0.68	-0.56
03/24/09	3,804	1.05	2.17	0.6	0.51
04/07/09	3,927	1.87	3.87	1.37	0.28

Occasionally a propane check was outside of the allowable limits, but when the check was repeated it usually passed under the same conditions. It was necessary to pass two consecutive propane checks if the initial check failed. The final result from each day is shown in the Table 9.

Linearity was also verified on the PM balance used for filter weights. The linearity verification results are shown in Table 10.

TABLE 10. LINEARITY VERIFICATION FOR PM BALANCE

PM Balance				
Description	$\lvert x_{min}(a_1-1)+a_o \rvert$	a_1	SEE	R^2
Measured	0.00	1.00	0.00	1.000
Criteria	20.00	0.99-1.01	20.00	0.990
Pass / Fail	Pass	Pass	Pass	Pass

Verification of the PM balance is required every 370 days although the check was performed after 180 days for quality purposes and passed with similar results.

3.2 1065 PEMS Audit

Before the start of engine testing, each PEMS was required to pass the verifications set forth in CFR Part 1065. Because the measurement of PM is a non-standard process there are no audits specified on the actual PM measurement, but the instruments still needed to pass the necessary flow, temperature, and pressure audits. Table 11 lists the Part 1065 audits performed on the lab and on the PEMS.

TABLE 11. SUMMARY OF PART 1065 AUDITS

Description	CFR Reference	Lab	PEMS
Linearity	1065.307	x [a]	x [b]
Torque Meter	1065.310	x	
Pressure, Temperature, Dewpoint	1065.315	x	
Fuel Flow	1065.320	x	
Intake Flow	1065.325	x	
CVS Verification	1065.341	x	
PM Balance Verification	1065.390	x	
[a] Linearity for lab performed on flow meters, torque meter, pressures, and temperatures [b] Linearity for PEMS performed on flow meters			

Since no analyzer verifications were performed, the most critical audits on the PEMS were the linearity verifications of flow measurements. Because all three types of PEMS use flow measurements to calculate a dilution ratio, the accuracy of the flow measurements is directly related to the accuracy of the reported PM emissions. The AVL and Horiba PEMS measure their total and dilution flow to calculate a dilution ratio while the Sensors PEMS measures the dilution and sample flow. The following equation is used to calculate the dilution ratio:

$$Dilution\ Ratio = \frac{Total\ Flow}{Sample\ Flow} = \frac{Total\ Flow}{Total\ Flow - Dilution\ Flow}$$

3.2.1 Horiba Flow Audits

The Horiba PEMS has four flow measurements in the system: dilution flow, DCS flow, make-up air flow, and total flow. During typical operation all flows but the dilution flow are held constant. The dilution flow rate is varied to sample proportionally from the raw exhaust based on changes in exhaust flow. The CFR requires linearity verifications on sample, dilution, and total flow (whichever two of the three that are measured) [2]. The DCS and makeup flows affect the accuracy of the dilution ratio and the filter flow, however both of these flows are maintained at a nominal value of 2 lpm it was decided not to perform a linearity verification in this situation. The steering committee elected to perform a spot check on the DCS flow to ensure its accuracy and verify the filter flow which includes both the total and make-up air flow. The filter flow is equal to the difference between the total flow and make-up air flow. Because the filter flow was designed to operate at a constant flow of approximately 28 lpm it was not practical or logical to verify the flow measurement over 10 even points down to zero flow as recommended in CFR Part 1065.307. After discussing the issue with Horiba and the steering committee it was decided to verify the filter flow over a range of plus and minus ten percent of its operating target, using eleven steps. The maximum range that the dilution flow could vary was approximately 21 to 31 lpm; the dilution flow was verified over this range in eleven even steps. The flow audits were initially performed with a TSI flowmeter, but this was replaced with a bubble flowmeter when it was discovered that the accuracy of the TSI flowmeter degraded as the pressure during the flow measurement deviated from atmospheric. The results from the linearity verifications are shown in Table 12 for the Horiba PEMS.

TABLE12. LINEARITY VERIFICATIONS FOR HORIBA PEMS

Verification Description	Intercept	Slope	SEE	R^2
Horiba1				
Dilution Flow				
Measured	0.29	0.98	0.05	1.000
Linearity Criteria	031	0.98-1.02	0.62	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Filter Flow				
Measured	0.07	0.97	0.03	1.000
Linearity Criteria	0.30	0.98-1.02	0.60	0.99
Pass/Fail	Pass	Fail	Pass	Pass
Horiba2				
Dilution Flow				
Measured	0.08	1.00	0.3	0.999
Linearity Criteria	0.31	0.98-1.02	0.61	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Filter Flow				
Measured	0.18	0.98	0.03	1.000
Linearity Criteria	0.30	0.98-1.02	0.60	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Horiba3				
Dilution Flow				
Measured	0.05	1.02	0.04	1.000
Linearity Criteria	0.31	0.98-1.02	0.62	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Filter Flow				
Measured	0.01	0.99	0.04	0.999
Linearity Criteria	0.30	0.98-1.02	0.60	0.99
Pass/Fail	Pass	Pass	Pass	Pass

Horiba-1 narrowly missed passing linearity verification for total flow with a slope of 0.97. This check was repeated several times without passing. However, the error as a percent of point was better than 0.5 percent for all eleven points. This result is a problem with applying the linearity criteria from Part 1065 to a flow that is not verified over the range from zero to full scale. Given the excellent agreement on a point-by-point basis, the steering committee elected to proceed without taking corrective action.

The linearity verification results for the Sensors PEMS are shown in Table 13.

TABLE 13. LINEARITY VERIFICATIONS FOR SENSORS PEMS

Verification Description	Intercept	Slope	SEE	R^2
Sensors1				
Sample Flow				
Measured	-0.01	1.00	0.00	1.000
Linearity Criteria	0.02	0.98-1.02	0.04	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Major Dilution Flow				
Measured	0.05	0.98	0.08	0.999
Linearity Criteria	0.09	0.98-1.02	0.17	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Minor Dilution Flow				
Measured	-0.04	1.01	0.01	1.000
Linearity Criteria	0.05	0.98-1.02	0.09	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Sensors2				
Sample Flow				
Measured	0.01	1.00	0.01	0.999
Linearity Criteria	0.01	0.98-1.02	0.03	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Major Dilution Flow				
Measured	0.07	1.01	0.05	0.999
Linearity Criteria	0.07	0.98-1.02	0.13	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Minor Silution Flow				
Measured	0.02	1.01	0.06	0.998
Linearity Criteria	0.04	0.98-1.02	0.08	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Sensors3				
Sample Flow				
Measured	0.01	1.00	0.01	0.999
Linearity Criteria	0.01	0.98-1.02	0.02	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Major Dilution Flow				
Measured	0.01	1.00	0.05	1.000
Linearity Criteria	0.07	0.98-1.02	0.14	0.99
Pass/Fail	Pass	Pass	Pass	Pass
Minor Dilution Flow				
Measured	0.01	0.96	0.01	1.000
Linearity Criteria	0.02	0.98-1.02	0.04	0.99
Pass/Fail	Pass	Fail	Pass	Pass

The Sensors PEMS had the capability of performing a self-audit using 1065 criteria. An external TSI flowmeter was provided as part of the Sensors equipment and its measurements were recorded by the Sensors software to linearity verifications on the dilution and sample flows. The total dilution flow is calculated by the addition of the major and minor dilution flows, so these two measurements are audited independently. The Sensors PEMS was able to pass all but the minor dilution flow audit for Sensors unit 3. This verification was performed repeatedly without passing. Since the total dilution flow would still pass a linearity verification in this case, no further action was taken. In the case of both the Horiba and the Sensors, the absolute accuracy of the flows are important in determining the mass of PM emitted. The AVL system is a real time particle sensor rather than a proportional batch sampler. For this type of instrument, only the dilution ratio and not the absolute accuracy of the total and dilution flows affect the measurement accuracy. For this reason the dilution ratio was audited instead of the total and dilution flow rates which are used to calculate the dilution ratio. It was also not possible to vary the total flow, which is held constant during normal operation. Although the dilution ratio was maintained at a constant of 5 throughout official testing, a six point check was performed ranging from 2 to 6 in steps of 1. Table 14 shows the results for the linearity verifications for the AVL units.

TABLE 14. LINEARITY VERIFICATIONS FOR AVL PEMS

Verification Description	Intercept	Slope	SEE	R^2
AVL1				
Flow Based Dilution Ratio				
Measured	0.01	0.96	0.01	1.000
Linearity Criteria	0.07	0.98-1.02	0.15	0.99
Pass/Fail	Pass	Fail	Pass	Pass
AVL2				
Flow Based Dilution Ratio				
Measured	0.03	0.97	0.02	1.000
Linearity Criteria	0. 70	0.98-1.02	0.14	0.99
Pass/Fail	Pass	Fail	Pass	Pass
AVL3				
Flow Based Dilution Ratio				
Measured	0.05	1.02	0.00	1.000
Linearity Criteria	0.07	0.98-1.02	0.14	0.99
Pass/Fail	Pass	Pass	Pass	Pass

The MSS dilution ratio was initially verified using both flow measurements as well as CO_2 measurements. Because the AVL PEMS had an internal CO_2 measurement it would have been possible to use a CO_2 span bottle to verify the dilution ratio, unfortunately it was not possible to ever introduce an undiluted CO_2 sample to CO_2 sensor to provide a span. When the sample is undiluted, the CO_2 cell is bypassed so that it does not measure. The results shown in Table 15 were generated using TSI flowmeters to measure the total and dilution flow and calculate the dilution ratio in the same manner as the PEMS. AVL-1 and AVL-2 were both unable to pass the slope criteria but were within three percent of point across the six point verification. The steering committee agreed to accept the dilution ratio accuracy tolerance of three percent.

3.2.2 Exhaust Flow

Official linearity verifications were not conducted on the PEMS exhaust flow meters at SwRI. The steering committee decided that a calibration from the manufacturer was sufficient so long as the flow meter was within five percent of the lab during engine testing. The three flow meters tested from Horiba and the three from Sensors were all within found to be within five percent of the lab measurement. An unofficial linearity verification was performed using the data from the steady state engine testing. The exhaust flow measurement was averaged during each state measurement sample and compared with the laboratory measured value over the same time period (50-270 seconds depending on the engine condition). There were between 64 and 84 data points per exhaust flow meter. The linearity plots are shown in Figure 13 for PEMS-1, Figure 14 for PEMS-2, and Figure 15 for PEMS-3.

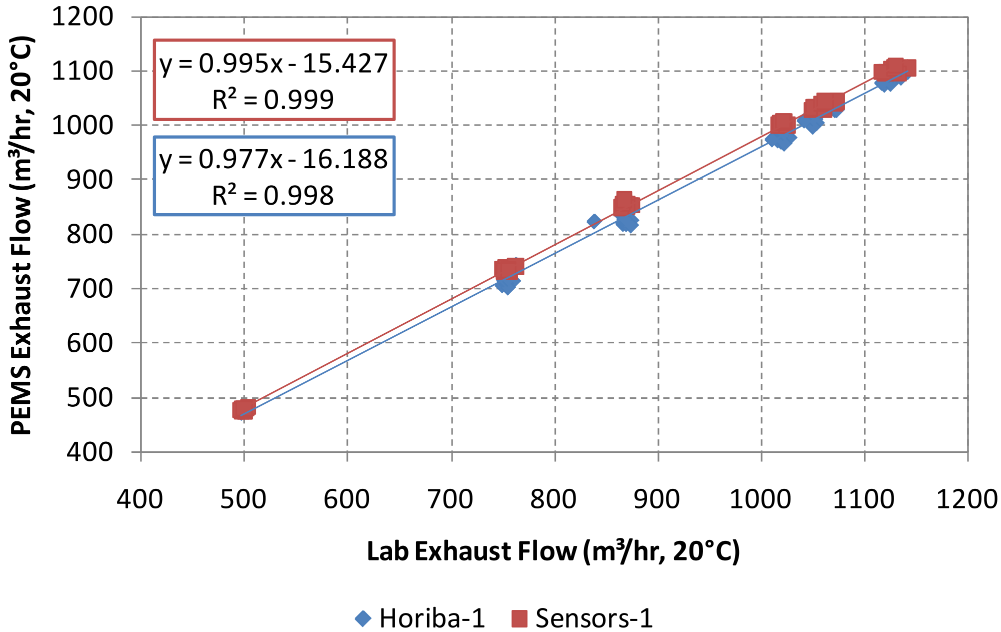


FIGURE 13. LINEARITY CHECK ON PEMS-1 EXHAUST FLOW DURING STEADY-STATE ENGINE TESTING

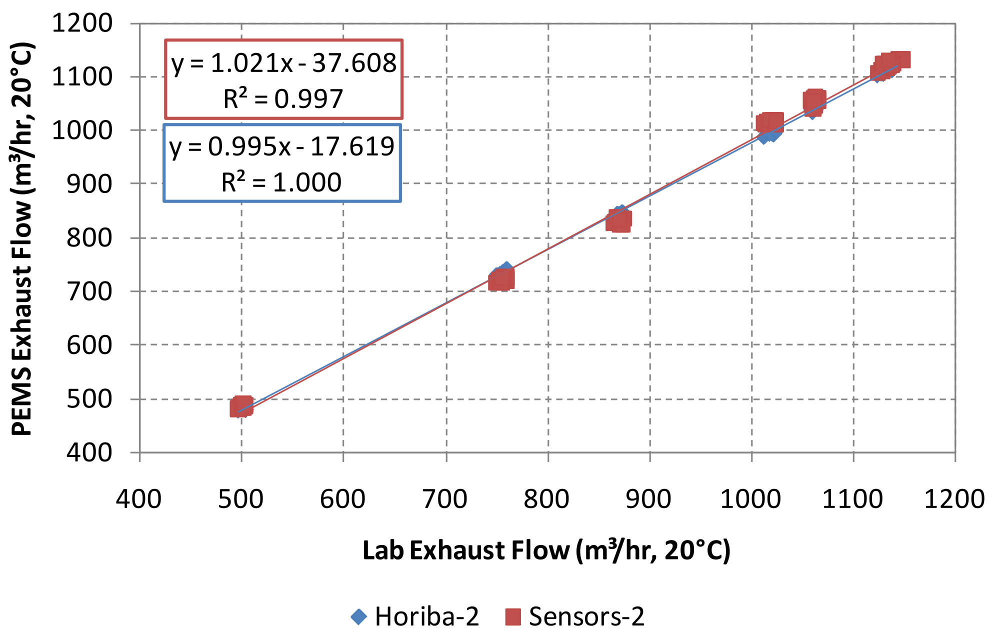


FIGURE 14. LINEARITY CHECK ON PEMS-2 EXHAUST FLOW DURING STEADY-STATE ENGINE TESTING

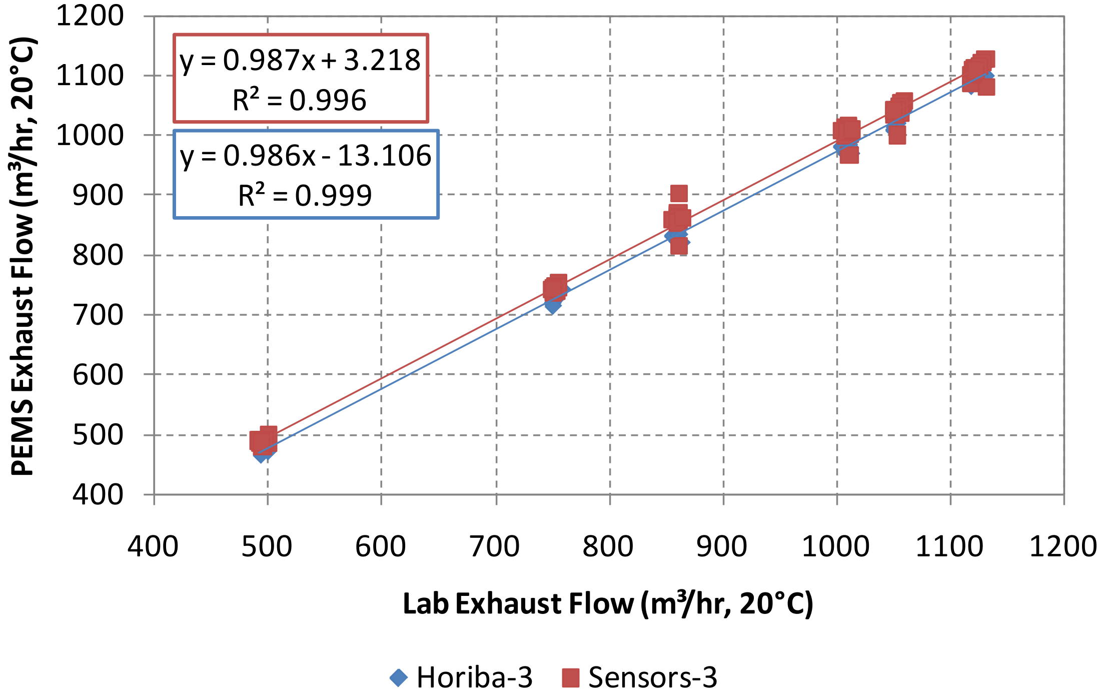


FIGURE 15. LINEARITY CHECK ON PEMS-3 EXHAUST FLOW DURING STEADY-STATE ENGINE TESTING

Each of the six exhaust flow meters was able to pass the standard error, slope, and correlation coefficient criteria for a raw exhaust flow measurement specified in CFR Part 1065.307 however only one was able to pass the intercept criteria (Sensors-3). This is likely due in part to the fact that the measurements did not extend below 470 m^3/hr making it more difficult to pass an intercept criteria that assumes evenly spaced data points extended down to zero. Conducting a linearity verification on the exhaust flow measurement during engine testing was for informational purposes only.

4.0 ENGINE DYNAMOMETER TESTING AND RESULTS

4.1 Testing Objective

The purpose of the engine dynamometer testing was to characterize the bias and precision errors of the PEMS during steady-state and transient engine operation. During steady-state engine operation, the PEMS measurements were compared with that of the CVS filter-based PM measurement to characterize the bias in each of the three PEMS. The transient engine testing was used to determine the precision of each PEMS by quantifying the variability of the PEMS measurement over a series of repeated transient NTE events.

4.2 Experimental Setup

4.2.1 Engine and Sampling System

Preliminary testing was performed using a 6.4 liter light heavy-duty diesel engine provided by Navistar, however the engine used to generate all official steady-state and transient data was a 2007 Volvo MP7 provided by Volvo Powertrain. The test plan initially called for official dynamometer testing to be performed on two different engines, but funding constraints reduced official testing to a single engine. The Volvo MP7 had a displacement of 10.8 liters and was rated at 280 kilowatts (375 horsepower). The engine was equipped with a variable geometry turbocharger (VGT) and a water-cooled high pressure exhaust gas recirculation (EGR) loop. The engine intake system was connected to a test-cell water-cooled intercooler. The engine is shown in Figure 16.

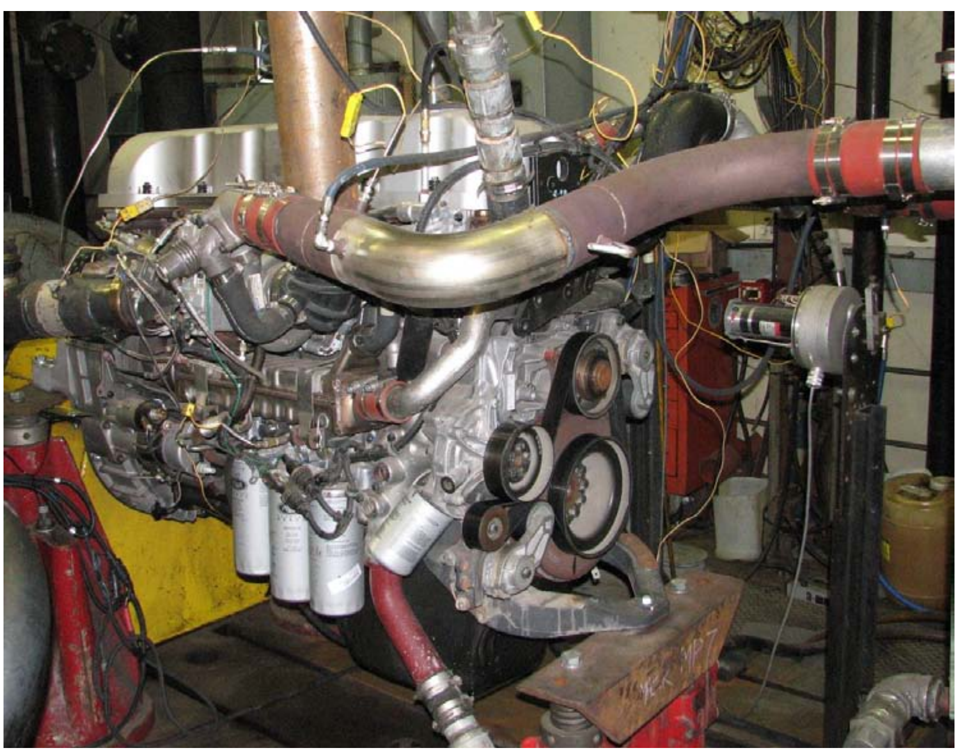


FIGURE 16. VOLVO MP7 INSTALLED IN A CVS TEST CELL

The engine was also equipped with a close-coupled diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF) combination. For the purpose of producing higher PM emission levels, a bypass was created around the aftertreatment system to allow an adjustable amount of exhaust flow around the DPF. A DOC was added to the bypass so that all of the PM in the exhaust would pass through an oxidation catalyst simulating a scenario of a cracked DPF. A picture of the bypass is shown in Figure 17.

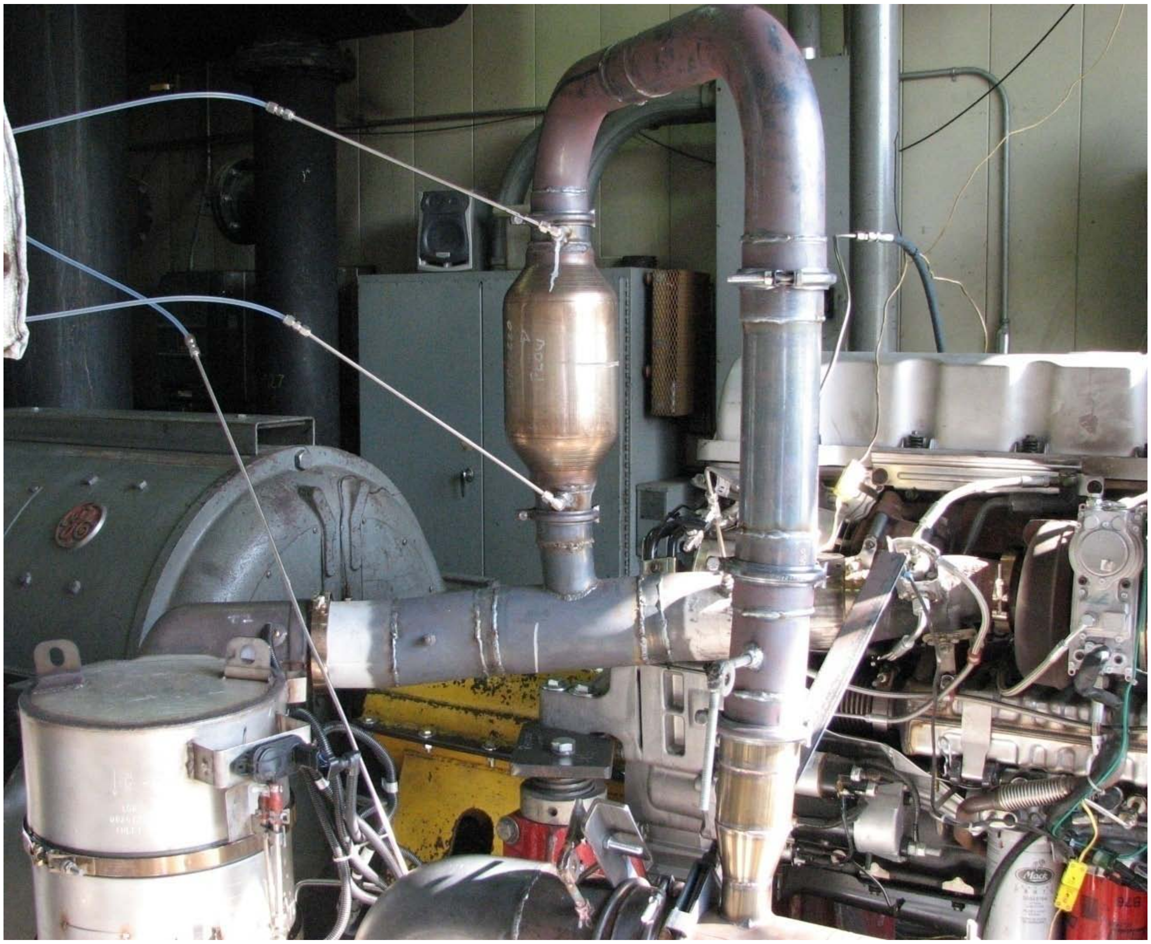


FIGURE 17. DPF BYPASS WITH DOC

The original stock aftertreatment was located in the main leg of the exhaust, while a separate catalyst was procured for the bypass leg. The DOC was 76 millimeters (six inches) in diameter with a length of 152 millimeters (12 inches). Three butterfly valves were placed in the exhaust system to control the amount of exhaust passing through each leg. The DPF was regenerated via an exhaust fuel injection system. For all testing, the bypass was open to some degree, however, the bypass leg was closed when active regenerations were performed on the DPF. The DPF bypass went through multiple iterations until the proper PM level was achieved during steady-state testing. A PM level of 0.025 g/hp-hr was easily obtainable during transient cycles, however it was extremely difficult to obtain this same PM level during steady-state engine operation. Table 15 lists the five different configurations of the bypass that were tested.

TABLE 15. LIST OF DPF BYPASS CONFIGURATIONS

Iteration	Pipe Diameter	Inlet Probe	DOC Diameter	Outlet Probe
1	3	No	3	1", Upstream
2	3	No	3	1", Downstream
3	3	3", Upstream	None	1", Downstream
4	3	3", Upstream	6	1", Downstream
5 (Final)	4	3", Upstream	6	3", Downstream

In the final configuration (iteration 5), two butterfly valves in the main leg of the exhaust were completely closed with only a one or two millimeter gap between the valve and the exhaust pipe. This not only forced a majority of the exhaust through the bypass, but significantly raised the exhaust backpressure. Based on measurements upstream and downstream of the bypass with the AVL PEMS, it was estimated that well over 50 percent of the exhaust was routed through the bypass in the final configuration. A diagram of the bypass system is shown in Figure 18.

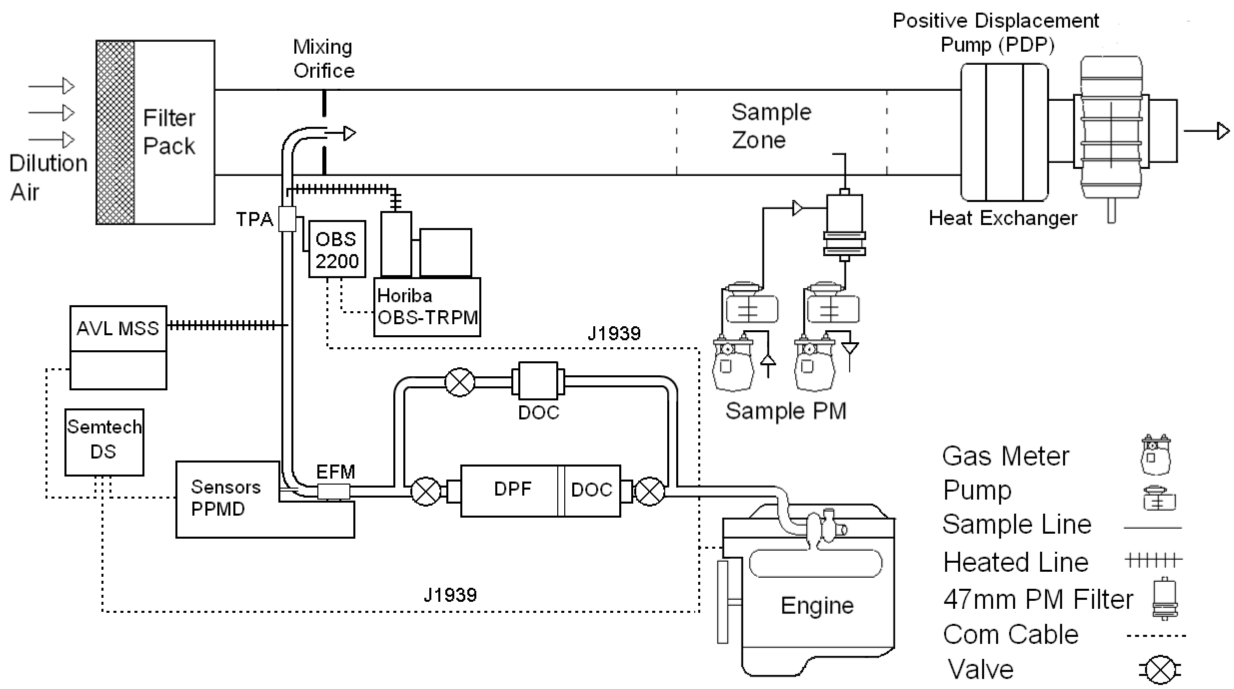


FIGURE 18. SCHEMATIC OF ENGINE DYNAMOMETER EXPERIMENTAL SETUP

The schematic is not to scale so that some distances may appear incorrectly. There are more than 10 pipe diameters between the mixing point of the bypass and the first PEMS sampling position for the Sensors Semtech PPMD. Additionally, there are approximately 10 pipe diameters between each of the PEMS sampling locations so that any flow disturbances caused by a different pitot tube or sample probe should not affect the other PEMS. The portion of exhaust between the first and the last sampling location is insulated to minimize the cooling of the exhaust and thermophoretic deposition of particles. The last sampling probe is that of the Horiba OBS-TRPM, which is just upstream of the entrance into the CVS tunnel. The gaseous PEMS units (Sensors Semtech DS and Horiba OBS-2200) were used only for data acquisition and trigger signals. No PEMS gaseous emissions were recorded during this program. The Semtech DS was used with both the Sensors PPMD and the AVL MSS, while the Horiba OBS-2200 was used in conjunction with the Horiba OBS-TRPM.

The outlet of the aftertreatment was routed to a constant volume sampling (CVS) tunnel for emissions measurement. The CVS consists of a positive displacement pump and an upstream heat exchanger; it was maintained at a nominal flow rate of 3,740 m^3/hr (2,200 scfm) for this testing. The dilution air is extracted through a filter pack from a temperature and humidity controlled area. The portion of the CVS tunnel that is exposed to the test cell environment upstream of the exhaust is insulated to prevent heating of the dilution air from the test cell. The particulate matter samples were extracted from the CVS as shown in Figure 18.

Intake air flow was measured by a laminar flow element (LFE) with a maximum flow of 1,700 m^3/hr (1,000 scfm). The LFE was oriented so that there were 10 diameters of straight pipe before the inlet and after the outlet to minimize flow disturbances. The fuel flow was measured by a Micro-Motion flow meter. The addition of intake air flow and fuel flow was used to determine the exhaust flow using the equations from CFR Part 89. The exhaust flow was used to calculate the exhaust PM concentration from the CVS filter as well as a check on the PEMS exhaust flow meters. A raw CO_2 analyzer was used in combination with the exhaust flow measurement to calculate a raw carbon balance fuel flow which was compared with the measured fuel flow and the dilute carbon balance fuel flow as a quality check.

The PM sampling system consisted of a 47mm teflon membrane filter (Whatman Teflo), a fine metal screen backing, and a plastic filter cartridge. The total flow is operated at a nominal flow of 60 standard liters per minute (2.1 scfm) which results in a filter face velocity of approximately 100 cm/s. The standard temperature and pressure used for all flow rates in this report is 20 °C and 101.325 kPa as specified in CFR Part 1065. The nominal dilution flow is 30 slpm (1.1 scfm) which resulted in a dilution ratio of 2 and a sample flow of 30 slpm (1.1 scfm). The system maintained a constant dilution ratio and achieved proportionality through sampling from the CVS. The system was heated to 47°C and had an approximate residence time of 0.8 seconds from the inlet of the sample probe to the filter. A cyclone with a 2.5 micron cutpoint at 17 slpm was positioned just downstream of the sample probe. The aforementioned PM sampling system was the laboratory reference used to generate all reference PM data used in this program.

4.2.2 Sensors PPMD

The PPMD was the PEMS unit installed closest to the outlet of the bypass, approximately 15 diameters downstream. An experiment was conducted to ensure the flow was fully mixed at this location as will be discussed later. The PPMD was installed in the horizontal orientation as shown in Figure 19.

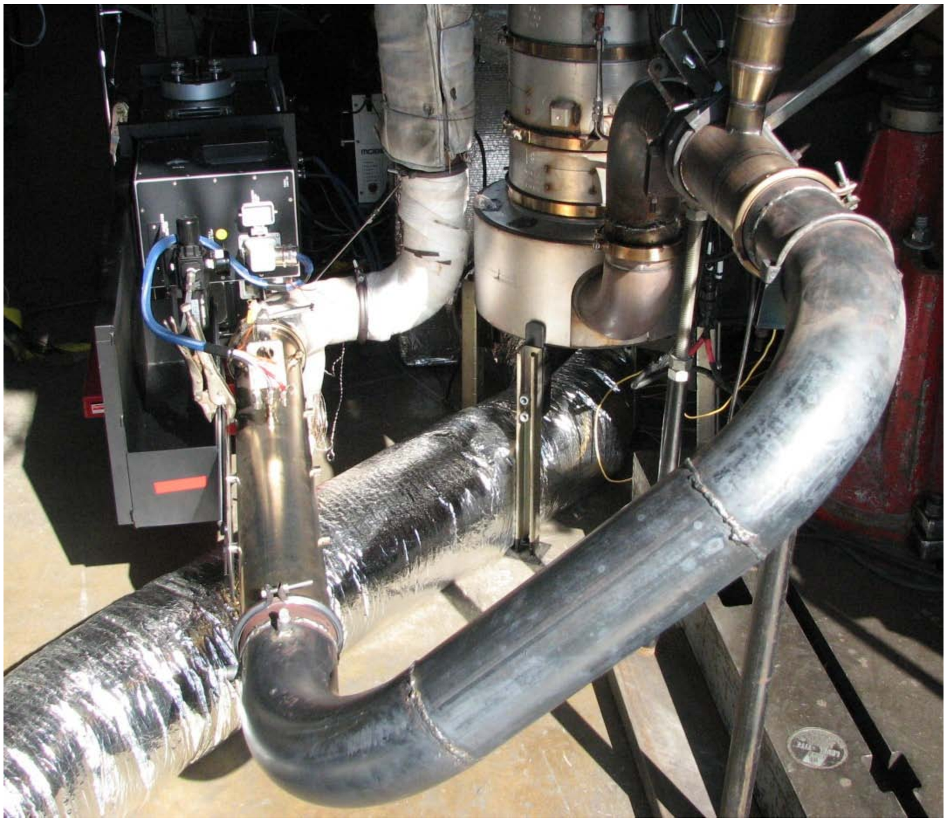


FIGURE 19. PPMD INSTALLED IN THE TEST CELL

The PPMD was equipped with a long straight pipe containing its exhaust flow meter (EFM) just upstream of the 90 degree elbow from which the sample is extracted. The dilution in the Sensors system takes place inside the instrument. The most common installation of the PPMD is in the vertical position, although it requires only the rotation of the moisture traps to properly operate the PPMD in the horizontal orientation. The Sensors PEMS was equipped with two stages of dilution known as MPS1 and MPS2. Although some preliminary testing was conducted using both stages of dilution, the steering committee decided to use only a single stage of dilution for all official tests. The PPMD is a proportional sampling system that varies its dilution ratio inversely with exhaust flow to maintain a minimum dilution ratio of 6 at the maximum exhaust flow rate of an engine. The PPMD measures PM using a Quartz Crystal Microbalance (QCM), which charges the particles using a corona needle, deposits the particle on a Quartz Crystal, and then measures the change in frequency of the crystal to determine the mass deposited. The PPMD is a batch sampling device meaning it does not report PM concentration in real-time but instead reports a single mass value per event. Because each crystal requires a pre and post frequency measurement to determine mass, a total of eight crystals are included to allow for continuous operation by switching crystals. Crystal sampling begins as soon as the engine enters the NTE zone and stops as soon as the engine exits the NTE zone. One of the of the eight crystals was used as a reference crystal to adjust the measurements for changes in temperature and pressure. This left up to seven crystals available for measurement although it was common to have one or two crystals not working on any given test. The timing of the samples during testing was designed around having a minimum of five working crystals available for measurement. The PPMD was included in the measurement allowance program because inertial microbalances had already been approved for PEMS applications in 40 CFR Part 1065.

4.2.3 AVL MSS

The AVL Micro Soot Sensor (MSS, also known as the Photo Acoustic Soot Sensor or PASS) was installed downstream of the PPMD in the middle of the vertical portion of the exhaust pipe leading to the CVS tunnel. The MSS is connected to the tunnel via a 2 meter heated sample line which was maintained at 52°C. The mixing of dilution air takes place in the dilution box just upstream of the sample probe so that the dilute sample is transported through the sample line. The MSS is shown in Figure 20.

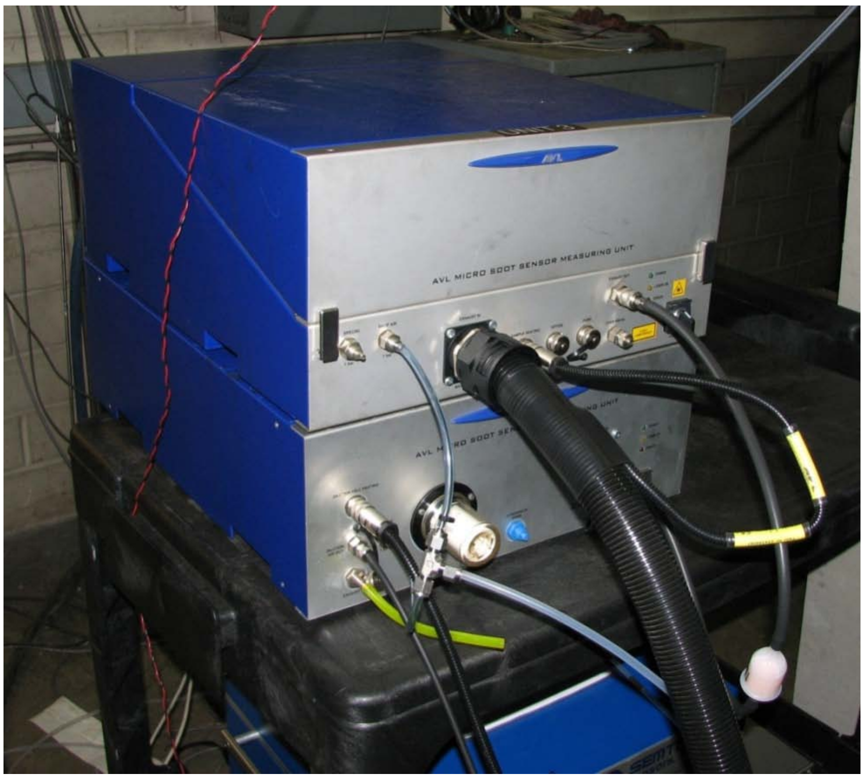


FIGURE 20. THE AVL MSS

The MSS consists of two boxes shown in the above figure. The top box is the measuring unit which contains the resonance chamber for the soot measurement. The bottom box is the conditioning unit which contains the sample and dilution pumps as well flow controllers. The dilution pump is optional as the MSS can also provide dilution air via an external input of 300 kPa of compressed air. The steering committee requested that the MSS operate using its internal dilution pump, since this is the way it would operate during in use testing. The MSS measures soot by heating the elemental carbon using a laser. When the soot is heated it emits a sound wave that is detected by a microphone. The MSS can report soot concentration on a 1Hz basis and uses a constant dilution ratio, which was set at 5 for all official testing. Because the MSS measures only soot and not total PM, it was included in this program as a partial participant. If both the Sensors and Horiba units could not complete the measurement allowance program it was to be considered for in-use. The AVL system does not have its own gaseous PEMS; or data storage device; instead it depends on the gaseous information from the Semtech DS and sends its concentration signal to the Sensors Semtech DS where the necessary information is recorded. For all testing in this program a single Semtech DS was used to record the signals from both the

Sensors Semtech PPMD as well as the AVL MSS. The probe for the Horiba OBS-TRPM is located approximately 1.65 meters (5 feet) downstream of the MSS. The Horiba system contains two separate exhaust pieces that are each about 150 mm (6 inches long). The upstream portion is a tail pipe adapter (TPA) which is a pitot tube exhaust flow measurement. The downstream pipe contained the probe for the PM sampling. The TPA and sampling probe can be seen in Figure 21.

FIGURE 21. THE PROBE AND TPA FOR THE HORIBA OBS-TRPM

4.2.4 Horiba TRPM

The Horiba system is a proportional sampling device that varies its dilution ratio in the same manner as the PPMD. The dilution air is introduced just downstream of the probe before the heated sample line. The point of dilution can be seen in Figure 21 where the three stainless steel lines converge into the stainless steel cylinder. The OBS-TRPM uses a TSI EAD (referred to here as a DCS) real time particle instrument to measure the particle concentration on a second by second basis and collects PM on a gravimetric filter simultaneously. The filter weight gain is used to provide a calibration constant to the real time particle signal and apportion the PM mass appropriately. The DCS instrument measures continuously, but the filter is designed to sample during valid NTE event operation from the same diluted exhaust stream. The filter sampling begins after five seconds in the NTE zone and will continue for a minimum sample time of 30 seconds even if the engine is no longer in the NTE zone. Because the EPA's PM standard is based on gravimetric filter analysis, the Horiba system was included in the program. The OBS-TRPM is comprised of several different boxes including the heated enclosure (HE), the diffusion charge sensors (DCS), the electrical enclosure (EE), and the mechanical enclosure (ME). The HE contains the 47mm filter holder, and the DCS is the real time particle sensor. Dilution air was provided using a commercially available oil-less compressor. The Horiba OBS-2200 gaseous PEMS was used to log the ECM J1939 broadcast, measure the exhaust flow, and provide an NTE trigger to the TRPM to start filter sampling. The combined TRPM-2200 system contains a total of 6 boxes plus an external compressor. The components of the Horiba system are depicted in Figure 22.

FIGURE 22. THE HORIBA OBS-TRPM AND OBS-2200

The TRPM used the same 47mm Whatman teflo filter, metal screen, and plastic cartridge as the CVS system. All weighing and conditioning of both the CVS and the TRPM filters was conducted in the SwRI filter weighing room. The filter weighing room is maintained at a temperature of 22 ± 1°C with a dewpoint of 9.5 ± 1°C in accordance with CFR Part 1065.190. Filters were stabilized in the weighing environment for at least 1 hour prior to both the initial and final weights. Each filter was weight was determined by the average of three weights on a scale with a resolution of 0.1 μg.

4.3 Bypass Mixing Verification

The flow from the DPF bypass was reintroduced into the main exhaust stream using a 76 mm (3 inch) probe facing downstream with an orifice near the tip of the probe to promote mixing. Testing was conducted to ensure the exhaust flow was fully mixed prior to the first sampling location, which was occupied by the Sensors PEMS. Two probe orientations were created at the spot where the Sensors sample was extracted. One of the probe orientations was parallel to the upstream exhaust elbow and one was perpendicular to the elbow. The orientation of the AVL sample probe is shown in Figure 23.

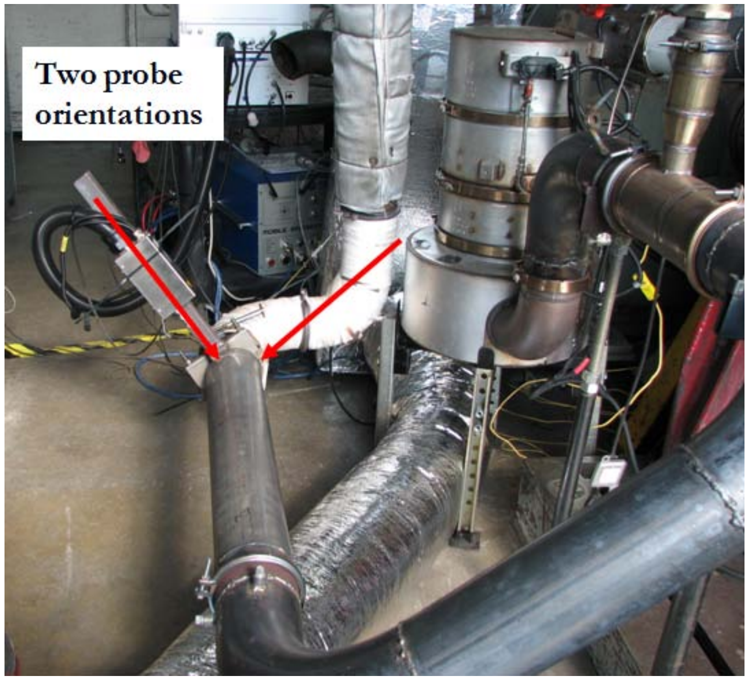


FIGURE 23. EXPERIMENTAL SETUP FOR MIXING VERIFICATION

At each of the probe orientations the MSS was used to measure the exhaust soot concentration using a variable length probe that could traverse the length of the 127 mm (5 inch) exhaust pipe. There were five sample locations for each orientation as shown in Figure 24.

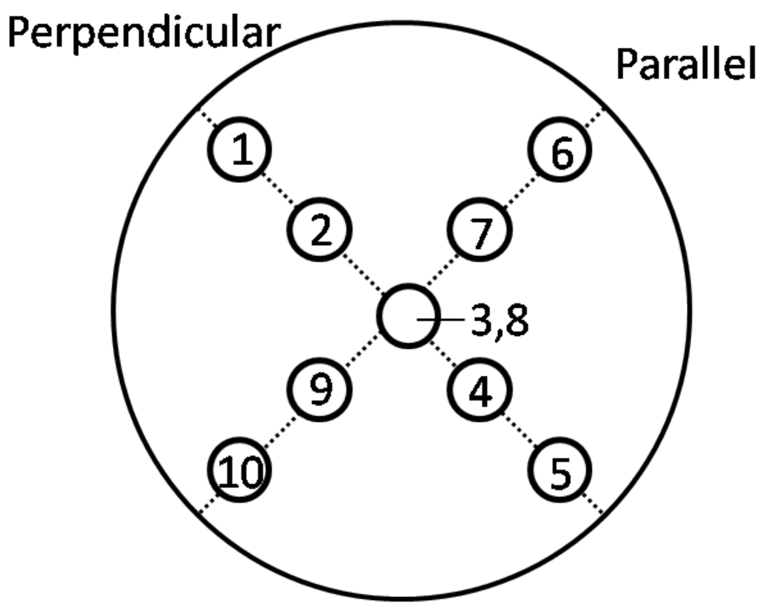


FIGURE 24. MIXING VERIFICATION SAMPLE LOCATIONS

Each of the positions were one inch apart, with position 3,8 being at the center of the exhaust pipe. For a measurement, the probe was started at location 1, moving down to 5 and then back to 1. The probe was then moved to position 6 moving down to position 10 and back to position 6. The MSS measurement was recorded for 80 seconds at each position, with the average of the last 30 seconds used for comparison. The steady-state modes with the highest and lowest exhaust flow rates were chosen to perform the mixing verification, to ensure proper mixing over the entire range of test conditions.

The mixing verification was performed several times with different bypass configurations with similar results in all cases. Only the results from the final mixing verification are presented since the other results from different configurations are not relevant to the data in this report. The data from the final verification is presented in Figure 25.

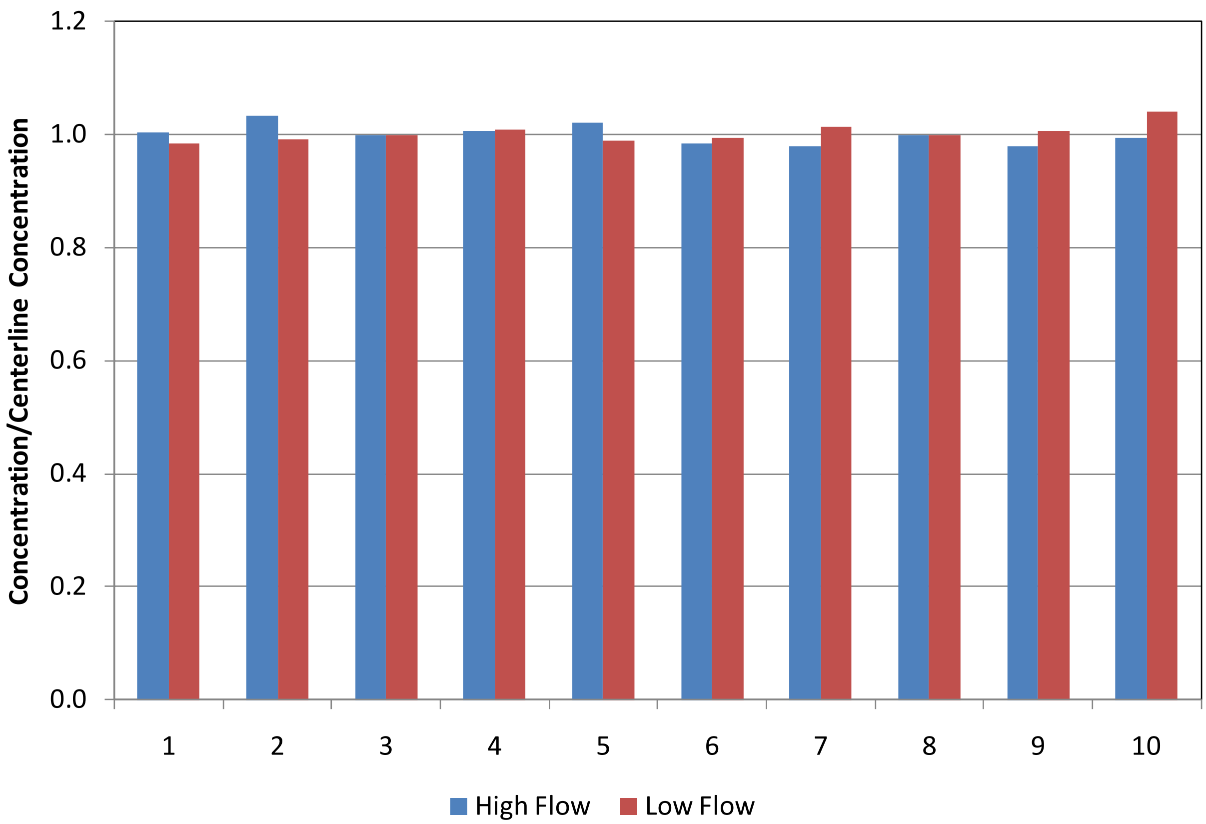


FIGURE 25. MIXING VERIFICATION RESULTS

The data is presented as the ratio of the average concentration at each location to the centerline concentration. The data was normalized in this way not only to remove some of the engine variability but also so that the two exhaust flow conditions with different soot concentrations could be compared on the same plot. Each data point represents the average of two samples taken at each location. The highest deviation from the centerline concentration was four percent at location 10, low flow which was considered acceptable, especially given that no trends were observed in the data. A paired t-test using equal variance was also performed on the data relative to the centerline position for the parallel orientation using the high and low flow. Locations 6 through 10 passed the t-test, except for location 10 at low flow, although the difference in the mean value between locations 10 and 7 was less than 4 percent. The steering committee was satisfied with the mixing results and directed SwRI to move forward with the program without any further modifications for the bypass setup.

4.4 PEMS Loss Corrections

Each PEMS manufacturer was given the opportunity to correct their final PM measurement to account for various particle losses encountered during the sampling process. Any loss correction had to be presented to the steering committee for approval before it was implemented in the program. Sensors and AVL both chose to implement loss corrections, while Horiba declined to apply a loss correction to their data.

4.4.1 Sensors PPMD Loss Correction

Sensors conducted work under a separate project at SwRI to experimentally assess the losses in the PPMD. David Booker presented the results of this work along with the proposed Sensors loss corrections at the meeting on December 10th, 2008 at SwRI. The final PPMD loss correction included thermophoretic, electrostatic, and CVS loss factors. The CVS loss correction factor was meant to estimate the particle losses in the CVS system, since this is the standard to which the PPMD is compared. Although typical loss correction factors will increase the estimated PM concentration, the CVS correction factor actually decreased the PPMD estimated concentration. The Sensors strategy was to use the thermophoretic and electrostatic loss corrections to determine what the true PM concentration is and then reduce that number by the amount of PM mass they believe will be lost in the CVS system. They did not wish to merely adjust to the correct concentration since the CVS system to which their instrument was compared did not correct for losses. A total CVS loss of 15 percent was estimated by Sensors based on general experience rather than specific data. The total loss correction was estimated to increase the PM concentration by 5 to 10 percent when including the electrostatic and thermophoretic loss factors. The proposed loss corrections were accepted by the steering committee and implemented in the Sensors PPMD post processor. All Sensors data in this report includes these correction factors unless otherwise stated.

4.4.2 AVL MSS Loss Correction

The proposed AVL loss correction was presented at the meeting on November 12th, 2008 at SwRI. The loss correction implemented by AVL was intended to correct for the thermophoretic losses in the system and is based off a paper by Stratmann et al [6]. The equation for the loss correction is shown below:

$$M_{soot} = \int mss(t + \Delta t)\, q_{ex}(t)\, \left(1 + L\left(T_{ex}(t)\right)\right) dt$$

$$L(T) = \begin{cases} 0 \text{ if T} < 150 \\ a + b(T\text{-}150)/300 \text{ otherwise} \end{cases}$$

The magnitude of the correction is temperature dependent and was estimated to be approximately 10 percent in most cases. This correction was accepted by the steering committee and implemented in the AVL Concerto post processor.

At the meeting at SwRI on December 10th, 2008, AVL stated that their loss correction was currently capped at a maximum loss of 25 percent regardless of the calculated value. AVL requested approval to remove this limitation and allow the equations output to be the correction, regardless of its magnitude. This change was accepted by the steering committee.

4.4.3 AVL MSS Total PM Correction

The AVL Concerto post processor includes a function that estimates the total PM based on the measured soot, exhaust temperature, and total hydrocarbon concentration, along with a number of adjustable input parameters including the volume of the catalyst, the light off temperature of the catalyst and the sulfur content of the fuel. Although this calculation was not approved for use with the official measurement allowance data, a portion of the AVL data was processed to examine the results from the total PM model. All AVL data presented in this report refers to the soot concentration corrected for losses unless otherwise stated.

4.5 Steady-State Testing Procedure

Originally the test plan called for two different engines at three different emission levels of PM: DPF out, 0.02 g/hp-hr level, and a 0.03 g/hp-hr level. The DPF out level is simply whatever the emissions happen to be with no bypass which was well below the 2007 standard of 0.01 g/hp-hr. The 0.02 and 0.03 g/hp-hr levels would be set by adjusting the DPF bypass to produce the corresponding brake-specific PM number from the CVS filter. Due to funding limitations the testing was reduced to a single engine at a single emission level. Because 0.03 g/hp-hr will be used for the first year of compliance testing and 0.02 g/hp-hr is used with the following years, it was important to investigate the performance of the PEMS covering these levels. For this reason an average of the two threshold PM levels, 0.025 g/hp-hr, was used as the target.

The objective of the steady-state testing was to evaluate the bias and precision of the PEMS using 180 data points for each PEMS manufacturer. The 30 points consists of six steady-state modes of engine operation (6), 10 repeats (10), one emission level (1), one engine (1), and three different PEMS units (3), 6*10*1*1*3=180. A PM steady-state error surface, $\Delta_{SS}\overline{m}_{PM}\left(\frac{g}{mol}\right)$, was developed for each PEMS manufacturer so that there are three steady-state PM error surfaces for use with calculation methods 1 and 2. For calculation method 3, the AVL MSS will have a unique $\Delta_{SS}\overline{m}_{PM}$ based on the calculations for method 3. As mentioned previously, the Sensors and Horiba PEMS will only use methods 1 and 2. To determine the most suitable six steady engine modes for steady-state testing screening tests were performed using the 80 points Cummins cycle and measuring the PM levels with the AVL MSS and the TSI Engine Exhaust Particle Sizer (EEPS). The EEPS primarily provides size distribution information, but mass concentration can be inferred using an assumed density. Since the AVL is the only PEMS that can report a real time mass concentration without further efforts such as filter weighing and post processing it was chosen to perform the screening work. The Cummins cycle steps through 80 steady-state engine modes as a transient cycle. The engine is stepped through 10 different speeds and eight engine loads at each of the selected speeds. The minimum speed of the cycle is the minimum NTE speed, and the minimum torque is 30 percent of the torque at the given speed meaning that the cycle effectively maps the NTE zone. Figure 26 shows the speed and torque points of the cycle.

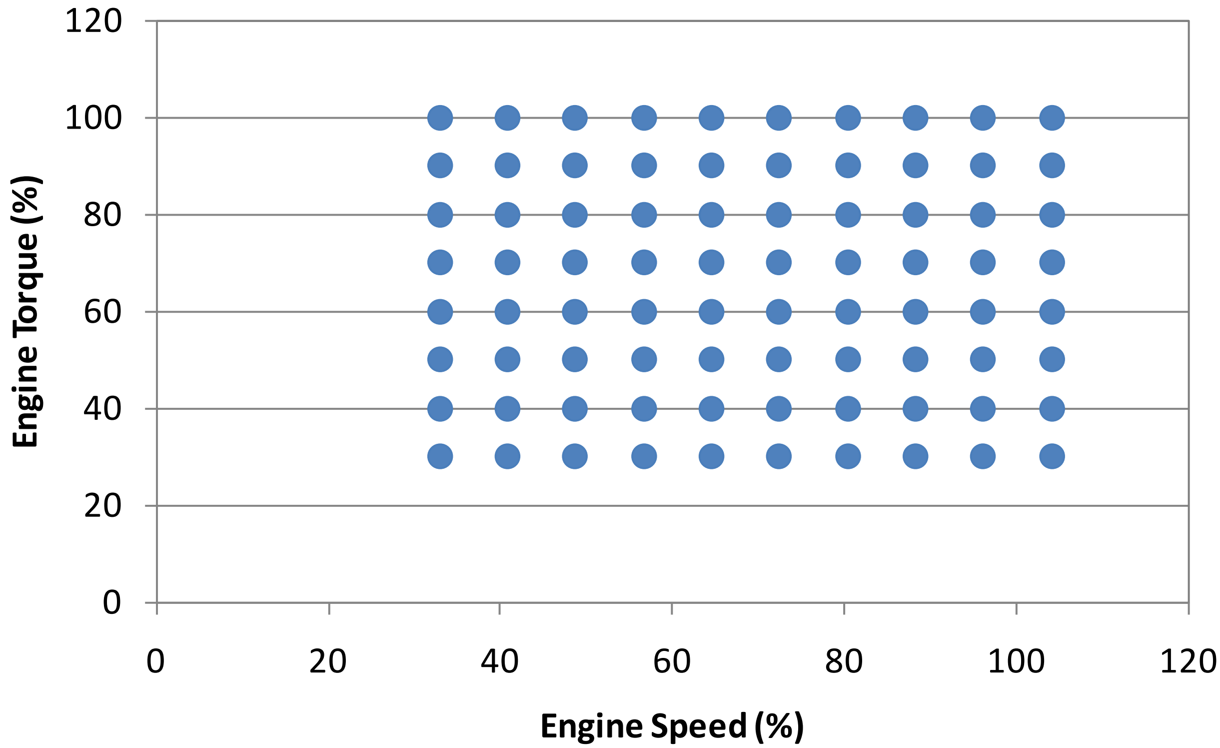


FIGURE 26. SPEED AND LOAD FOR THE 80 POINTS CYCLE

The engine remained at each of the points for 88 seconds with a one second transition between modes. Because the speed and load were only incrementally changed in between each mode, it was assumed that each point would stabilize relatively quickly. The fact that this cycle was used only as a method of screening also contributed to the decision to change modes quickly. Even with such short modes, the total cycle length was 2 hours. To allow for purging, and calibrating the gas analyzers, the cycle was divided into two 40 points cycles each lasting one hour. The gas analyzers were necessary because this cycle was also used to tabulate ECM fuel rate errors for this error surface.

The PM emissions were estimated by measuring each of the 80 modes with the EEPS and MSS, then choosing two of the modes to perform a filter measurement and compare the ratio of the filter measurement to the EEPS and MSS as an estimate of the CVS filter BSPM at each of the 80 modes. Although this method is not highly accurate, it provided a way to quickly obtain rough estimates of the engine PM levels over a wide range of speed and torque conditions. Of the initial 80 points, only 12 were estimated to produce brake-specific PM of greater than 0.02 g/hp-hr. The final six modes were chosen with the intent of covering as much of the NTE zone as possible while still maintaining high BSPM levels, and a range of PM exhaust concentrations. Several iterations of adjusting the bypass, taking filter measurements, and narrowing down the number of points occurred before the steering committee approved the final six points for steady-state testing. Originally the DPF bypass was adjusted to produce the 0.025 g/hp-hr of PM based on a filter measurement during a short version of the NTE transient cycle. The PM emissions at steady-state were much lower at the same bypass setting. Since it was desirable to conduct the steady-state testing at the same PM levels as the transient testing, it was necessary to adjust the system to allow a much greater amount of the flow through the bypass. Six points were chosen out of the twelve to provide a range of PM concentration, exhaust flow rates, and engine operating conditions. The six points that were chosen are shown in Figure 27 along with the NTE zone.

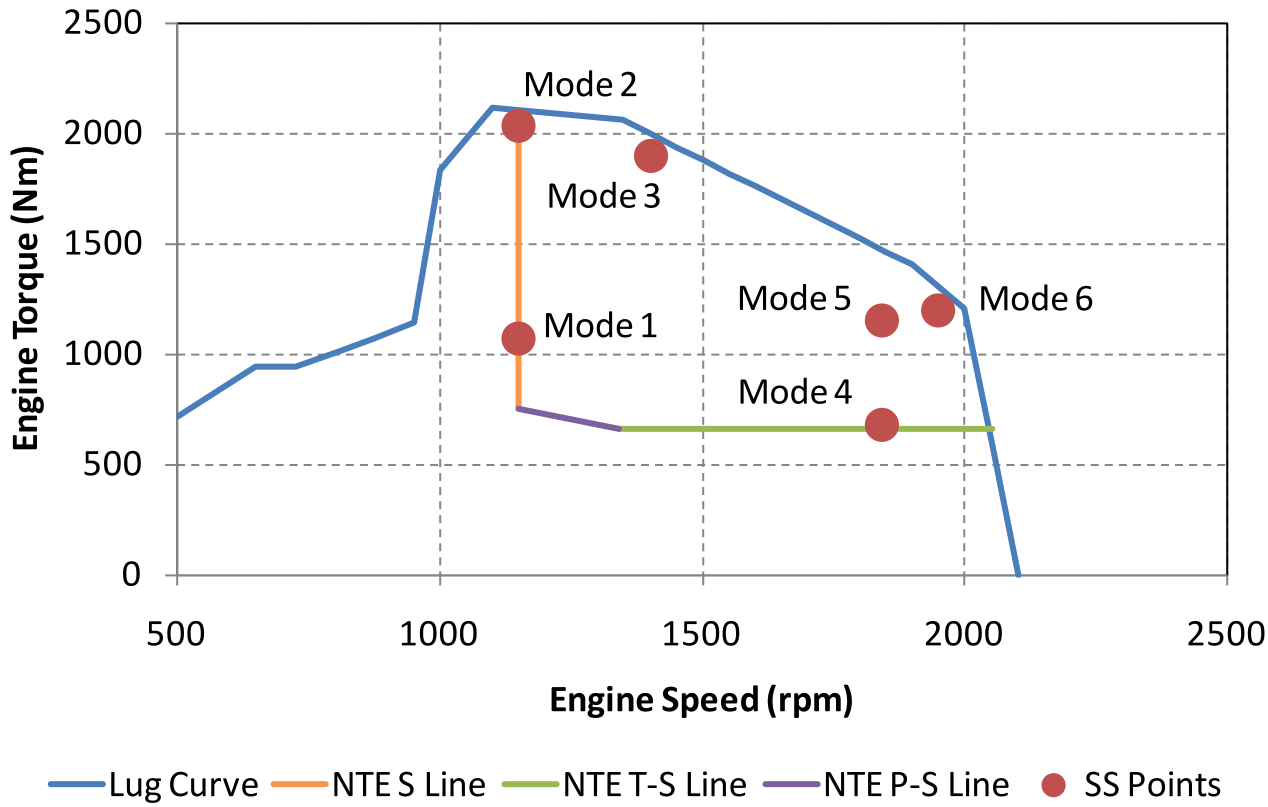


FIGURE 27. FINAL SIX STEADY-STATE MODES

Although the MSS was used to screen the 80 points, the actual concentration at each position was verified with CVS filter measurements before selecting the points. The exhaust PM concentration was calculated by multiplying the CVS PM concentration by the CVS dilution ratio. The CVS dilution ratio was calculated by dividing the average CVS flow rate by the average exhaust flow rate. The CVS dilution ratio ranged from 3 to 7.5 resulting in an overall dilution ratio of 6 to 15 when including the secondary PM filter dilution.

The steady-state testing was conducted as a modal transient cycle with each mode repeated twice for a total of 12 modes per cycle. 6 different cycles were created with the order of the modes randomized in each cycle. Table 16 lists the sample order of the modes in the 6 steady-state cycles.

TABLE 16. SAMPLE ORDER FOR STEADY-STATE CYCLE TESTING

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
Sample 1	3	1	3	3	4	6
Sample 2	6	4	1	4	2	1
Sample 3	5	3	6	1	1	4
Sample 4	2	6	2	2	5	3
Sample 5	4	5	5	6	3	5
Sample 6	1	2	4	5	6	2
Sample 7	5	2	4	6	5	4
Sample 8	2	1	2	4	3	1
Sample 9	1	4	3	1	4	6
Sample 10	3	5	1	2	6	3
Sample 11	6	6	5	5	2	5
Sample 12	4	3	6	3	1	2

The steady-state testing was conducted as a ramped modal cycle with the engine remaining at each operating condition for three minutes before the start of sampling. An external trigger from the lab was provided to each of the PEMS and the CVS filter system so that sampling would begin simultaneously for all instruments. The engine then remained at the operating condition for 5 seconds after the end of sampling to ensure that no delay in the end of sampling by any of the PEMS caused part of the transition period to be captured as a sample. The engine remained at the condition for five seconds after sampling had finished to ensure all systems had finished sampling before the operating condition changed. The order of the modes was randomized and each mode was repeated twice within a single cycle for a total of 12 data points for each cycle. Six different cycles were created, which would create a total of 72 data points. Although the target was only 60 valid points for each set of PEMS, in practice several cycles had to be repeated to collect enough valid data. An example of one of the steady-state cycles is shown in Figure 28.

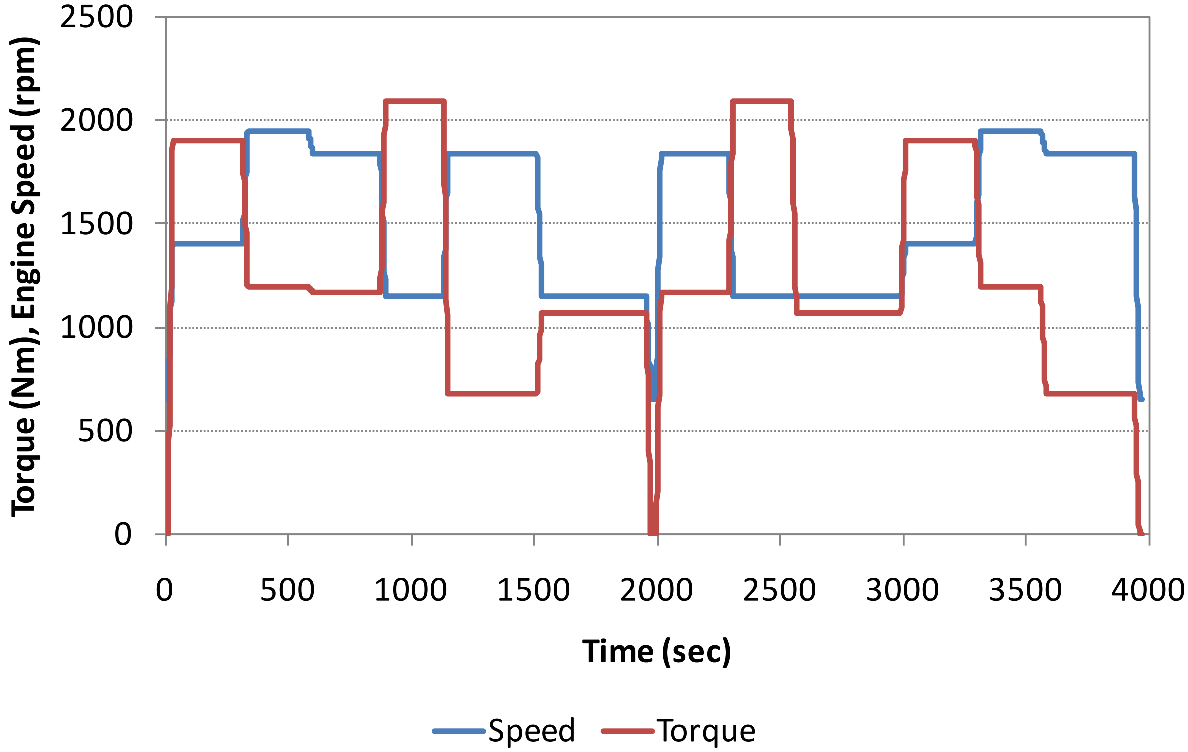
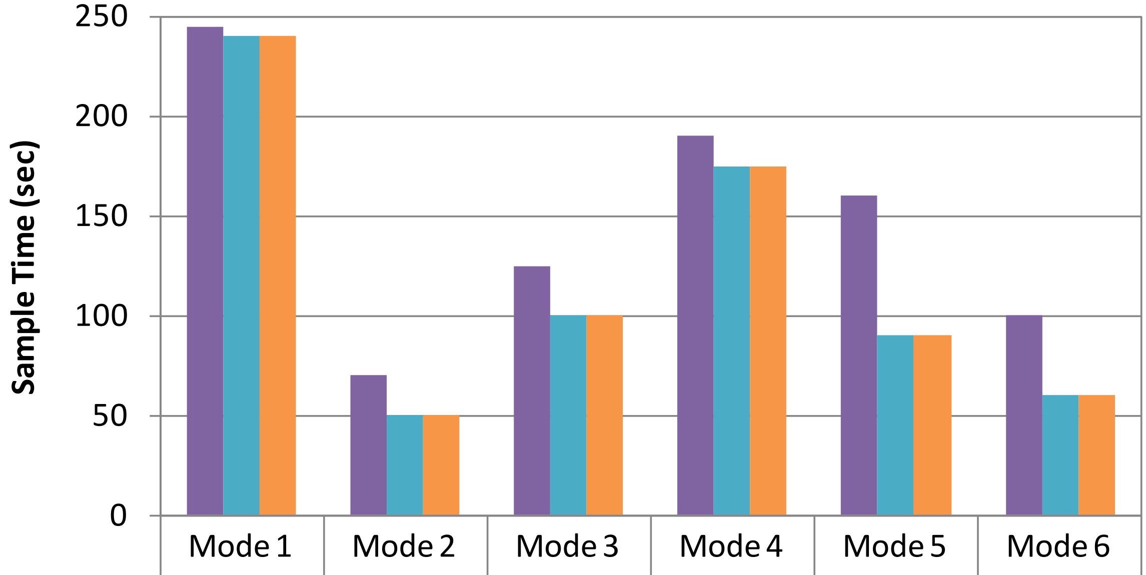


FIGURE 28. EXAMPLE OF STEADY-STATE CYCLE

To ensure a comparably accurate filter weight, a filter weight gain of 100 µg was targeted for each mode. By collecting this amount of material on each filter, the weighing variability and tunnel background contribution could be minimized. Collecting more material than this for each steady state sample would have caused problems with the Horiba and Sensors PEMS by limiting the amount of time they could operate before switching filters or cleaning crystals. To produce a similar filter weight gain at six different steady-state modes with different mass rates, the sampling time was adjusted for each mode to meet this target. The sample time ranged from 50 seconds to 245 seconds. Since the sampling time for each mode was different, the total length of time spent at each mode was different as well. The sample time for each mode for each round of the PEMS is shown in Figure 29.



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
PEMS 1	245	70	125	190	160	100
PEMS 2	240	50	100	175	90	60
PEMS 3	240	50	100	175	90	60

FIGURE 29. STEADY-STATE SAMPLE TIMES

Figure 30 shows the average filter weight gain for all six modes for each of the three PEMS.

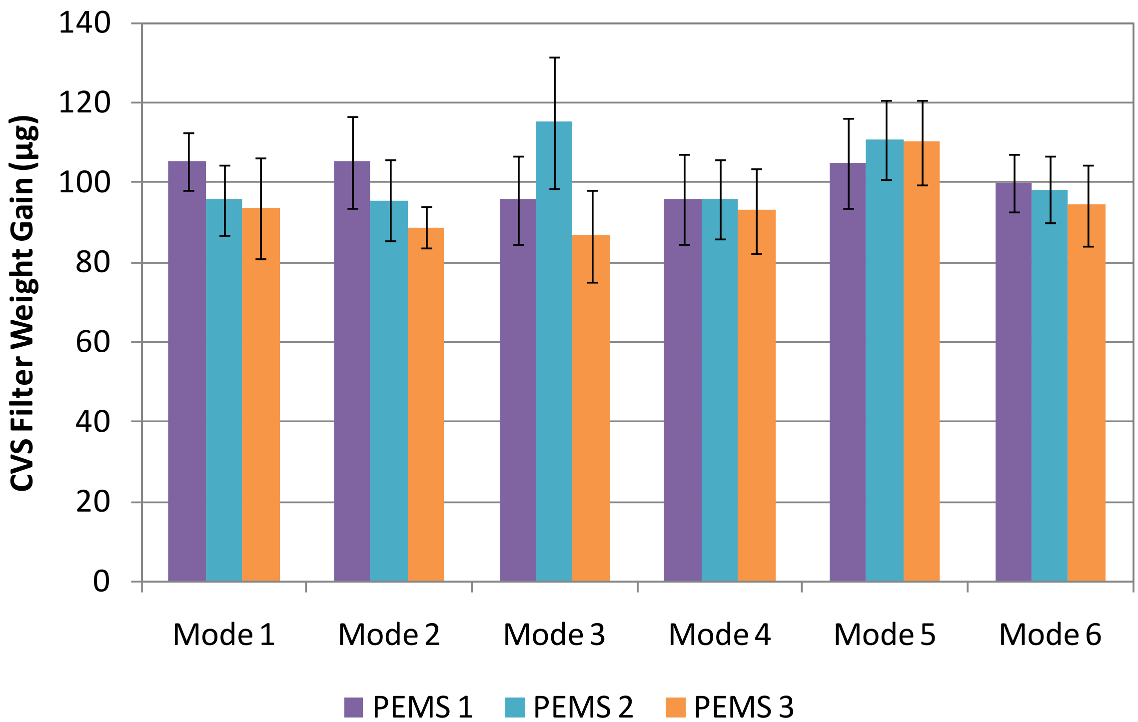


FIGURE 30. CVS FILTER WEIGHT GAIN FOR STEADY-STATE TESTING

Before presenting any of the PM concentration data it should be mentioned the choice of units in this work. The test plan called for the PM concentration to be calculated in terms of µg/mol. Although it is an uncommon unit for describing mass concentration it was considered for fundamental to use mol for volume rather than m^3 in which case a standard reference condition must be defined. For reference, 1 mg/m³ of air at 20°C and 101.325 kPa is equal to 24.055 µg/mol. In several cases the values in mg/m³ are provided in parenthesis for reference, but all official data was calculated and plotted using µg/mol.

The preliminary steady-state results from PEMS 1 were presented at the December 11th, 2008 meeting at SwRI. After reviewing the first set of steady-state data, the steering committee felt that the concentrations from the six steady-state points were not effectively covering the desired range. Five of the modes are clustered between 115 and 161 µg/mol (4.8 and 6.7 mg/m³) with the remaining mode at 325 µg/mol (13.5 mg/m³). At the recommendation of the steering committee the bypass setting was slightly adjusted for PEMS 2 and PEMS 3 in an attempt to fill in some of the region between 161 and 325 µg/mol. Due to a shift in the engine out PM emissions, it was possible to increase the concentration for modes 2, 3, 5, and 6 while maintaining the same levels for modes 1 and 4. In fact, the dampers were actually adjusted to flow less exhaust through the bypass indicating that the engine out PM had not only changed relatively between operating conditions but increased overall. Figure 31 shows the median CVS filter PM concentration for each of the three sets of PEMS.

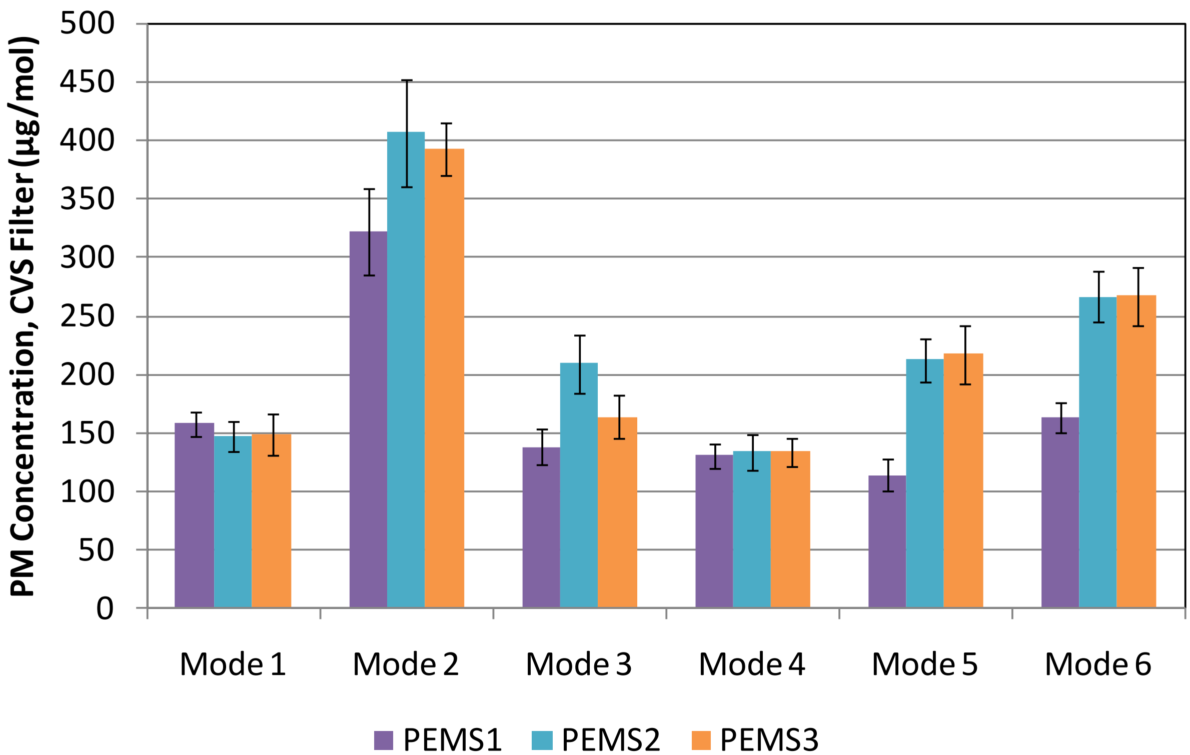


FIGURE 31. STEADY-STATE EXHAUST PM CONCENTRATION (µG/MOL)

The mode with the highest concentration, mode 2, increased up to nearly 423 µg/mol while the lowest concentration increased from 115 µg/mol on mode 5 to 132 µg/mol on mode 4. It is interesting to note that mode 5 and 6 increased in concentration by 87 and 64 percent, respectively while mode 4 increased by less than 2 percent. This increase in concentration came while opening the valve in the DPF leg of the exhaust, thereby increasing the flow of exhaust through the DPF. Modes 2 and 3 both shifted downwards between PEMS 2 and PEMS 3 without any change in the exhaust valve positions. Figure 32 shows the brake-specific PM values as measured by the lab reference for all three sets of PEMS.

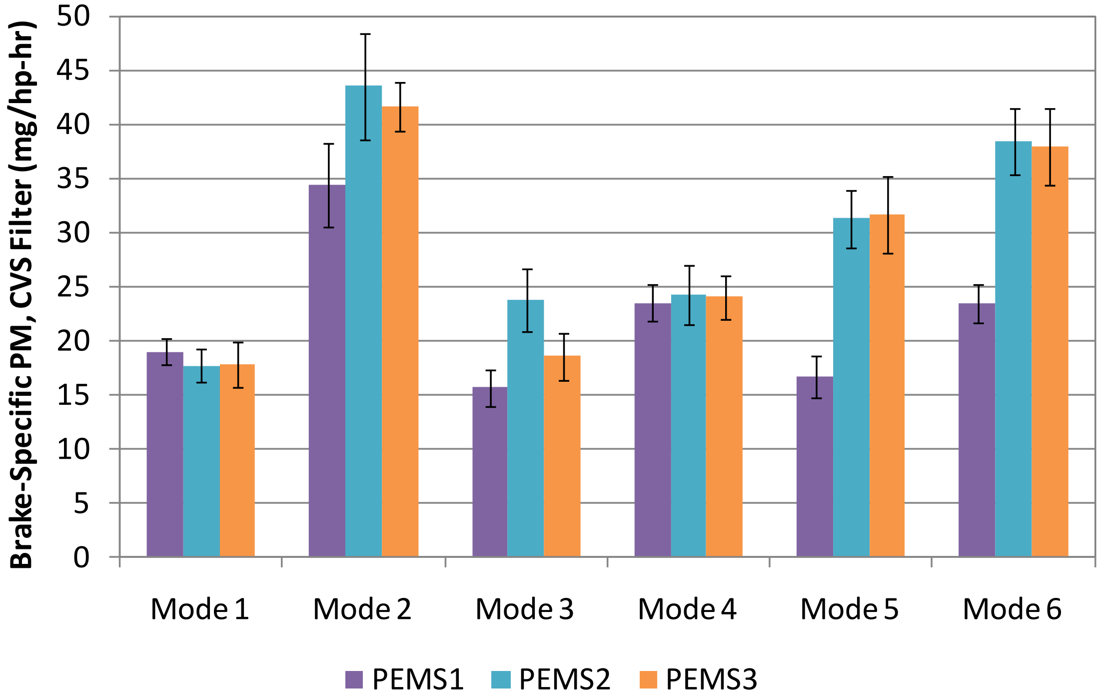


FIGURE 32. STEADY-STATE BRAKE-SPECIFIC PM, CVS FILTER (MG/HP-HR)

The brake-specific PM ranged from 15.7 mg/hp-hr to 43.5 mg/hp-hr.

4.6 Data Yield During Steady-State Testing

The test plan called for a minimum of 10 valid data points for each mode for each PEMS, allowing for a minimum data set of 30 for each 5^{th} and 95^{th} percentile delta that was generated. In reality the target of 10 data points per PEMS per mode was not met in all cases due to additional points that were invalidated by post processing software that had been updated after the testing had been completed. While very few data points were removed during post processing for the Horiba and AVL PEMS, Sensors supplied SwRI with several new post processors after the completion of testing that invalidated a significant portion of the Sensors data. Since the information on what criteria would invalidate the data was not available at the time of testing, it was not possible to know how many additional tests would be required to achieve the necessary number of data points. The Sensor's post processor was revised to include some points that were deemed valid data but had been excluded by the post processor. The final set of data for the Sensors PEMS had between 28 and 34 points per mode. Figure 33 shows the number of valid data points for steady-stat testing.

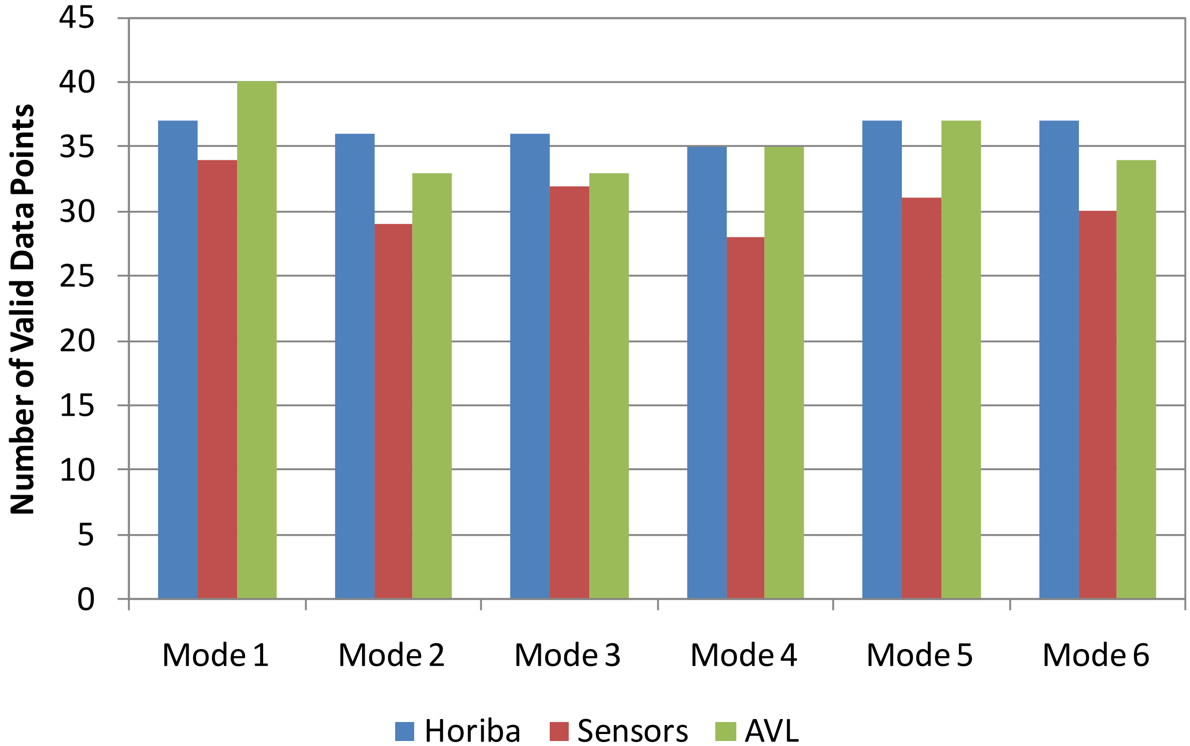


FIGURE 33. NUMBER OF VALID DATA POINTS FOR STEADY-STATE TESTING

The total number of possible data points was either 40 or 41 depending on the mode. Samples were taken 41 times at each mode, but modes 2, 3, 4, and 6 each had one point excluded due to mishandling of the CVS filter.

4.6.1 Data Yield During Steady-State Testing

Table 17 shows the steady-state data yield by each of the PM-PEMS relative to the possible data yield obtained by the CVS. A total of 29 steady-state cycles were conducted for all three PEMS with each of the six steady-state modes repeated twice in each cycle for a total of 12 data points per cycle. Twenty-one of these cycles were considered valid tests from the perspective of the function of the cycle command, NTE external trigger, filter sampling, and at least one or more of the PEMS capturing valid data. During these valid tests four data points were missed due to a mishandling of the CVS filter, but the rest were considered valid data points from the perspective of the lab measurements. Data from the PEMS was removed for a variety of reasons including problems with the datalogging, sampling, exhaust flow measurement, mechanical failures, and filter handling. Appendix E contains a complete list of the reasons data was excluded, but several notable problems will be discussed here.

TABLE 17. DATA YIELD BY EACH PM-PEMS

	Possible	Horiba	Sensors - NewPP	Sensors – Revised PP	AVL
Mode 1	41	37	22	34	40
Mode 2	41	36	25	29	33
Mode 3	41	36	25	32	33
Mode 4	41	35	24	28	35
Mode 5	41	37	17	31	37
Mode 6	41	37	23	30	34
Total	246	218	136	184	212

The Horiba system requires an external source of compressed air capable of supplying approximately 30 lpm at 400 kPa or higher. A commercially-available oil-less compressor was provided by Horiba for use with the system. Unfortunately this compressor had a tendency to stop working on quite a few occasions during testing. Three different compressors of the same model were provided and each experienced this problem. It was believed that the compressor was overheating and shutting off to protect itself, although changes in the test cell temperature did not seem to influence its performance. The compressor would begin to work again after 10 to 15 minutes presumably once it had cooled off. If the compressor stopped working while the Horiba system was in operation, the system lost all of its dilution air once the small air tank had been depleted. This resulted in an undiluted exhaust stream being sampled onto the filter which would quickly overload the filter at the PM concentration levels used in this work not to mention fail proportionality required of the Horiba system. If the compressor stopped working at any point during an official test, the Horiba data for that test was voided. Figure 34 shows an example of a steady-state cycle where the compressor stopped working.

A problem occurred with Sensors 1 involving the auto zero function of its exhaust flow meter. Every hour the Sensors system would attempt to zero the exhaust flow meter by switching the pressure transducers to ambient for a period of time less than a minute. On the Sensors 1 the solenoid switching the pressure transducers from exhaust measurement to zero was not working properly causing the zero function to occur while pressures were being measured from the exhaust. Because the steady-state cycle lasted longer than one hour, this would cause an erroneous exhaust flow measurement on the last two modes of each steady-state cycle. Figure 35 shows an example of the EFM zero problems during a test.

The EFM auto zero function was disabled for the remaining tests on Sensors 1, and for Sensors 2 and 3.

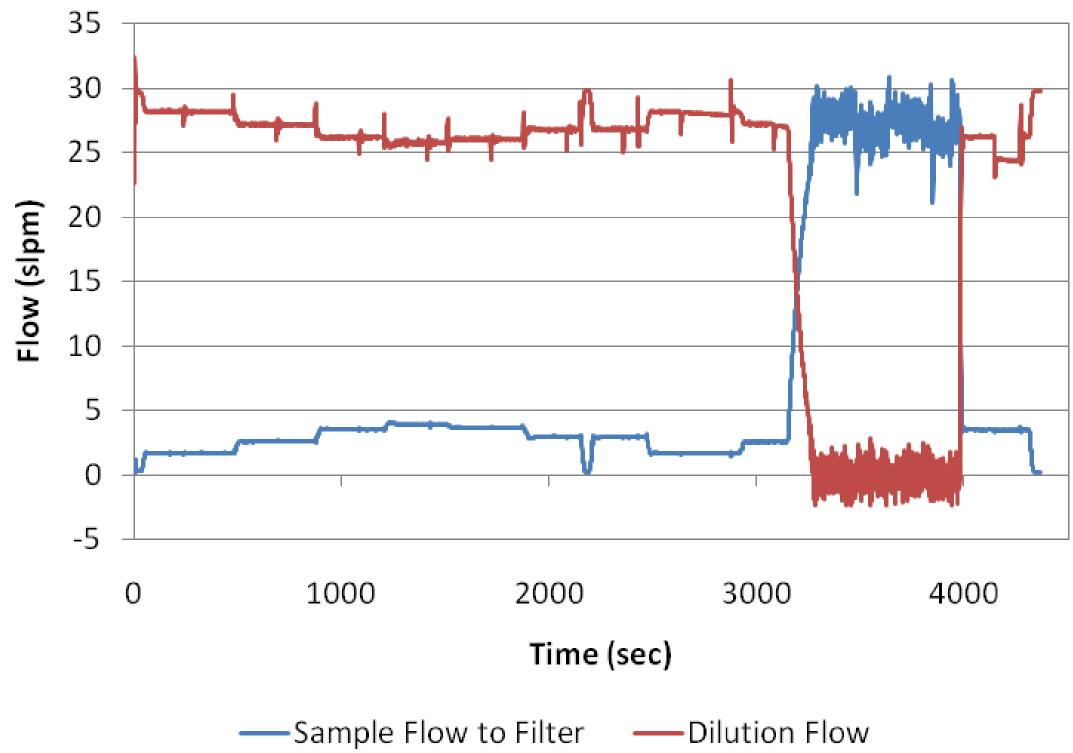


FIGURE 34. HORIBA SAMPLE FLOW TO THE FILTER AND DILUTION FLOW WHILE COMPRESSOR STOPS

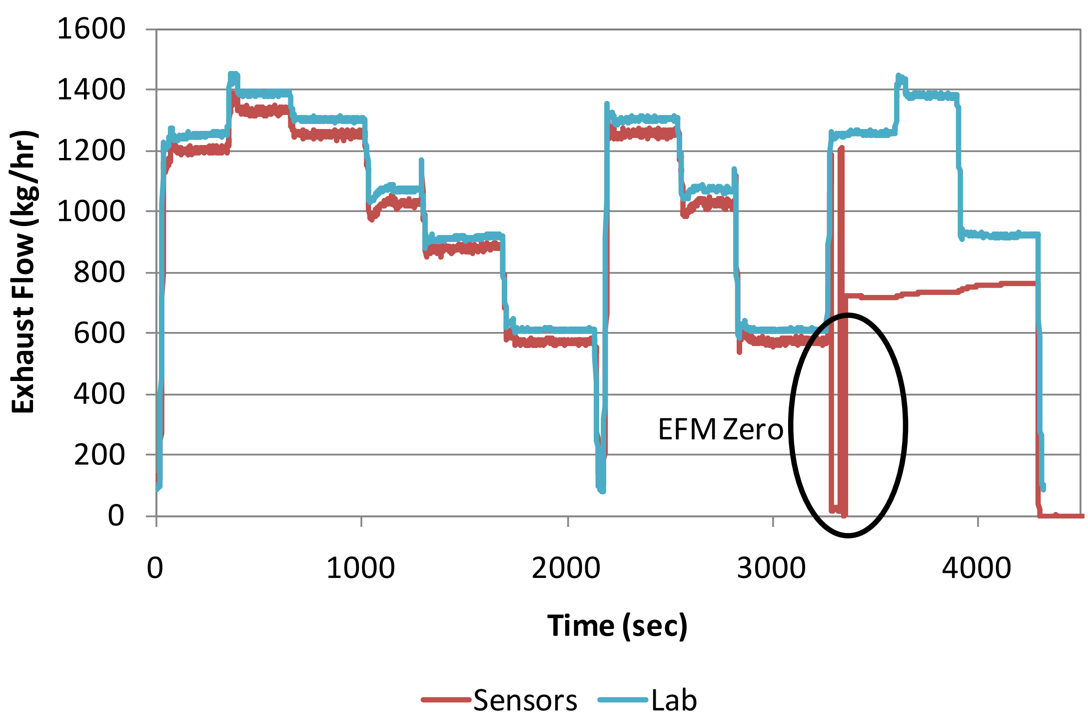


FIGURE 35. SENSORS EFM ZERO DURING STEADY-STATE CYCLE

4.7 Accounting for CVS Variability During Steady-State Testing

The steady-state data has variability due to the PEMS, CVS, and test article. By computing a paired difference for each data point, the test article variability is removed from the data. This concentration delta still contains variability associated with the PEMS and the CVS. The data collected in this program does not allow for independent assessment of the PEMS and CVS variability, but by assuming a CVS variability it becomes possible to assign the remaining variability to the PEMS.

The following procedure for estimating the PEMS and CVS variability was proposed by Bill Martin at the December 12th 2008 meeting at SwRI and was accepted by the steering committee.

1. Since test article variation is the same for each individual observation by the CVS ($x_{PEMS,i}$) and PEMS ($x_{CVS,i}$), compute the paired differences,

$$\Delta_i = (x_{PEMS,i} - x_{CVS,i}) .$$

   These paired differences (i.e., delta values or concentration deltas) contain random variation from the CVS, random variation from the PEMS, and a mean offset between CVS and PEMS (bias error).

2. Divide the entire set of delta values into j = 1 to M subsets based on the values of χ_{CVSi}. The data sets are not subdivided by engine operating mode or PEMS serial number, but only the level of the reference concentration.

3. For each subset, there are i = 1 to N_j values. The median and the MAD are used as the descriptive statistics.

4. Calculate the median delta value, $\Delta_{50,j}$, the median absolute deviation of the Δ_i values, MAD_j, and the estimate of the standard deviation of the CVS random error, $SD_{CVSrandom,j}$.

$$\Delta_{50,j} = median(\Delta_i)\Big|_{i=1,N_j}$$

$$MAD_j = median(\left|\Delta_{ij} - \Delta_{50,j}\right|)\Big|_{i=1,N_j}$$

$$SD_{CVSrandom,j} = \frac{5\,\mu g}{\frac{1}{N_j}\sum_{i=1}^{N_j} L_{CVS,filter,i}} \cdot \frac{1}{N_j}\sum_{i=1}^{N_j} x_{CVS,i}$$

$$SD_{CVSrandom,j} = \frac{5\,\mu g}{\sum_{i=1}^{N_j} L_{CVS,filter,i}} \cdot \sum_{i=1}^{N_j} x_{CVS,i}$$

$$SD_{CVSrandom,j} = \frac{5\,\mu g}{\overline{L}_{CVS,filter,j}} \cdot \overline{x}_{CVS,j}$$

where $L_{CVS,filter,i}$ is the PM sample filter loading. 5 µg is the assumed CVS variability as proposed by the steering committee based on a nominal filter loading of 100 µg.

For each subset j, calculate a corrected delta for each Δ_i value, in subset j, as follows:

if $MAD_j^2 > 0.45495 \cdot SD_{CVSrandom,j}^2$

then

$$\Delta'_{ij} = (\Delta_{ij} - \Delta_{50,j}) \cdot \sqrt{\frac{(MAD_j^2 - 0.45495 \cdot SD_{CVSrandom,j}^2)}{MAD_j^2}} + \Delta_{50,j}$$

else

$$\Delta'_{ij} = \Delta_{50j}$$

Note that this approach correctly passes through any significant offsets observed in the data. These offsets should be passed through even if they persist only for a subset of data, such as a given mode.

5. The entire set of corrected delta values is then to be used to establish the error surface for the steady-state data. The 5th, 50th, and 95th delta values are used to establish the 1st, 50th, and 99th percentile values which are the inputs to the Monte Carlo model.

4.8 Steady-State Testing Results

4.8.1 Comparison between PEMS and Lab Delta PM

All steady-state data presented has already been corrected for the steady-state variability as mentioned above. The steady-state concentration deltas from PEMS 1 for Horiba, Sensors, and AVL, are shown in Figure 36, Figure 37, and Figure 38, respectively.

Each point on the x-axis represents the median exhaust PM concentration from the CVS filter for a single mode. The y-axis represents the 5th, 50th, and 95th percentile of the deltas, PEMS – Lab. As mentioned previously there was a clear gap in the data between 162 µg/mol and 325 µg/mol which represents a large portion of the target concentration range for a 0.025 g/hp-hr level. Figure 39, Figure 40, and Figure 41 show the deltas for PEMS 2 where three of the modes were between 208 and 267 µg/mol.

Horiba-1 and Horiba-2 performed similarly with mode 2 showing a significant negative bias, mode 4 showing a positive bias and the other four modes closer to zero. Sensors-2 showed a much greater negative bias than Sensors-1. Sensors-1 had a 50th percentile of between 0 and -26 µg/mol for five of the six modes while Sensors-2 was between -32 and -104 µg/mol for the 50th percentile for the same five modes. In addition, mode 2 had a 5th percentile of -340 µg/mol at a reference concentration of 442 µ g/mol. For the same mode on Sensors-1 the 5th percentile was -157 µg/mol at a reference concentration of 326 µg/mol. AVL-2 was lower than AVL-1 with 50th percentiles between -34 µ g/mol and -70 µ g/mol. The 50th percentiles for AVL-1 were between 13 µ g/mol and -32 µ g/mol. No indication of the changes in performance for these PEMS was discovered through the recommended checks and audits. The PM deltas for Horiba-3, Sensors-3, and AVL-3 are shown in Figure 42, Figure 43, and Figure 44, respectively

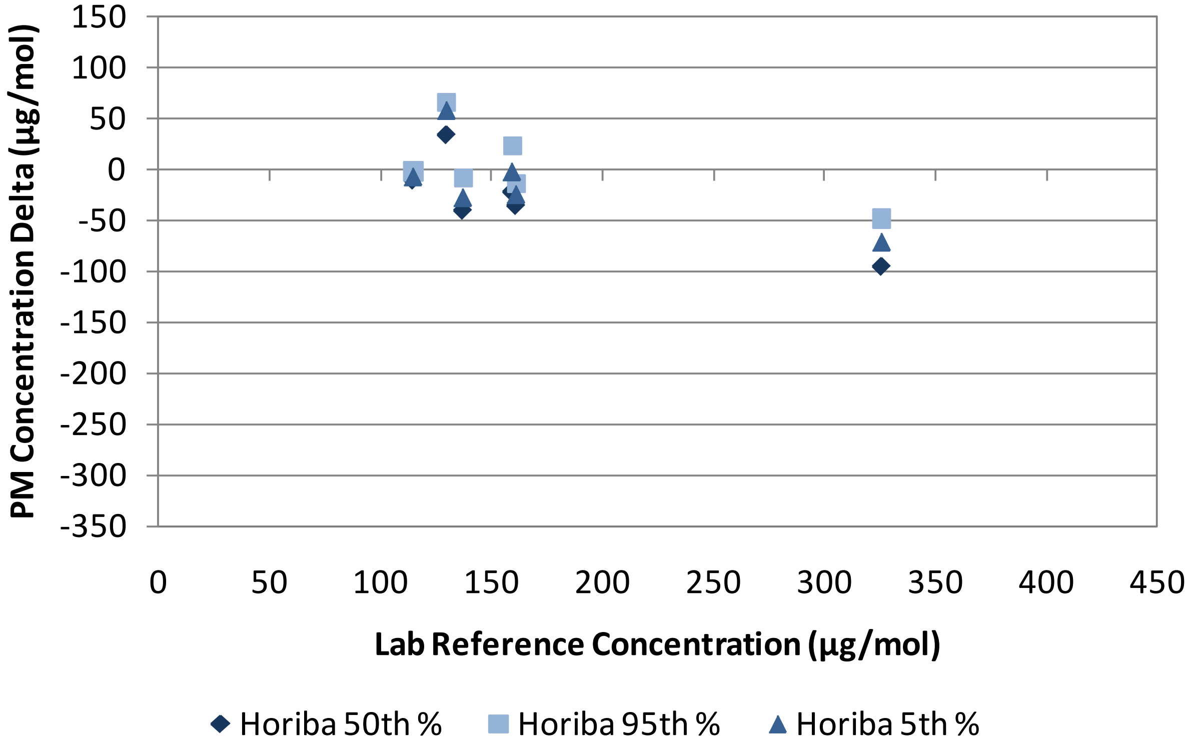


FIGURE 36. HORIBA-1 STEADY-STATE PM CONCENTRATION DELTAS

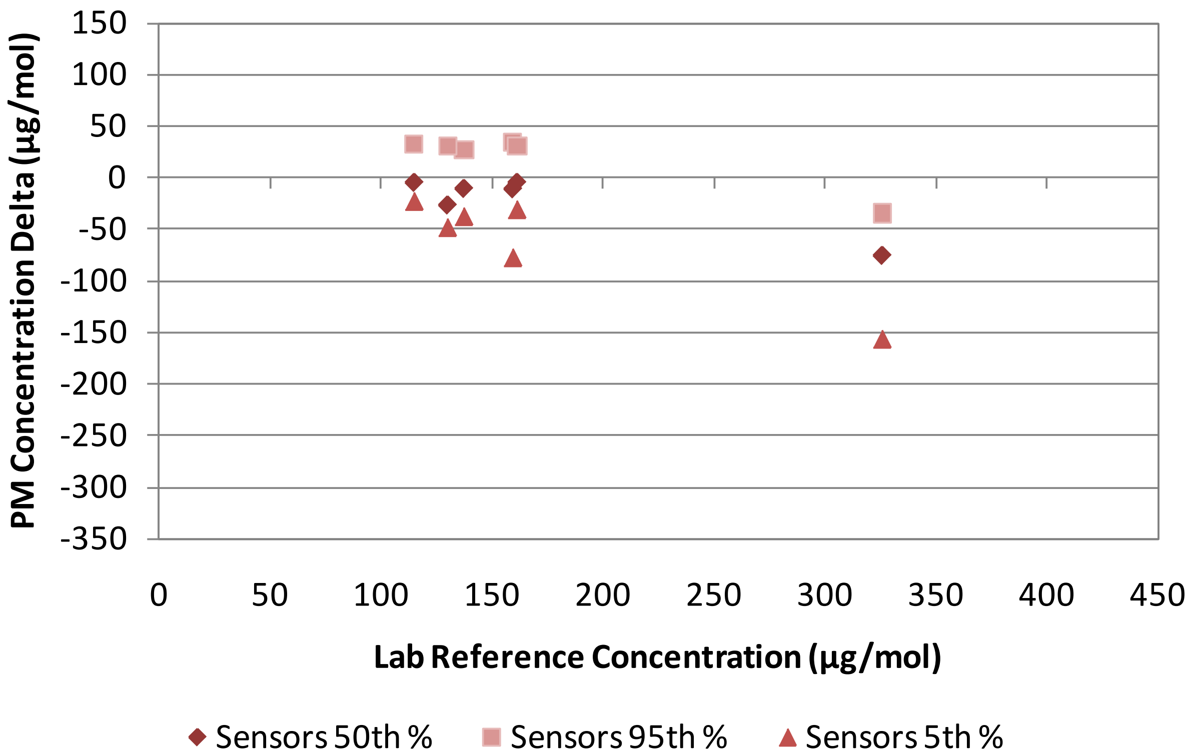


FIGURE 37. SENSORS-1 STEADY-STATE PM CONCENTRATION DELTAS

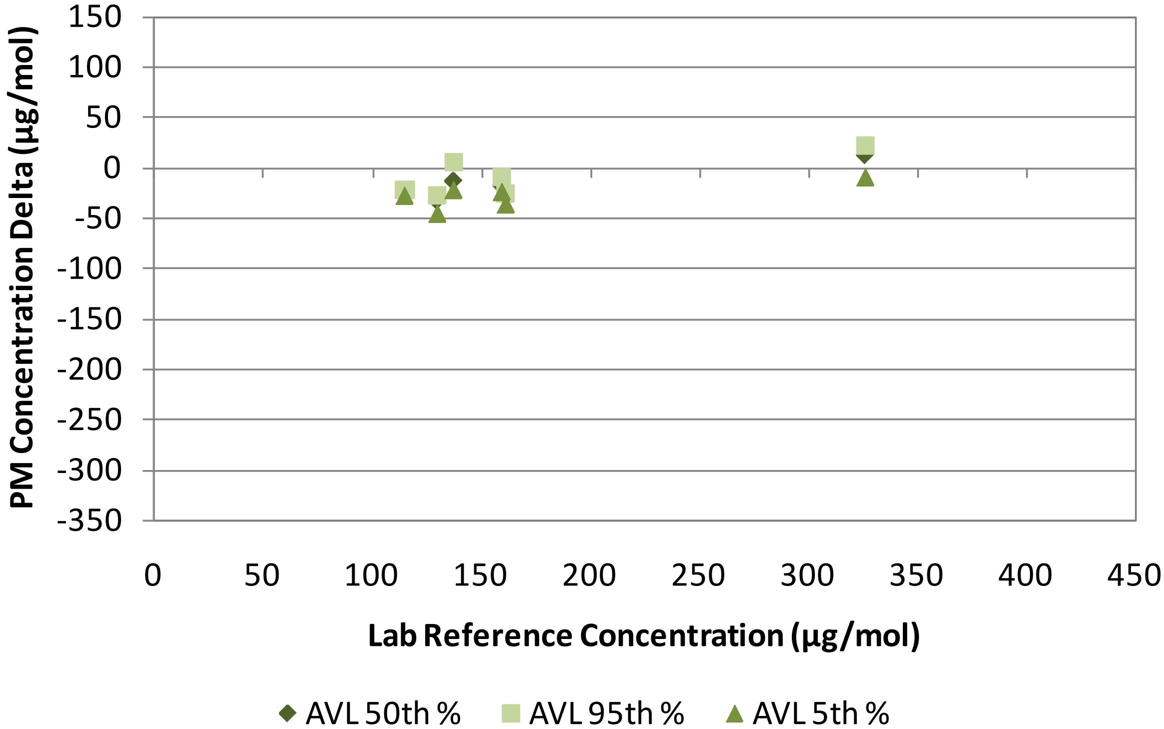


FIGURE 38. AVL PM CONCENTRATION DELTAS FOR STEADY-STATE TESTING ON PEMS 1

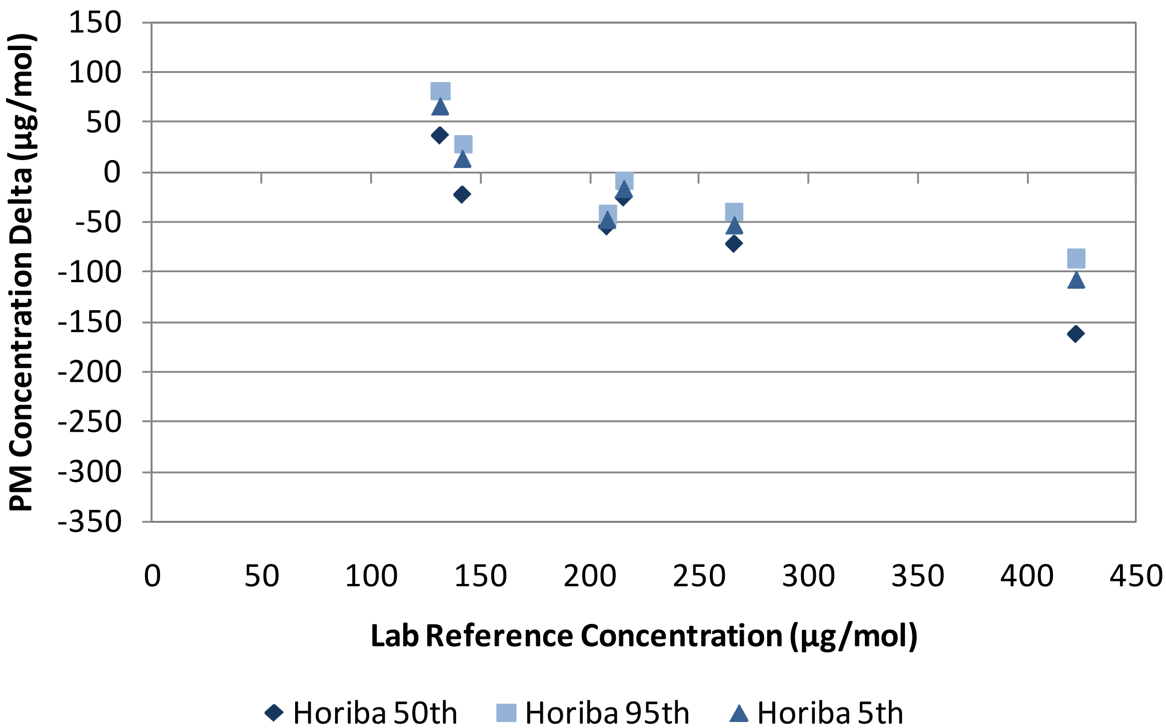


FIGURE 39. HORIBA-2 STEADY-STATE PM CONCENTRATION DELTAS

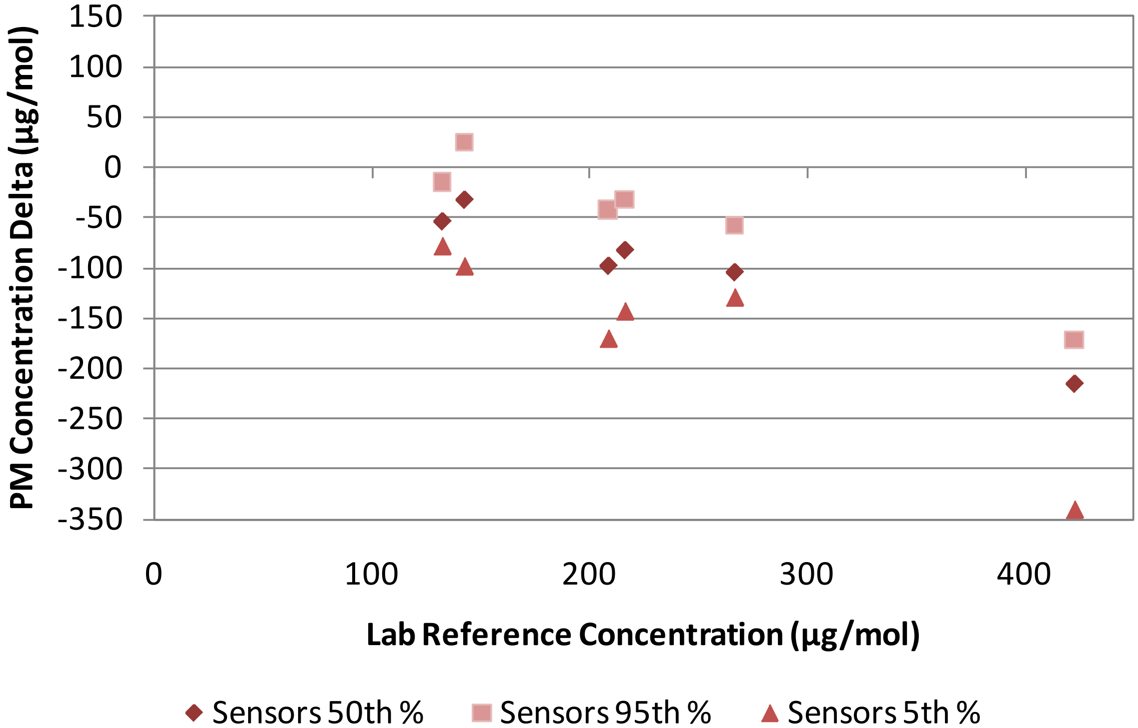


FIGURE 40. SENSORS-2 STEADY-STATE PM CONCENTRATION DELTAS

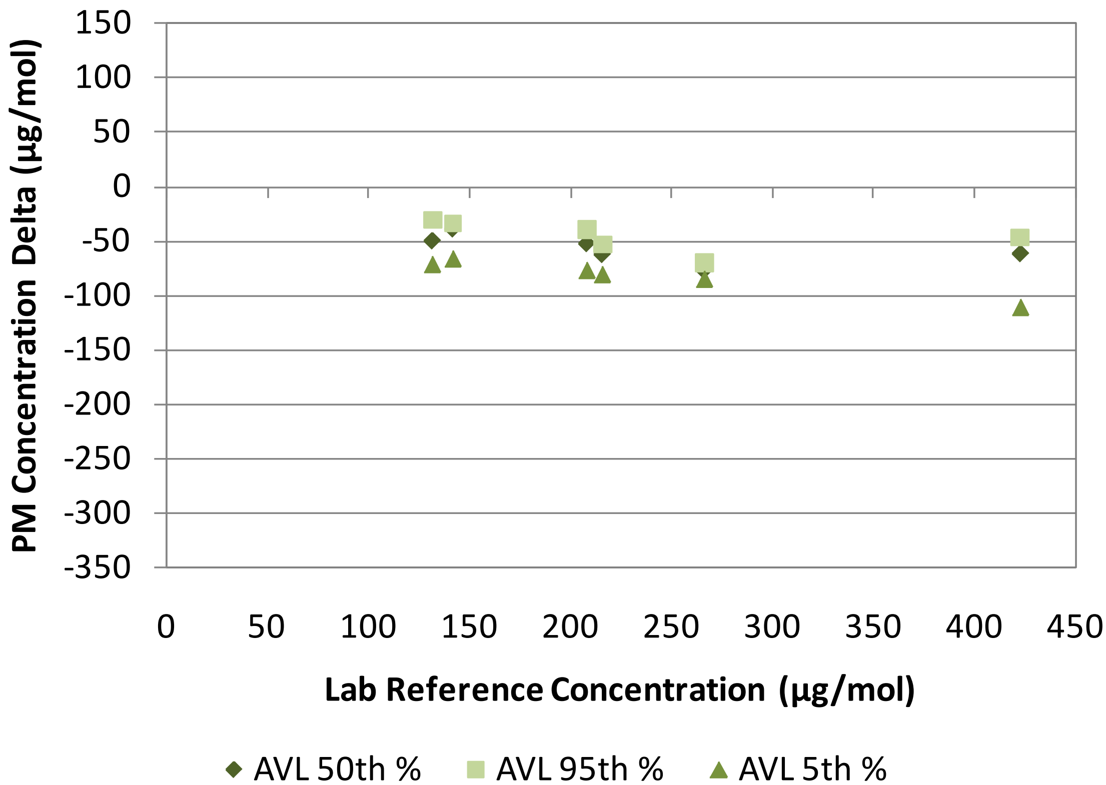


FIGURE 41. AVL-2 STEADY-STATE PM CONCENTRATION DELTAS

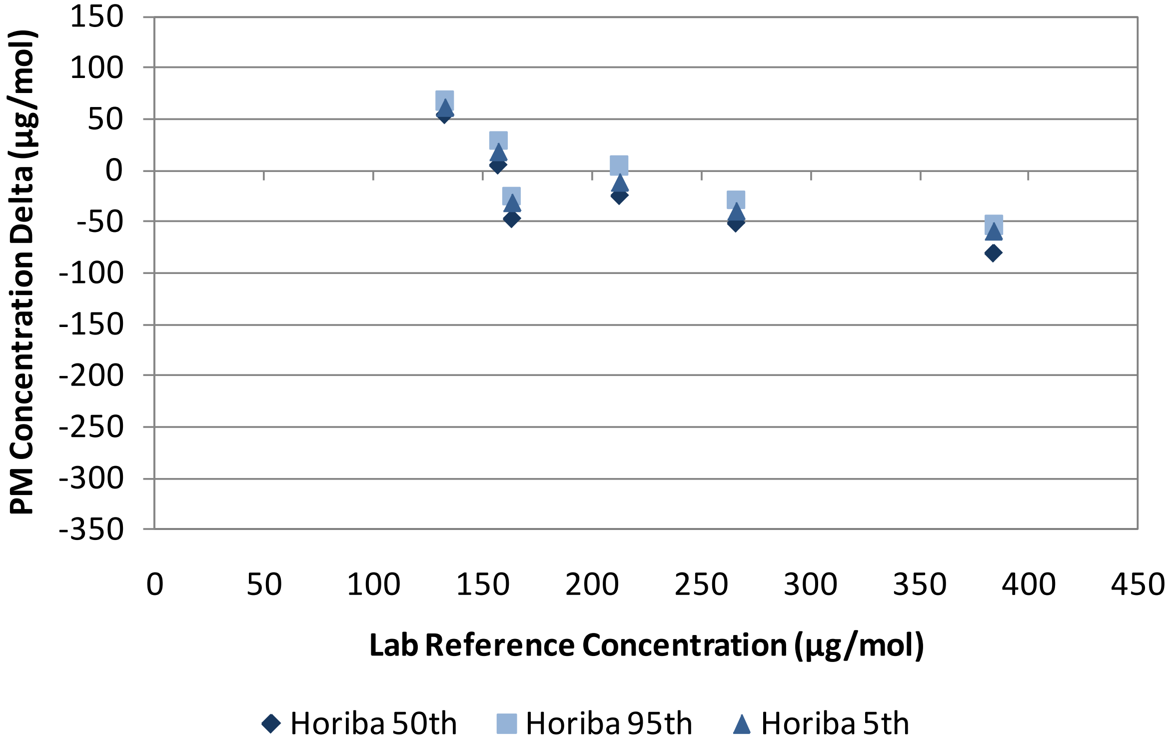


FIGURE 42. HORIBA-3 STEADY-STATE PM CONCENTRATION DELTAS

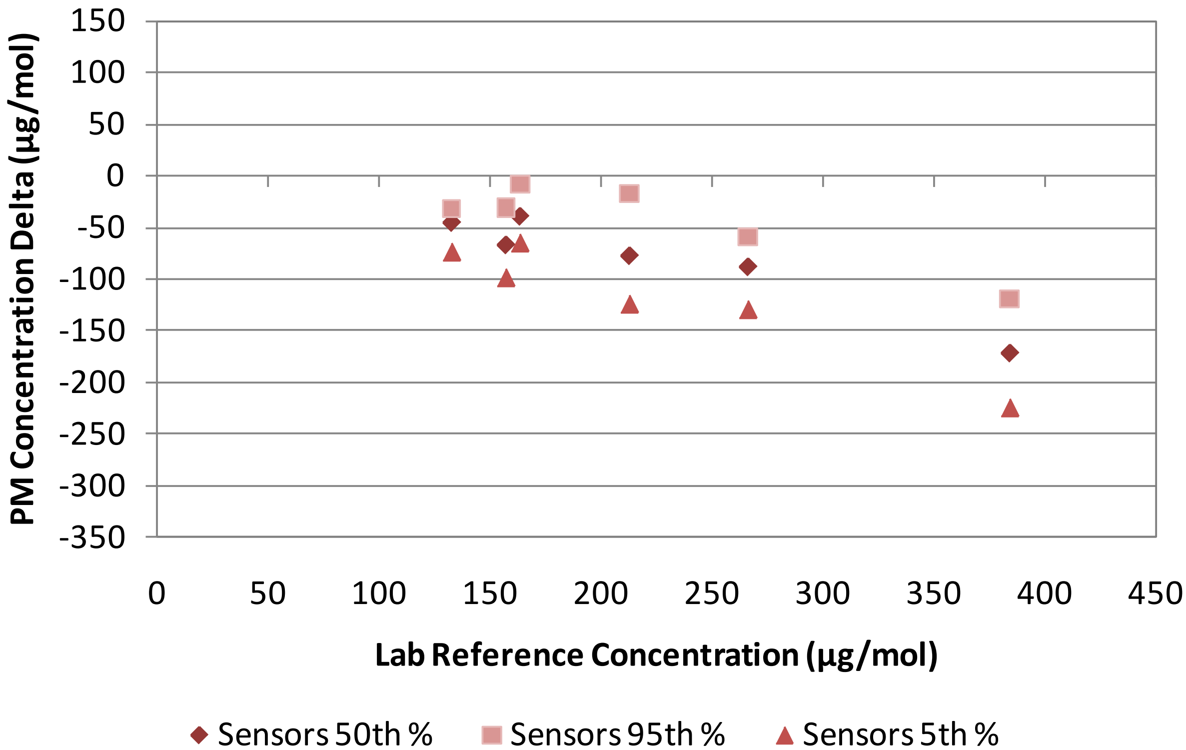


FIGURE 43. SENSORS-3 STEADY-STATE PM CONCENTRATION DELTAS

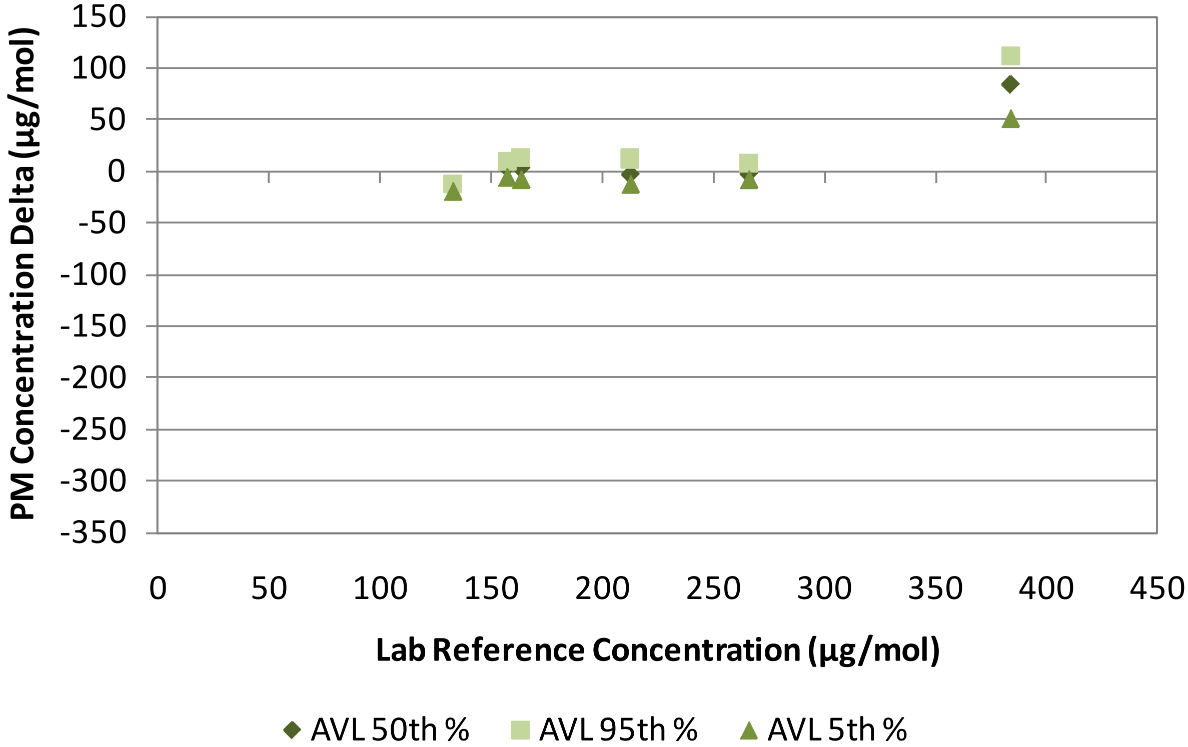


FIGURE 44. AVL-3 STEADY-STATE PM CONCENTRATION DELTAS

Horiba-3 and Sensors-3 are within the same ranges of their first two instruments, while AVL-3 produced an extremely high bias at the highest concentration (mode 2). The 50th percentile of mode 2 for AVL-3 was 84 µg/mol, while it was 13 µg/mol and -62 µg/mol for AVL-1 and AVL-2, respectively.

When the data from all three PEMS is considered, the range of concentrations from 5 mg/m³ to 18 mg/m³ is covered, although there is still a majority of the data located between 5 and 7 mg/m³ as a result of the data from PEMS 1. The individual deltas for the Horiba, Sensors, and AVL are shown in Figure 45, Figure 46, and Figure 47, respectively. Please note that each point represents a single measurement, not pooled data.

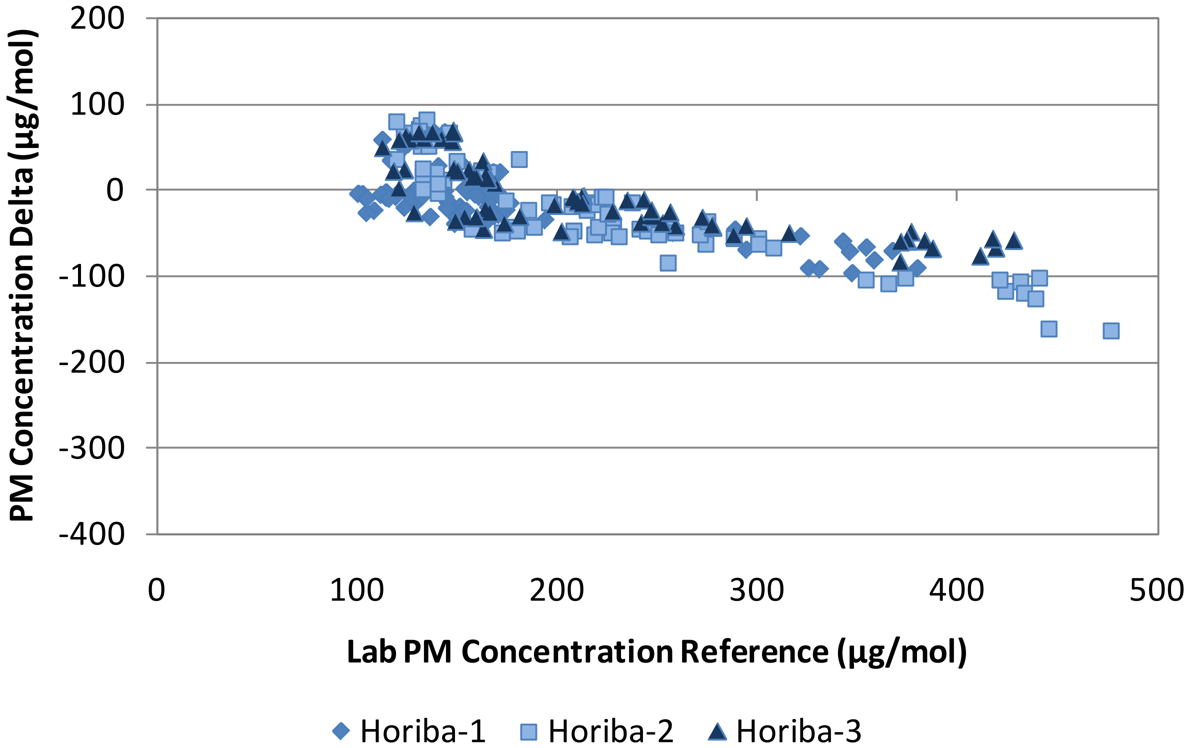


FIGURE 45. STEADY-STATE CONCENTRATION DELTAS FOR HORIBA

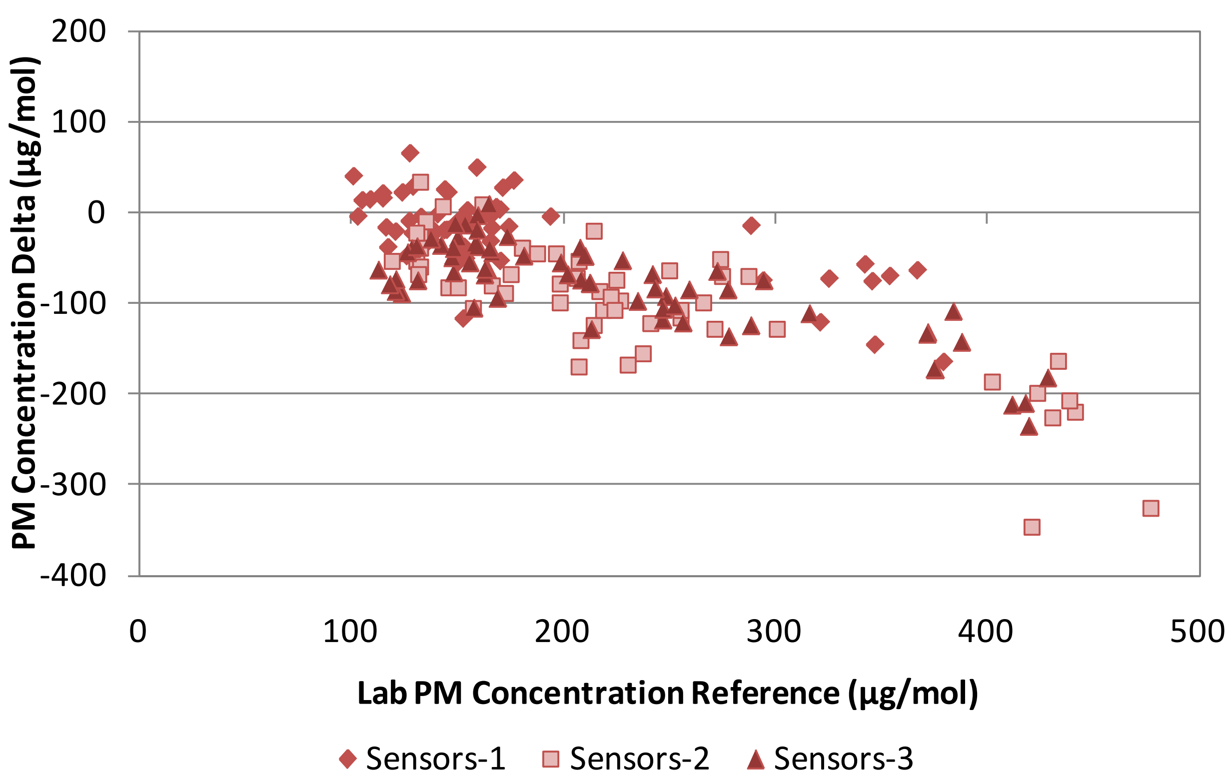


FIGURE 46. STEADY-STATE CONCENTRATION DELTAS FOR SENSORS

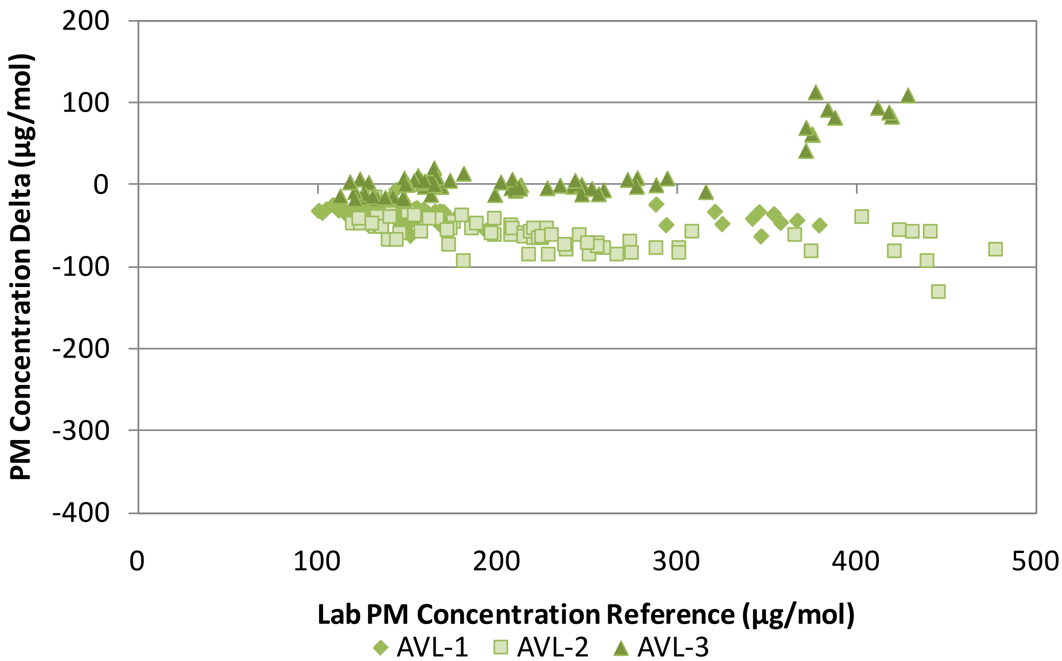


FIGURE 47. STEADY-STATE CONCENTRATION DELTAS FOR AVL

Because the reference concentration of several of the modes was similar, the steering committee decided to group the data by reference concentration rather than by operating mode. The data was split up into groups of approximately 20 data points based on reference concentration for developing the steady-state PM error surface. The Horiba data was grouped into 11 sets, the Sensors data into 9 sets, and the AVL data into 10 sets.

Figure 48, Figure 49, and Figure 50 show PEMS PM concentration plotted against the PM concentration determined by the reference laboratory filter method for steady-state NTEs. These plots mainly show the qualitative PEMS to PEMS scatter relative to the filter method.

4.8.2 Correlation between PEMS and Lab PM

Figure 51 shows a linear regression between each set of PM-PEMS and the CVS filter method. Good correlation was observed between the MSS and lab, with as coefficient of determination (R^2) of 0.84 and a slope of 0.89. The slope suggests that the MSS PM concentration is 11 percent lower than that determined by the lab. This trend is expected since the MSS is measuring soot and the lab reports total PM. The slope seemed to be high because the MSS PM concentration in the range between 15 and 20 mg/m³ was higher than that of the lab.

The linear regression between the Horiba TRPM and the lab resulted in R^2 of 0.55 and a slope of 0.86, indicating some correlation. After further investigation, it was recognized that the weak correlation was due to Mode 4 (high speed, light load) of the SS testing, with concentration levels of about 5 mg/m³. By removing this mode from the data, a R^2 of 0.85 was obtained and the slope was moved from 0.86 to 0.88. It is likely that Mode 4, could have resulted in overestimation of PM due to nanoparticle formation with the Horiba dilution system, although CVS testing at this condition did not show a nanoparticle mode. Based on the slope of the correlation, the Horiba PM concentration was 14 percent lower than that reported by the lab.

The linear regression between the Sensors PPMD and the lab results in R^2 of 0.34 and a slope of 0.64. The weak correlation was due to data scatter. Except in the narrow range between 5 and 7 mg/m³, the Sensors PPMD showed underestimated PM. Based on the slope, the Sensors PPMD PM concentration was 36 percent lower than that reported by the lab.

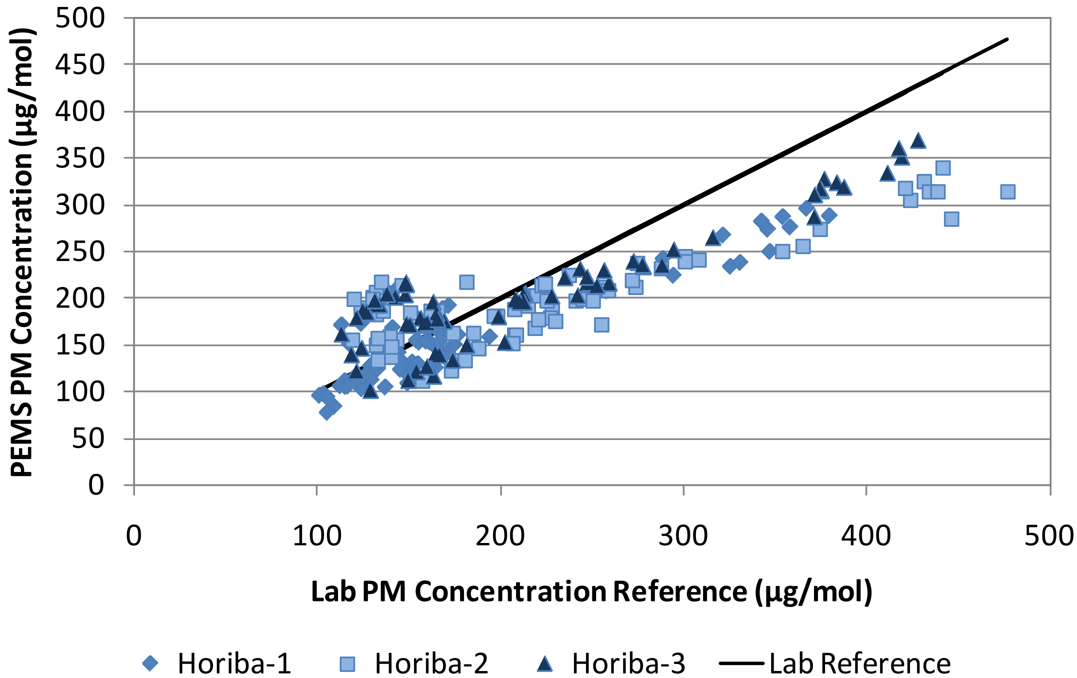


FIGURE 48. STEADY-STATE HORIBA PEMS PM CONCENTRATION VERSUS THE LABORATORY REFERENCE

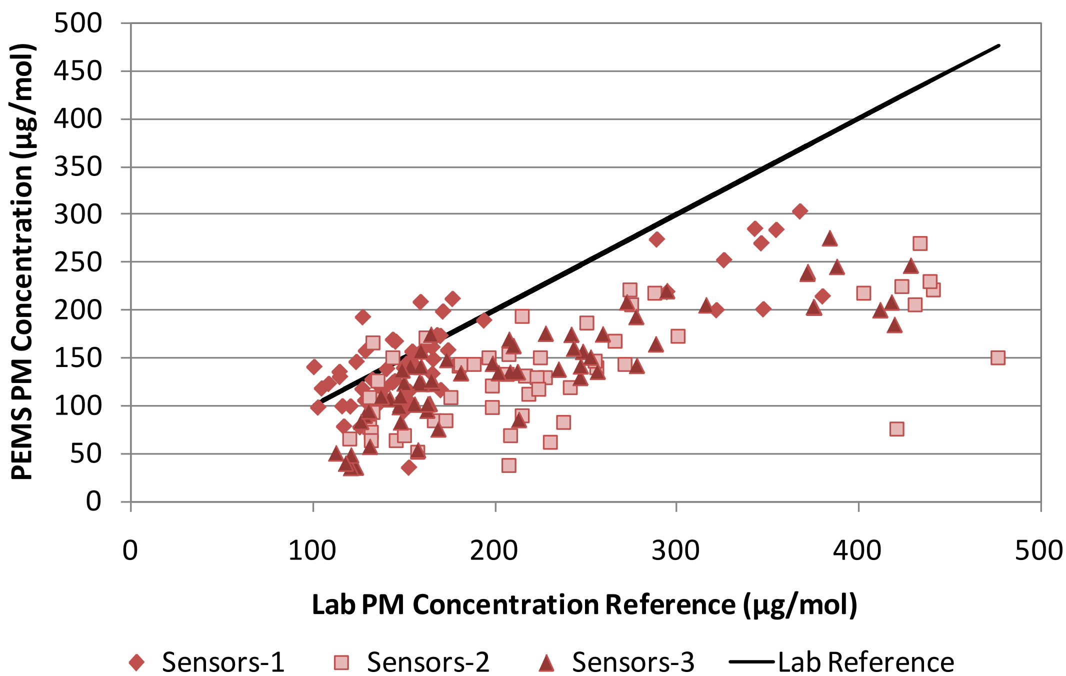


FIGURE 49. STEADY-STATE SENSORS PEMS PM CONCENTRATION VERSUS THE LABORATORY REFERENCE

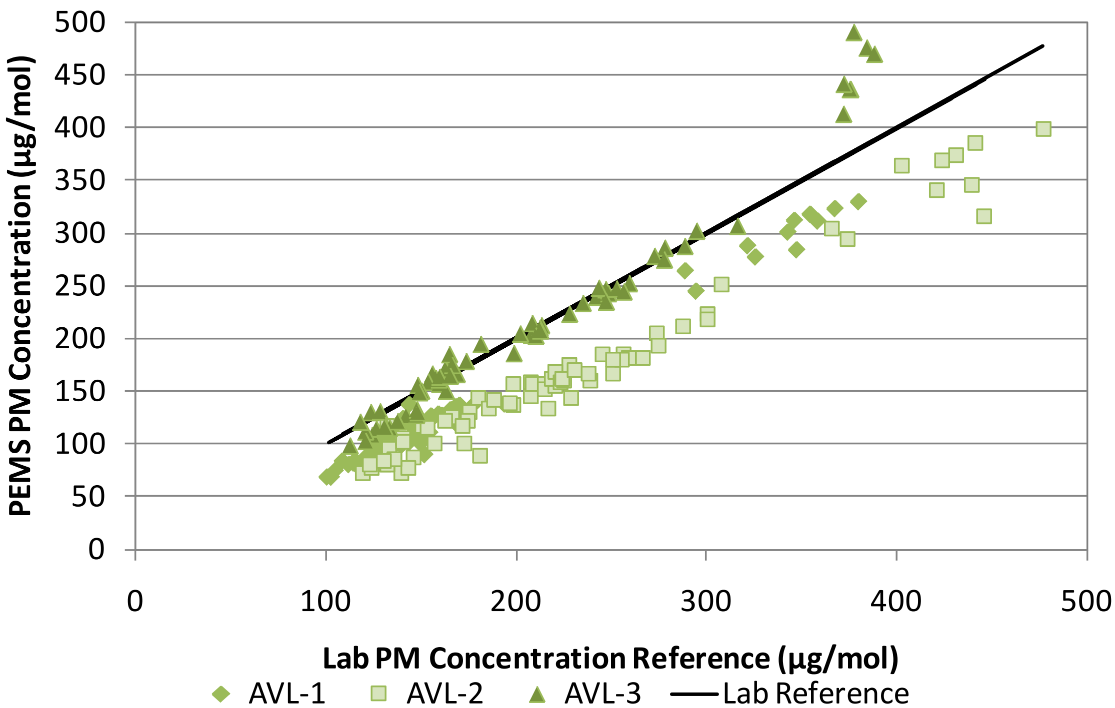


FIGURE 50. STEADY-STATE AVL PEMS PM CONCENTRATION VERSUS THE LABORATORY REFERENCE

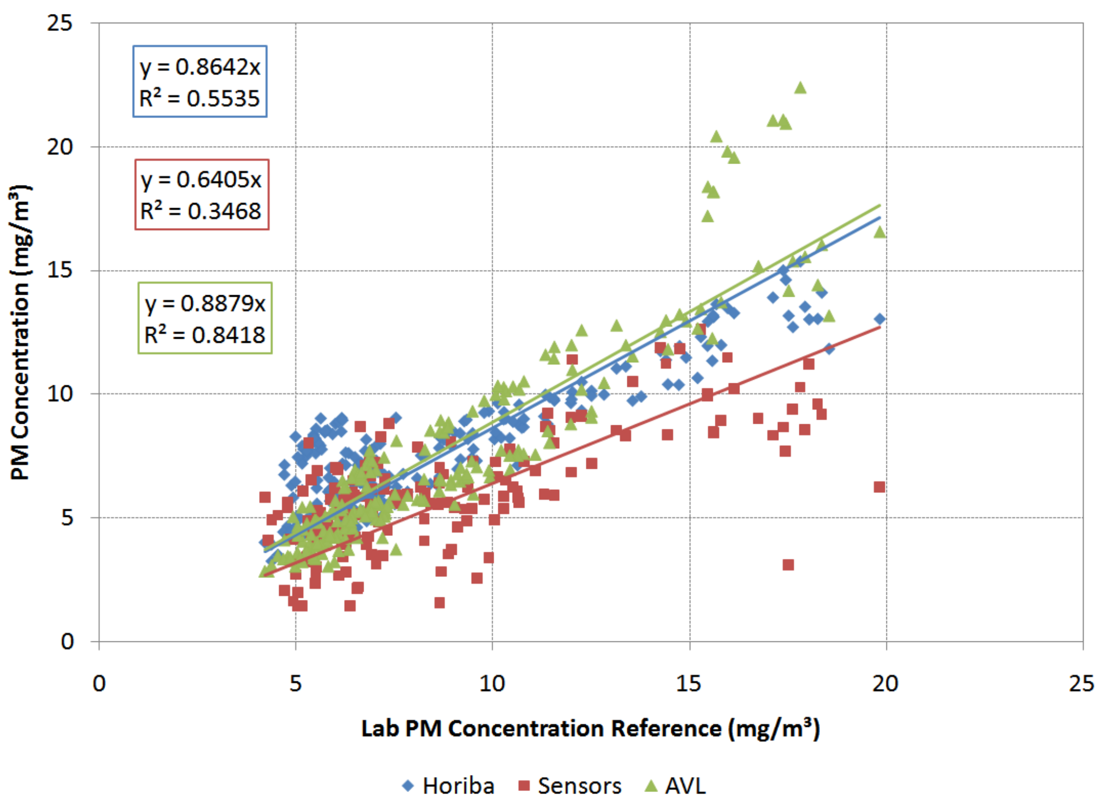


FIGURE 51. LINEAR REGRESSION CORRELATION BETWEEN PEMS AND LAB

4.8.3 *Steady-State PM Error Surfaces*

Figure 52, Figure 53, and Figure 54, show the original concentration deltas that were presented to the steering committee on April 2nd, 2009 at SwRI. The Sensors data includes some additional points that were added later due to changing the error tolerances of their post processor. Each marker on the plot represents one of the j = 1 to M subsets of data divided up by concentration value. Each plot shows both the 5th and 95th percentiles which are based on the actual data. The error surfaces for the Monte Carlo model were based on the 1st and 99th percentiles which were extrapolated from the 5th and 95th percentiles assuming a normal distribution of the data.

The steering committee elected to smooth the error surface by not including some of the data points that were within the envelope of surrounding points. A similar decision was made on some of the error surfaces included in the gaseous measurement allowance program.

Figure 55, Figure 56, and Figure 57 show the final steady-state error surface of Horiba, Sensors, and AVL, respectively. The data presented in these plots has already been processed to remove the CVS variability and adjusted to the 1st and 99th percentile form the 5th and 95th percentile. The lines on the plot represent the final error surfaces as approved by the steering committee. The Horiba and AVL error surfaces were accepted by the steering committee during the conference call on June 29th, 2009. Some of the sensors data was reprocessed with different tolerances to increase the data yield, so the sensors error surface was not accepted by the steering committee until the July 14th, 2009 meeting in Indianapolis.

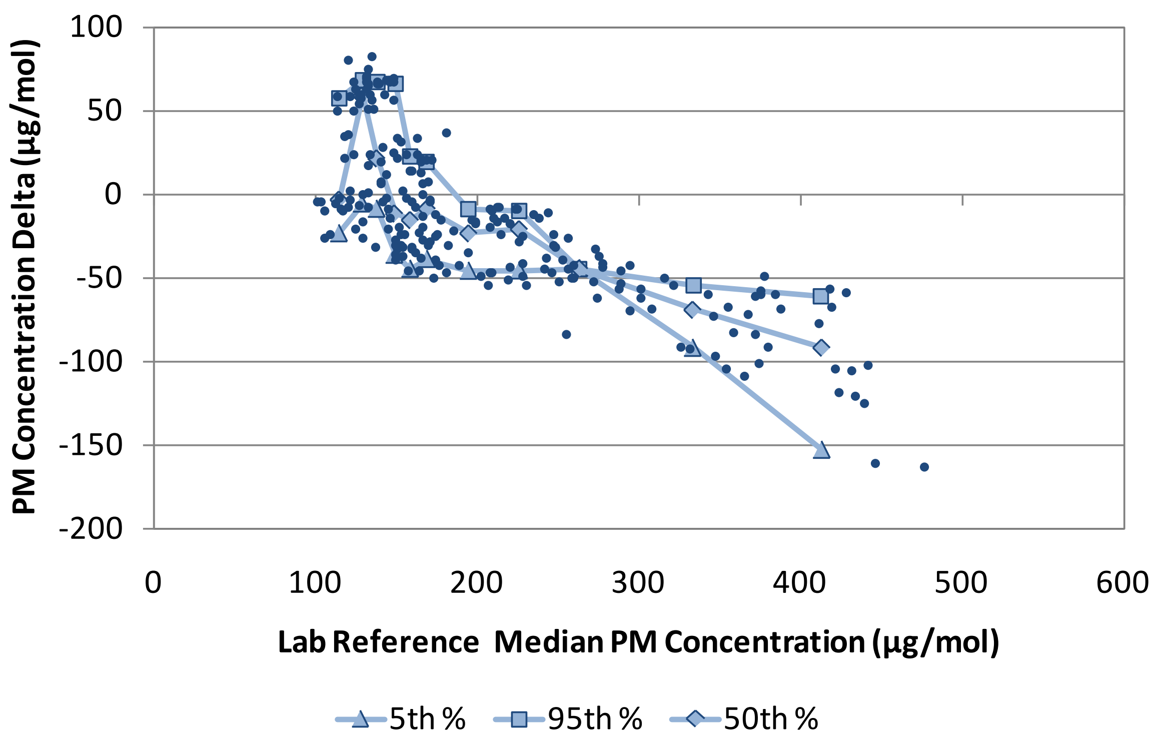


FIGURE 52. STEADY-STATE CONCENTRATION DELTAS FOR HORIBA

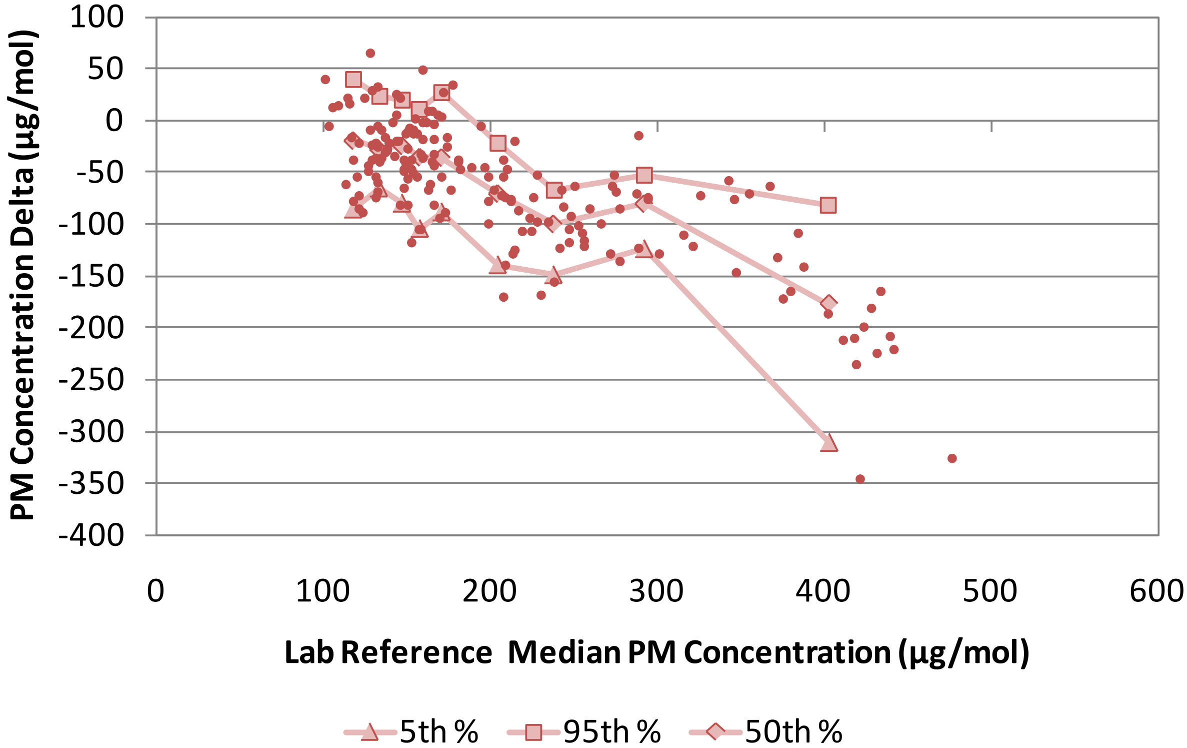


FIGURE 53. STEADY-STATE CONCENTRATION DELTAS FOR SENSORS

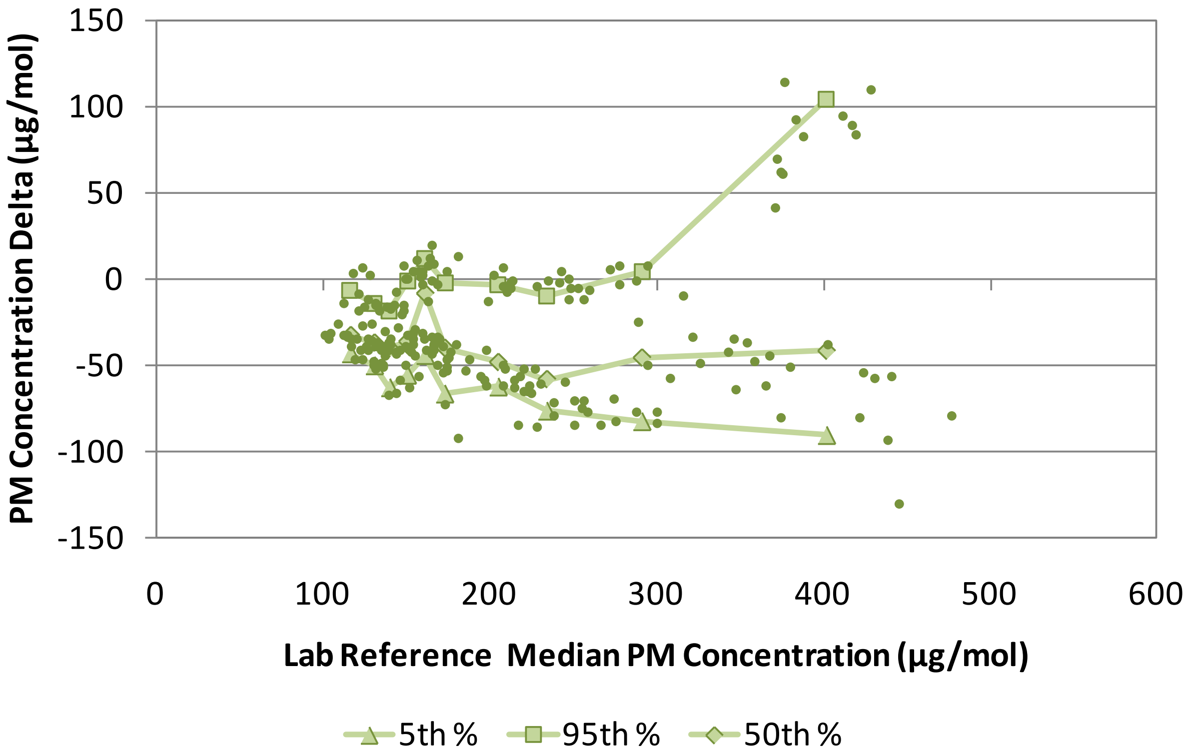


FIGURE 54. STEADY-STATE CONCENTRATION DELTAS FOR AVL

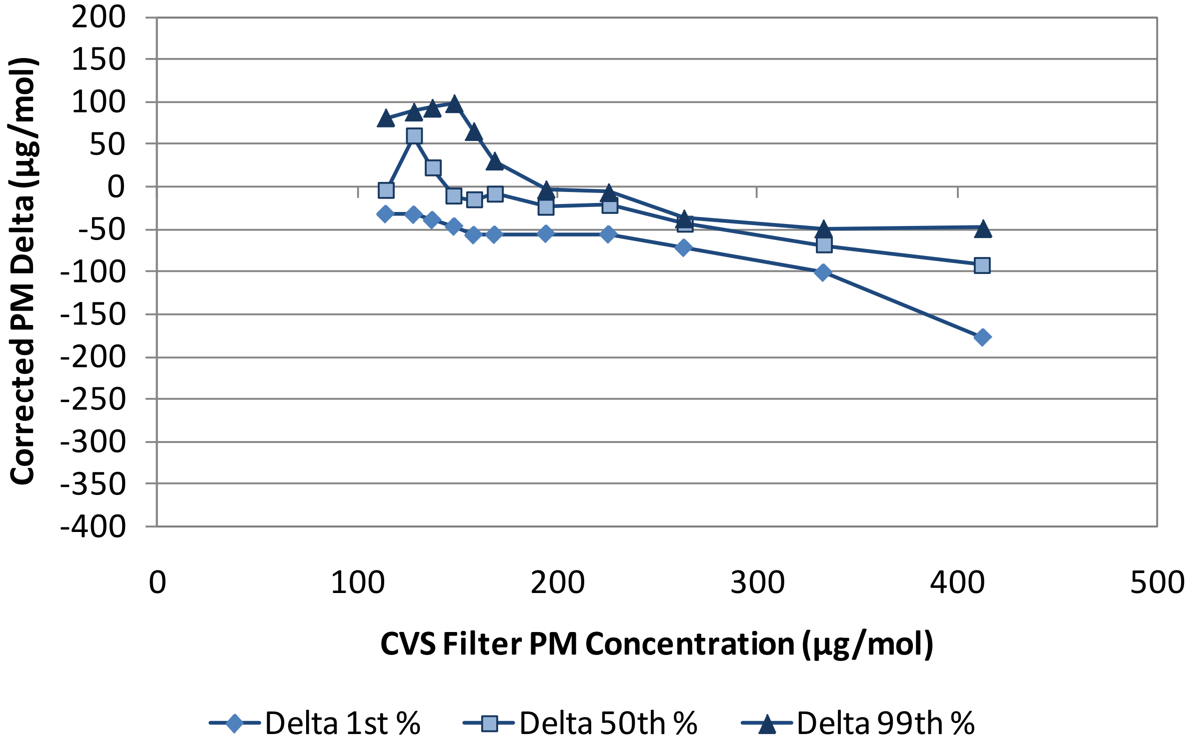


FIGURE 55. FINAL STEADY-STATE PM ERROR SURFACE – HORIBA

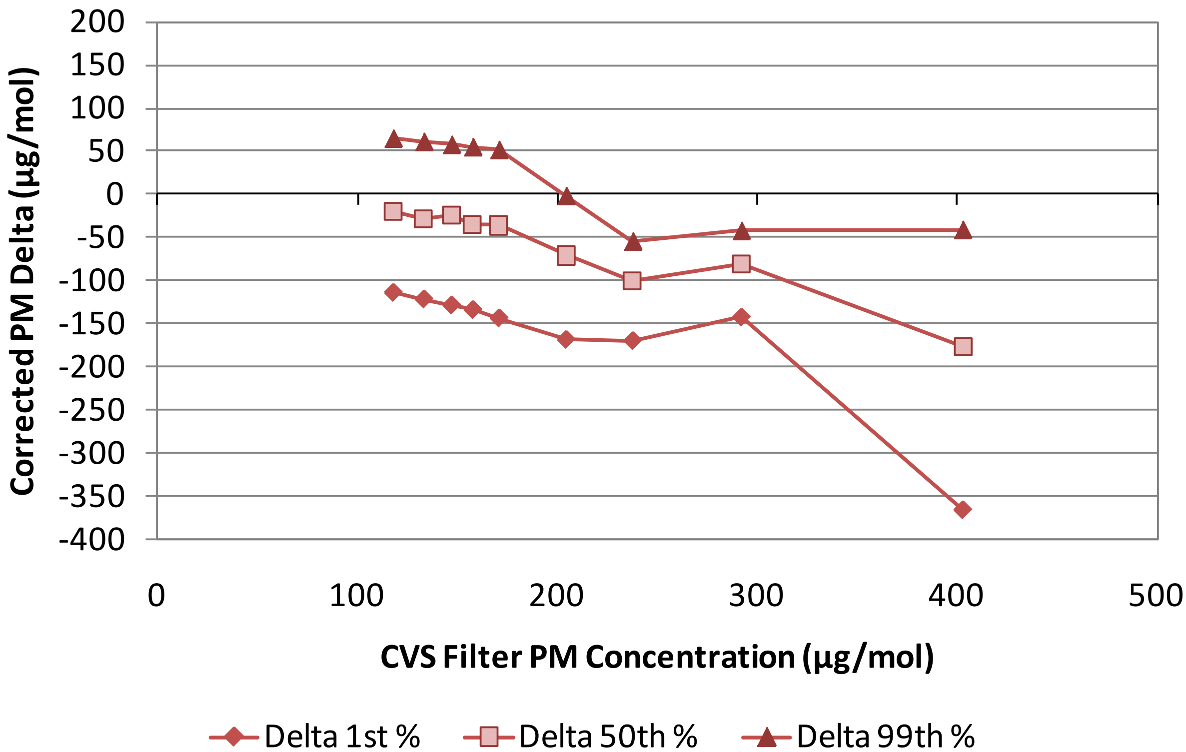


FIGURE 56. FINAL STEADY-STATE PM ERROR SURFACE – SENSORS

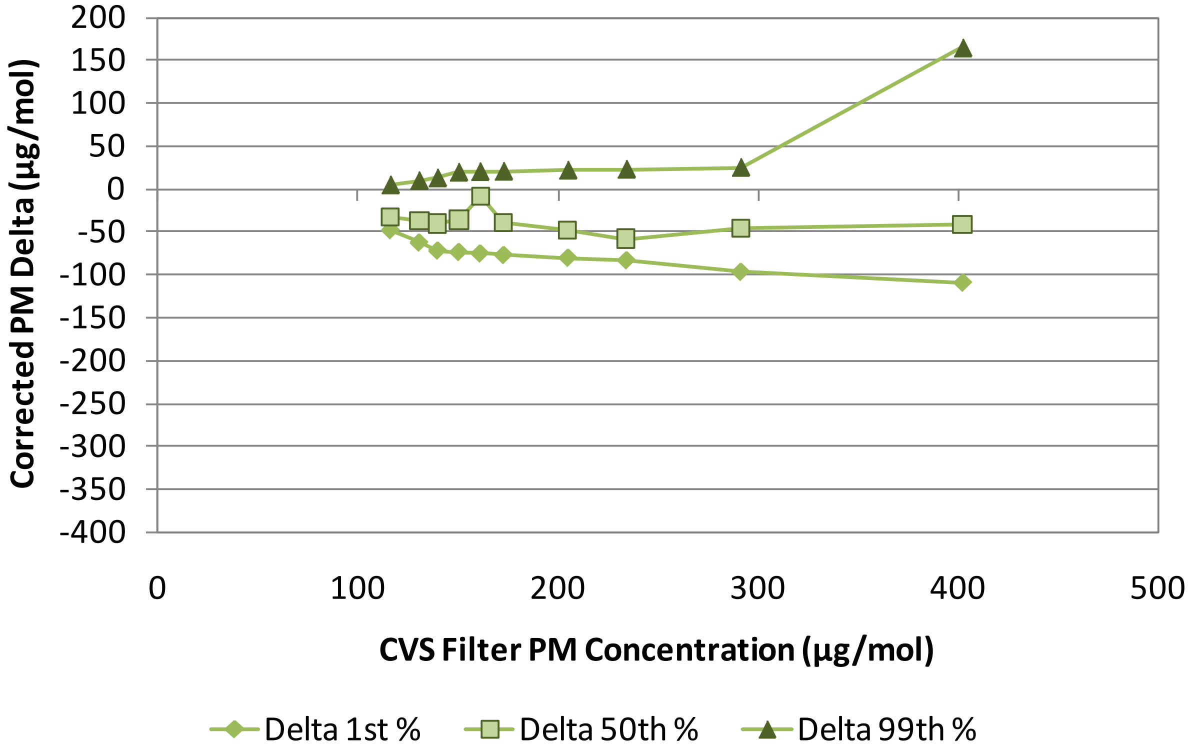


FIGURE 57. FINAL STEADY-STATE PM ERROR SURFACE – AVL

With a few exceptions the PEMS generally exhibited a low bias, with the majority of the 50th percentile deltas falling below zero. The Horiba and Sensors both showed a degree of level dependence with the negative bias generally increasing for higher PM concentrations. At a lab reference concentration of 413 µg/mol the Horiba 50th percentile was -92 µg/mol and the Sensors 50th percentile was -177 µg/mol at a lab reference concentration of 403 µg/mol. The AVL 50th percentile was generally level independent and remained between -8 and -58 µg/mol for the entire range of concentrations tested. While the 1st percentile for the AVL also remained relatively constant throughout the concentration range, the 99th percentile jumped to a much higher value at high concentration. The AVL 99th percentile jumped from 25 µg/mol at 291 µg/mol to 165 µg/mol at 402 µg/mol. The cluster of positive deltas that caused this large increase in the 99th percentile data is due solely to mode 2 with PEMS 2. The majority of the positive deltas observed for the Horiba were due to mode 4 which was a high speed light load condition. Since it is understood that the DCS (EAD) real time particle sensor in the Horiba system is more sensitive to smaller particles it was assumed that may have a larger number of sub-50 nm particles than the other 5 modes tested, causing more of the filter mass to be attributed to mode 4.

4.9 Transient Engine Results

The transient engine testing was designed to characterize the precision error of the PEMS. A transient cycle consisting of 30 NTE events, 32 seconds each, was repeated multiple times and any differences in the PEMS measurements were attributed to PEMS variability under the assumption that the engine operation and PM emissions remained constant. No lab reference value was captured on an individual NTE event basis, because it is not possible to collect PM on a CVS filter for each NTE. Instead filter measurements were taken for each integrated transient

NTE cycle as a general indicator of the PM emissions of the engine during the entire cycle. The cycle used in this testing was developed using the cycle generator from the gaseous measurement allowance program. In the gaseous program the cycle generator was used to develop 20 unique cycles with different orders of NTE events and different transitions between events. The steering committee elected to generate one single cycle for the current work that would be used for all transient testing. Additional time was added in between NTE events to ensure that the PPMD could sample throughout the cycle without missing any NTE events under the assumption of 7 working crystals (6 for sample and one reference crystal). In addition several short non-valid NTE events were added to the cycle to challenge the PEMS for measurements of non-valid NTE events.

The DPF bypass was adjusted to produce an integrated cycle BSPM of approximately 0.03 g/hp-hr based on the CVS filter. Instead of readjusting the bypass for each set of PEMS, the exhaust valves were set to the same position each time. The NTE events were all approximately 34 seconds in duration. The original events from the cycle generator were each 32 seconds, however the Sensors PEMS would occasionally see these events as shorter than 30 seconds and exclude them. Many of the NTE events contained extreme accelerations and decelerations stopping just short of the lower boundaries of the NTE window. Considerable time was spent to ensure that the J1939 signal remained in the NTE window during events, although the engine performance shifted slightly and occasionally an event was invalidated. If any NTE event did not remain in the NTE windows for at least 30 seconds it was not included in the data for the transient error surface. A total of 16 cycles were run for PEMS, 17 for PEMS2, and 18 for PEMS3. Figure 58 shows repeat engine speed traces for the transient cycle with the first and last official cycle conducted with each PEMS. Figure 59 shows the repeat torque traces for the transient cycle. The COV on cycle work was 0.7 percent over 51 cycles.

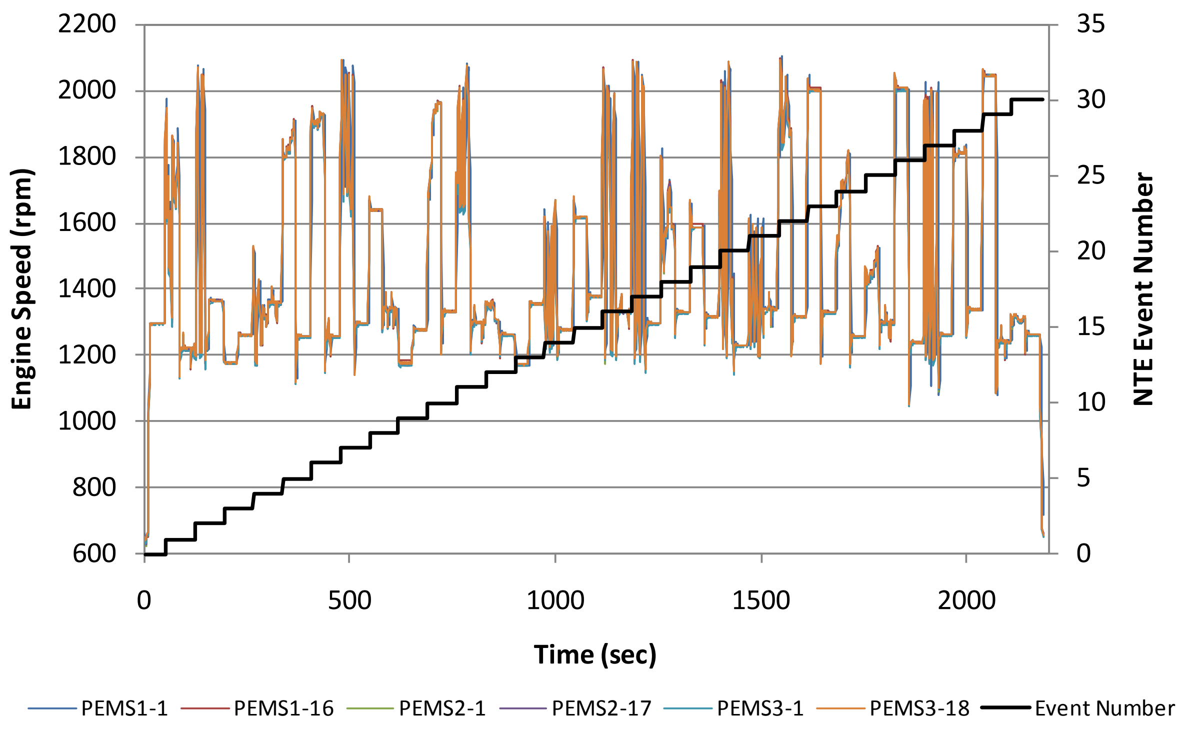


FIGURE 58. REPEAT ENGINE SPEED TRACES FOR NTE TRANSIENT CYCLE

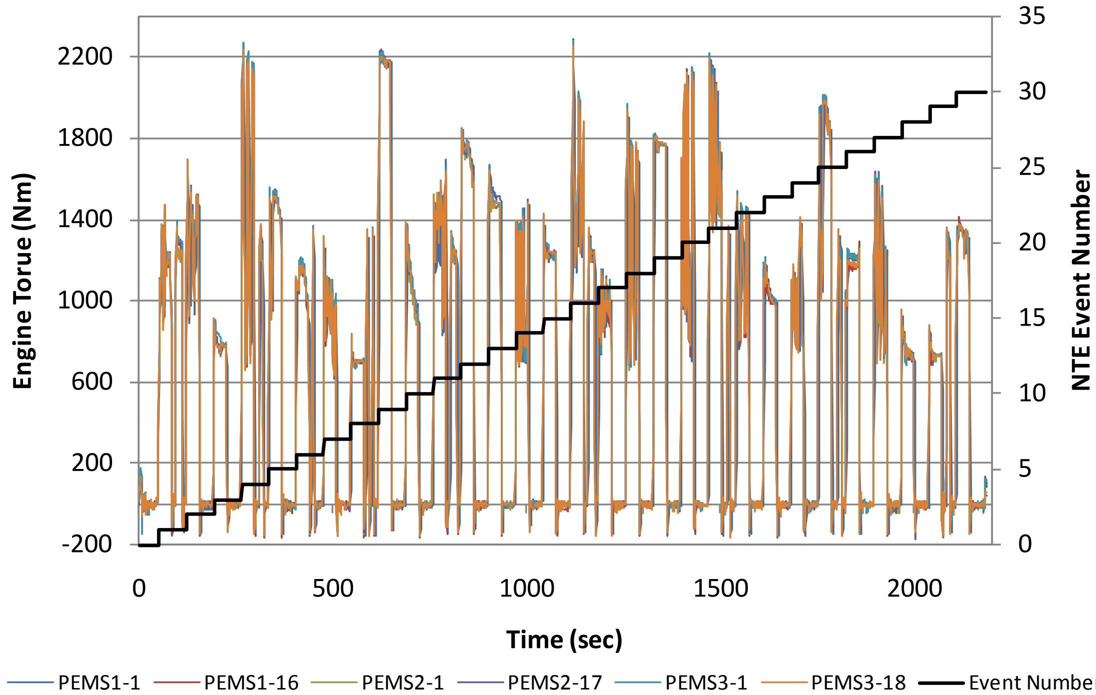


FIGURE 59. REPEAT ENGINE TORQUE TRACES FOR NTE TRANSIENT CYCLE

The exhaust concentration of soot, as measured by the AVL PEMS is shown in Figure 60. The measured exhaust concentrations of soot ranged from 5 to 3800 µg/mol (0.2 to 160 mg/m³) during NTE operations, with concentrations of 5 to 14 µg/mol (0.2 to 0.6 mg/m³) outside of the NTE window. The widest dynamic range observed during an NTE event was for event 9 where the initial spike in soot concentration was measured as high as 3800 µg/mol before falling down to 55 µg/mol near the end of the event. Figure 61 gives a closer look at events 20 through 23 to show the variability of the real-time signal over the three sets of PEMS. It should be noted that the AVL PEMS is shown here only because it reports the measured soot concentration on a second by second basis without additional processing.

Although the Horiba PEMS was used in this program as a batch sampler rather than a second by second instrument for official results, Figure 62 shows the second-by-second data of the Horiba PEMS along with the AVL. There were major differences on some of the peak concentrations most notably NTE event 9, where the measured AVL concentration was nearly four times higher than the measured Horiba concentration. With no reference, the purpose of this figure is only to show that there are differences without trying to quantify the accuracy. The Sensors PEMS performs its measurements as a batch sampler so that there was no real-time exhaust concentration reported.

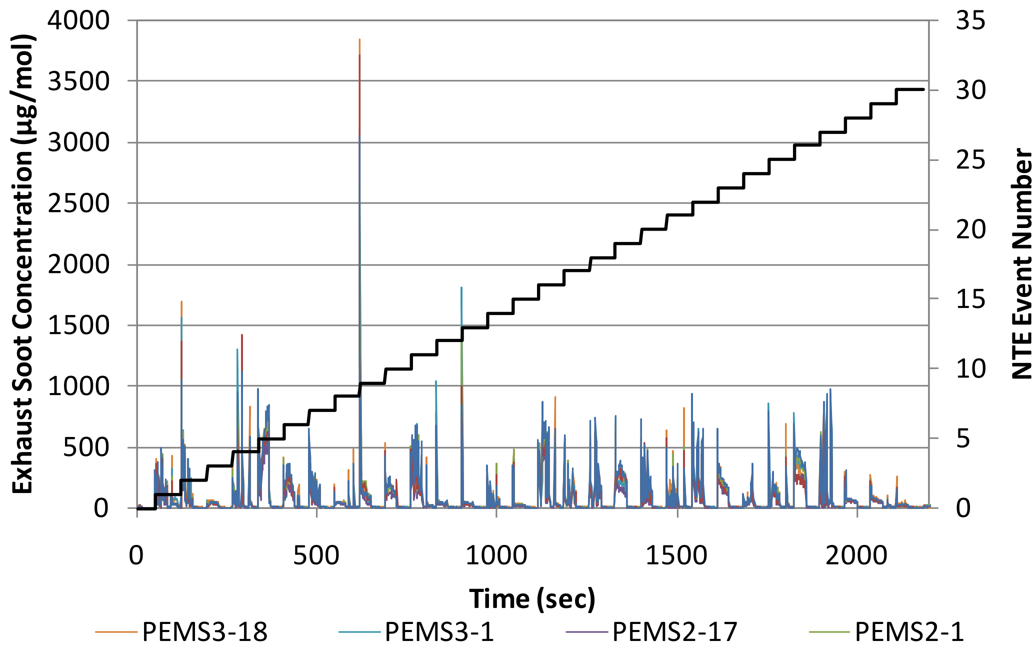


FIGURE 60. REPEAT AVL SOOT CONCENTRATION TRACES FOR NTE TRANSIENT CYCLE

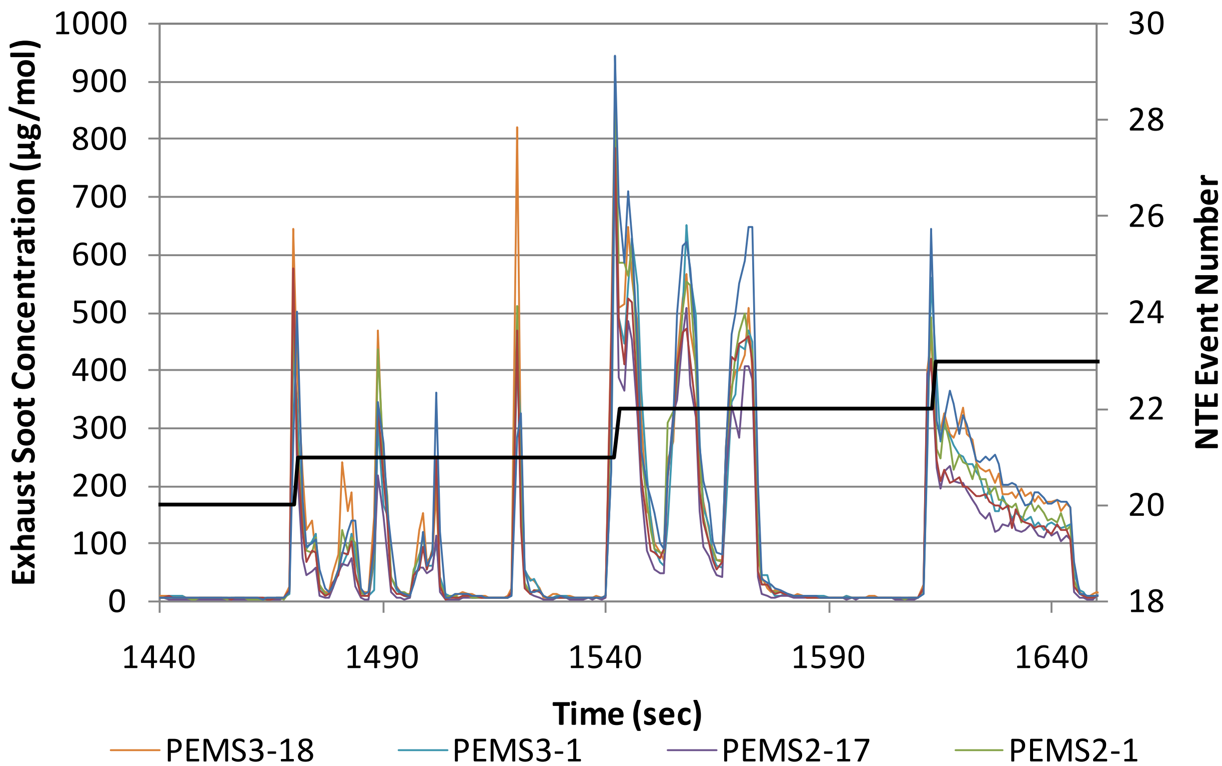


FIGURE 61. AVL SOOT CONCENTRATION DURING NTE TRANSIENT CYCLES, EVENTS 20-23

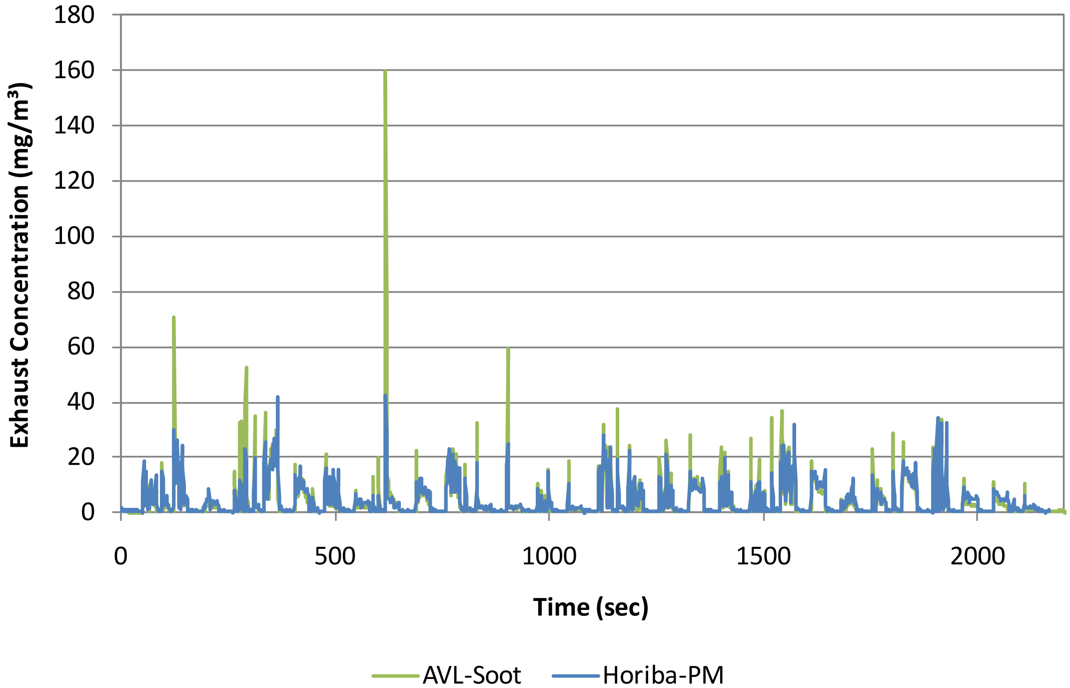


FIGURE 62. COMPARISON OF AVL AND HORIBA REAL TIME SIGNALS DURING TRANSIENT CYCLE

To properly quantify the precision of the PEMS it is important that the reference value remain constant otherwise changes in the source PM emissions will be attributed to the PEMS as measurement variability. In examining the CVS filter results, it was clear that the engine PM emissions varied somewhat during testing. After reviewing the transient PEMS data at the January 28th, 2009 meeting at SwRI, the steering committee requested that the idea of a correction to the PEMS data be applied to account for changes in the engine performance. A correction factor based on the cycle integrated CVS BSPM was presented to the committee during the April 2nd, 2009 meeting at SwRI and was accepted for use on all of the transient data. The correction factor was calculated as follows:

$$CF_i = \frac{\sum_{i=1}^{N} CVS_i}{N \cdot CVS_i} = \frac{CVS_{avg}}{CVS_i}$$

The correction factor is multiplicative and applied to the PEMS data in the following manner:

$$PEMS_{corrected,i,j} = CF_i \cdot PEMS_{measured,i,j}$$

The CVS BSPM along with the correction factor is shown in Figure 63.

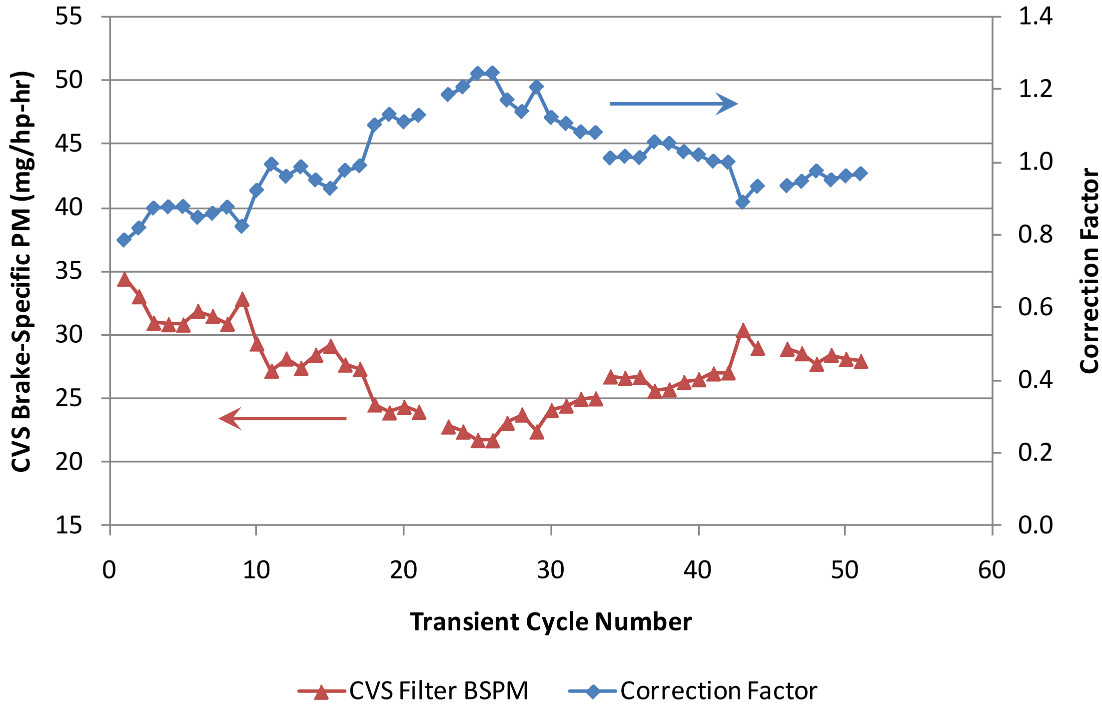


FIGURE 63. CVS BSPM AND CORRECTION FACTOR FOR TRANSIENT CYCLE

The correction factor ranged from 0.78 to 1.24. There were two cycles in which the CVS filter measurement was void; in these cases the correction factor was set to one. The CVS brake specific PM ranged from 34.4 mg/hp-hr to 21.7 mg/hp-hr with an average of 27.2 mg/hp-hr. The COV was 11.4 percent when cycles for all three PEMS are included. The COV was 7.2, 6.0, and 4.8 percent for cycles from PEMS1, 2, and 3, respectively.

While processing some of the AVL data and comparing to the lab, it was discovered that the incorrect CVS BSPM value had been used for one of the cycles. The value of 31.9 mg/hp-hr from cycle 1956 had also been used for cycle 1965 instead of the correct value of 28.4 mg/hp-hr. The entire set of transient CVS data was scrutinized again and no additional errors were found. This erroneous correction factor was included in the final transient error surface included in the model. The transient error surface was found to shrink for all PEMS by between 1 and 2 percent with the correction applied. Given the small change in the outcome no action was taken to correct this mistake. The transient error surfaces presented in this report are those used in the Monte Carlo model.

Figure 64, Figure 65, and Figure 66 show the concentration deltas for Horiba, Sensors, and AVL, respectively. In the transient testing there was no lab reference to create deltas. Rather the delta was calculated from the 50^{th} percentile of the lab data as follows:

$$Delta_{i,j} = CF_i * mPM_{i,j} - 50^{th}_i$$

Where $mPM_{i,j}$ is the average flow-weighted PM concentration for the j^{th} repeat of the i^{th} NTE event. 50^{th}_i is the 50^{th} percentile of mPM for the i^{th} NTE event. CF_i is the previously described correction factor to adjust for engine variability.

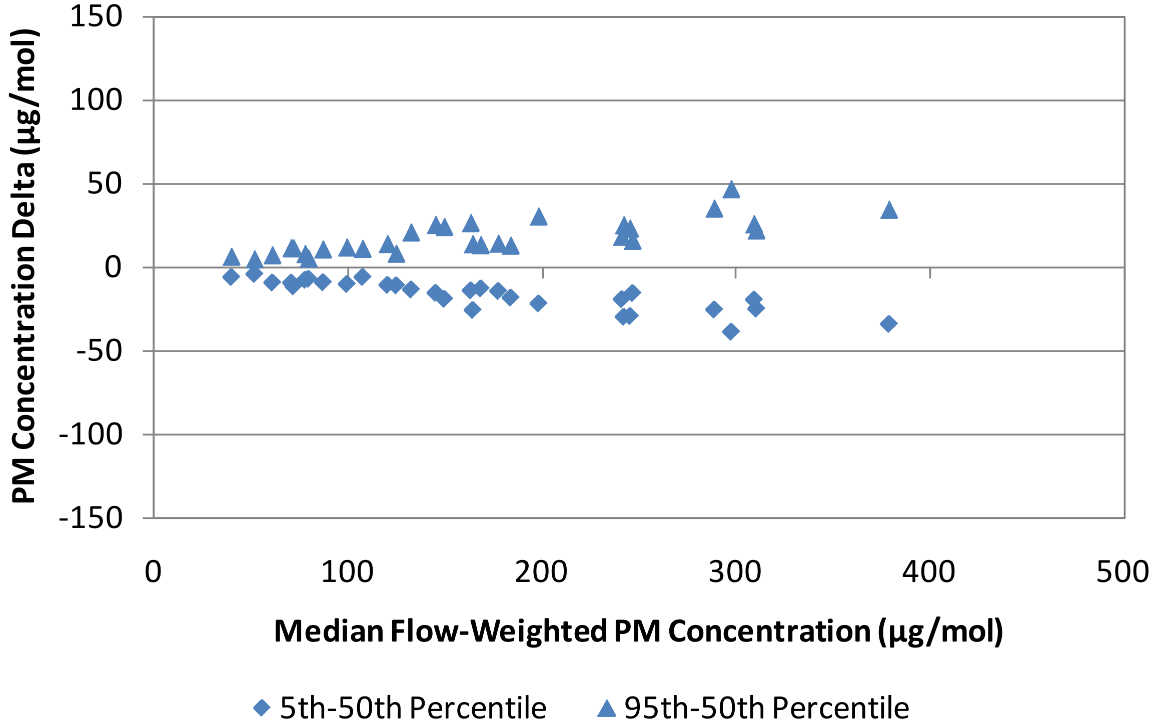


FIGURE 64. HORIBA CONCENTRATION DELTAS FOR TRANSIENT ENGINE TESTING

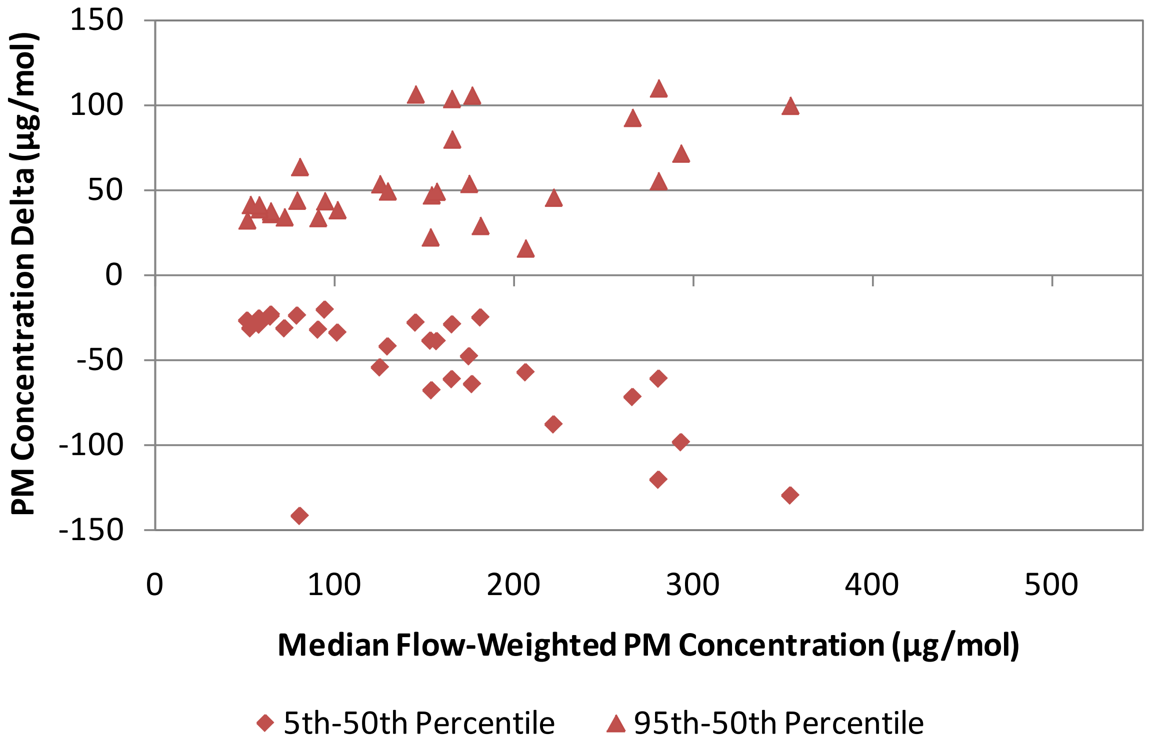


FIGURE 65. SENSORS CONCENTRATION DELTAS FOR TRANSIENT ENGINE TESTING

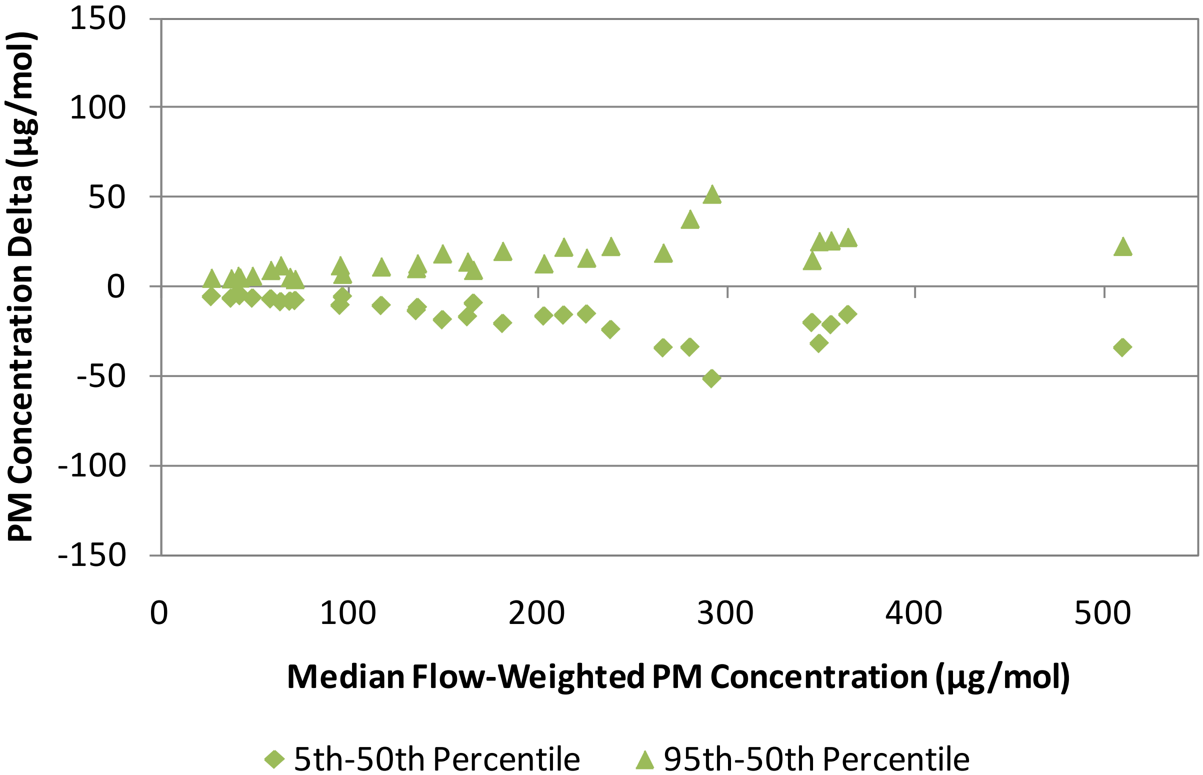


FIGURE 66. AVL CONCENTRATION DELTAS FOR TRANSIENT ENGINE TESTING

The 5th and 95th percentiles of the Horiba and AVL PEMS were bounded by plus and minus 50 µg/mol. The Sensors PEMS had slightly larger deltas extending just beyond 100 µg/mol for the 95th percentile and -150 µg/mol for the 5th percentile. The bias from the data was removed by subtracting the 50th from the 5th and 95th percentiles.

The steady-state error surface was designed to quantify the accuracy of the PEMS while the transient error surface was designed to quantify the precision of the PEMS. However, a portion of the PEMS precision error is inherently captured in the steady-state error surface. At the meeting on July 15th, 2009 in Indianapolis four different approaches were presented to the steering committee for removing the steady-state contribution to the precision error from the transient error surface. The steering committee elected to proceed with approach 3; for simplicity the other three approaches will not be described.

In this approach, the data from all three PEMS from the same manufacturer were pooled together (ie Sensors1, Sensors2, and Sensors3). This resulted in a total of 18 steady-state data points and 90 transient data points. A median and a MAD value were calculated for each of the 108 data points and used to calculate a MAD relative error, transient effect, root mean squared or $MAD_{re,tr,rms}$. The $MAD_{re,tr,rms}$ is defined as follows:

$$MAD_{re,tr,rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{MAD_{tr,i}}{Median_{tr,i}}\right)^2 - \frac{1}{N}\sum_{i=1}^{N}\left(\frac{MAD_{ss,i}}{Median_{ss,i}}\right)^2}$$

Where tr denotes transient and ss denotes steady-state. Using an rms value eliminates the need for estimating the steady-state variability at each of 90 transient data points. The error surface was defined as the 90 percent confidence interval around zero (or no bias) as:

$$5th\ Percentile = -1.65 \cdot PM \cdot MAD_{re,tr,rms}$$
$$95th\ Percentile = 1.65 \cdot PM \cdot MAD_{re,tr,rms}$$

Effectively the error surface is a straight line with a slope of +/- 1.65·$MAD_{re,tr,rms}$ and an intercept of zero. The transient error surface is shown in Figure 67 for Horiba, Figure 68 for Sensors, and Figure 69 for AVL.

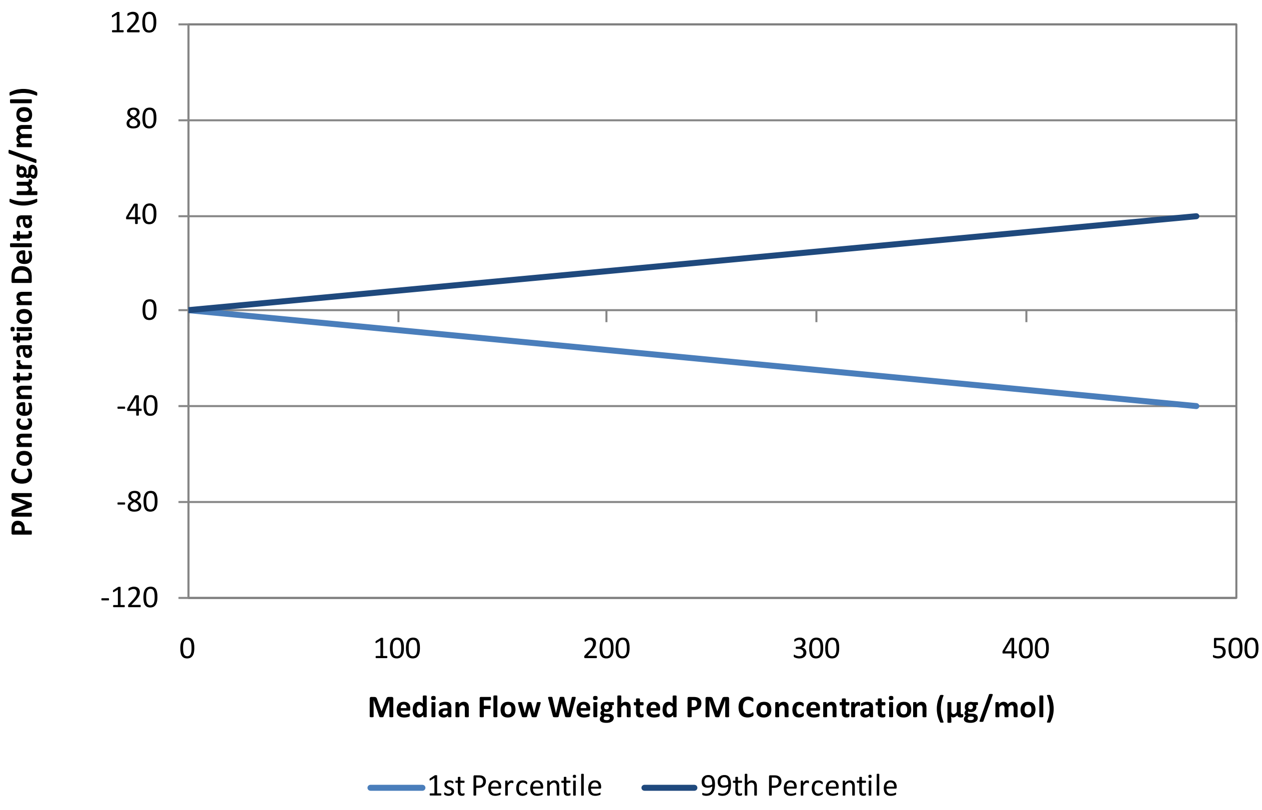


FIGURE 67. FINAL HORIBA TRANSIENT PM ERROR SURFACE

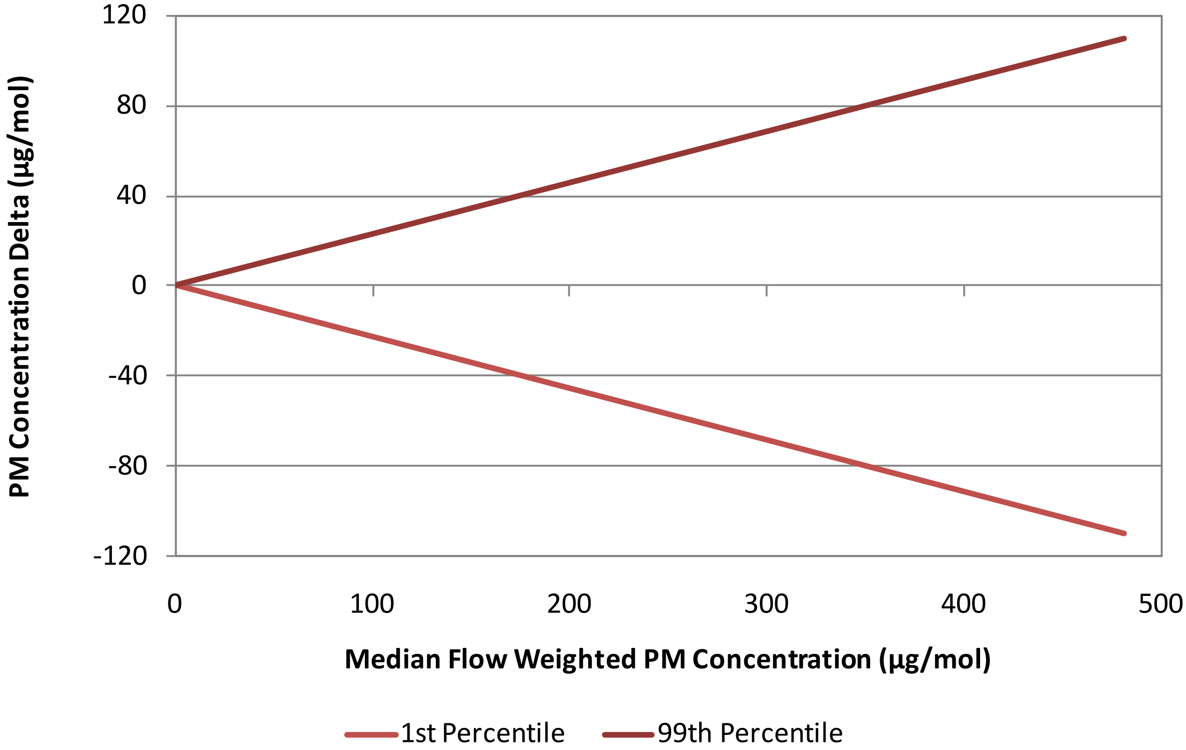


FIGURE 68. FINAL SENSORS TRANSIENT PM ERROR SURFACE

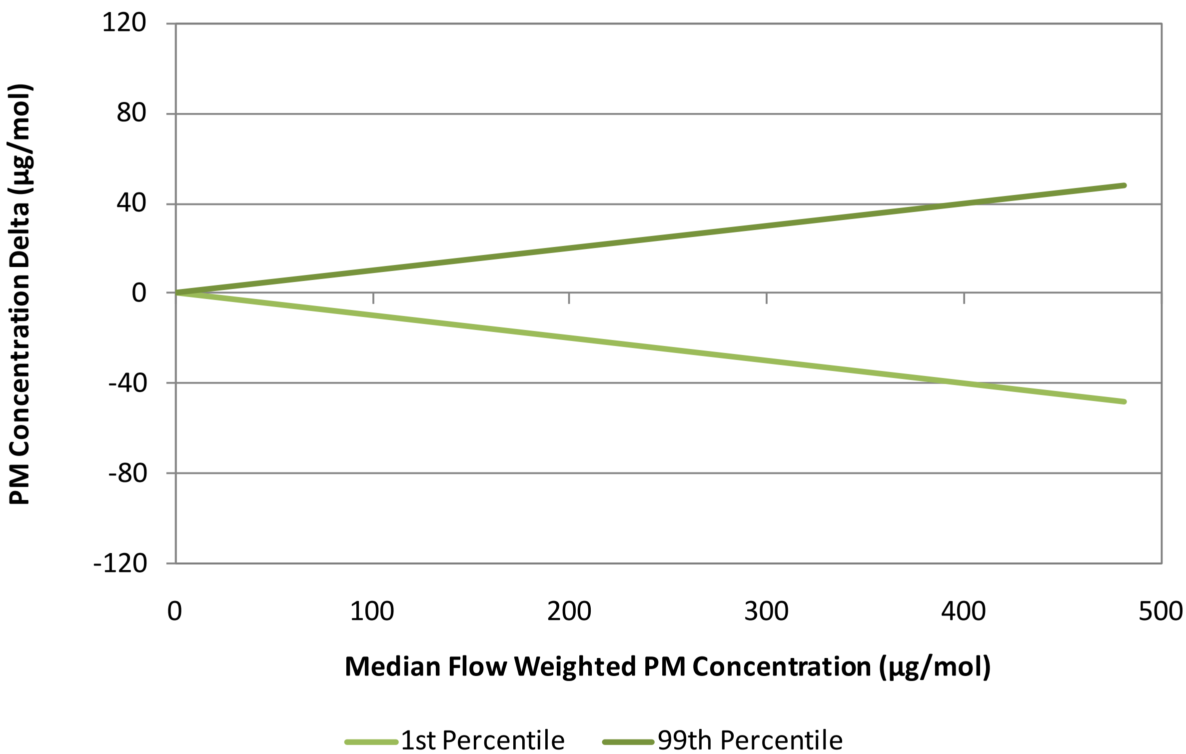


FIGURE 69. FINAL AVL TRANSIENT PM ERROR SURFACE

The median flow weighted PM concentration on the x-axis of each graph is extended to the highest measured concentration observed by any of the PEMS during transient testing. The slope of the transient PM error surface is 0.083 (1.41) for Horiba, 0.228 (3.27) for Sensors, and 0.099 (1.66) for AVL. The 1st percentile for the PEMS are -34, -92, and -40 µg/mol at the maximum PM concentrations observed by each of the PEMS during steady-state testing (around 400 µg/mol) for the Horiba, Sensors, and AVL systems. The 1st percentiles during steady-state testing at the same PM level were -177, -366, and -110 µg/mol for the Horiba, Sensors, and AVL, respectively. Because the steady-state error surface was much larger than the transient it tended to dominate the model results as discussed later.

4.10 CE-CERT Mobile Lab Correlation

The test plan called for the validation of the model to be performed by the mobile emissions laboratory (MEL) operated by the University of California at Riverside Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT). The mobile laboratory consisted of a full-flow CVS system inside the trailer of a Class A truck. The mobile lab was capable of measuring gaseous emissions and filter based PM. The mobile lab was arrived at SwRI on April 9th, 2009 to compare brake-specific PM emissions and ensure that the reference during in-use validation is similar to the reference used during laboratory testing. The CE-CERT MEL was parked behind the SwRI test cell and an exhaust transfer line was fabricated to allow the MEL to measure the full engine exhaust in the same way as the SwRI test cell. Because the CVS measurement technique requires the full flow of engine exhaust for emissions measurement, the exhaust system was designed in such a way that the exhaust pipe could easily be switched between the SwRI CVS and the MEL CVS using the same length and geometry of exhaust pipe. Figure 70 shows the exhaust system used for the CE-CERT correlation.

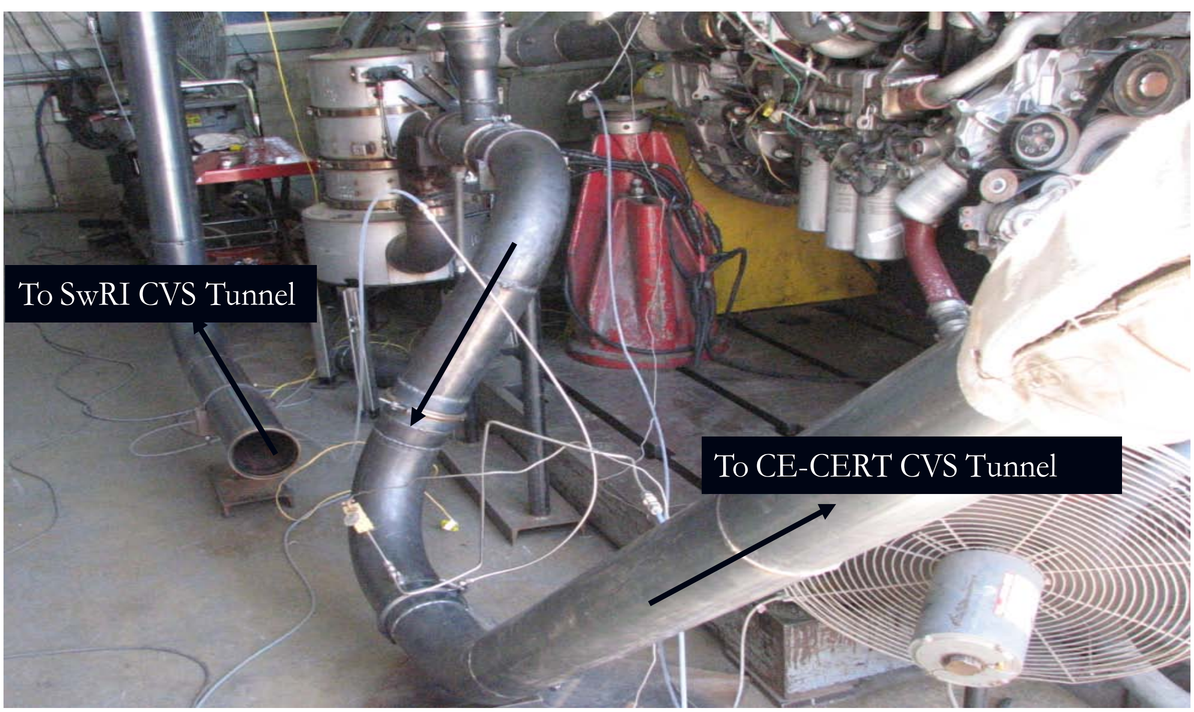


FIGURE 70. EXHAUST CONFIGURATION FOR CE-CERT CORRELATION

Prior to the start of testing, the MEL CVS and SwRI CVS both underwent a propane check to ensure the sampling systems were operating at the correct flows. Further details of the audits performed by CE-CERT on the MEL can be found in the CE-CERT report (reference?). The MEL was set to the same CVS flow, secondary dilution ratio, and filter face velocity as the SwRI CVS to make the measurements as close as possible. One key factor that could not be controlled was the dilution air for the MEL CVS. The SwRI CVS was able to draw flow that is conditioned and maintained between 20 and 30ºC. The MEL CVS drew its dilution air from the ambient which prevented the control of temperature and relative humidity of the dilution air. Each sampling system was conditioned by sampling for 10 hours during steady-state DPF engine operation at a high exhaust temperature. Active DPF regeneration occurred during this conditioning period. A total of 16 short NTE transient cycles were conducted using each CVS system. The short NTE transient cycle was a modified version of the NTE transient cycle used for official transient PEMS testing. The short cycle included 16 of the original 30 NTE events and lasted 755 seconds compared to 2130 seconds for the full NTE cycle. Table 18 shows the order of testing.

TABLE 18. TEST PROCEDURE FOR CE-CERT CORRELATION

	Active Regen	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Active Regen	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Day 1	1	SwRI	SwRI	SwRI	SwRI	1	CE-CERT	CE-CERT	CE-CERT	CE-CERT
Day 2	1	CE-CERT	CE-CERT	CE-CERT	CE-CERT	1	SwRI	SwRI	SwRI	SwRI
Day 3	1	SwRI	SwRI	SwRI	SwRI	1	CE-CERT	CE-CERT	CE-CERT	CE-CERT
Day 4	1	CE-CERT	CE-CERT	CE-CERT	CE-CERT	1	SwRI	SwRI	SwRI	SwRI

A manually triggered active DPF regeneration was performed before the start of each set of four test cycles to maintain a similar PM loading level on the DPF. Each day the test order was switched so that the SwRI tests were first on days 1 and 3 and the CE-CERT tests were first on days 2 and 4. Each test was conducted as a hot-start with a 20 minute hot soak in between test cycles or in between the DPF regeneration and the first test cycle. Figure 71 shows the brake-specific PM results from the 16 cycles.

The data from test 9 for CE-CERT was removed due to a filter weight that was deemed to be an outlier. The average SwRI BSPM was 0.0287 g/hp-hr with a COV of 5.2 percent based on 16 repeats. The average CE-CERT BSPM was 0.0265 g/hp-hr with a COV of 3.5 percent based on 15 repeats. The reported CE-CERT emissions were on average 7.7 percent lower than the SwRI reported emissions. The average reported $BSCO_2$ by CE-CERT was 2.6 percent lower than average SwRI reported value. One possible source of discrepancy between the two systems was the heat loss in the exhaust pipe prior to its entrance into the CVS. The SwRI system was completely sheltered within the test cell, while the CE-CERT exhaust pipe was protruding outside in such a way that it was exposed to wind and ambient temperature effects. This could have resulted in a higher thermophoretic deposition of particles inside the exhaust pipe resulting in lower emissions for the CE-CERT system. However, the test plan stated that agreement within ten percent was considered sufficient, so the correlation was considered complete and the issue was not investigated further.

A series of tunnel blanks were measured from both systems over sample periods of 15, 30, and 60 minutes. Figure 72 shows the filter weight gains as a function of sample time.

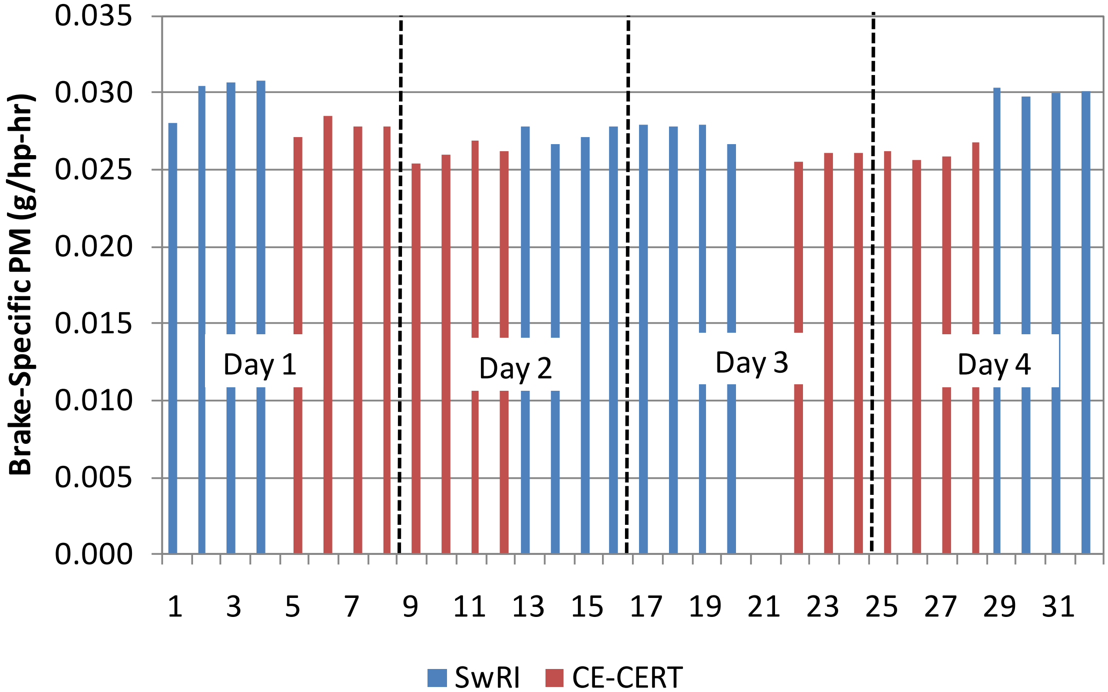


FIGURE 71. BRAKE-SPECIFIC PM RESULTS FROM CE-CERT CORRELATION

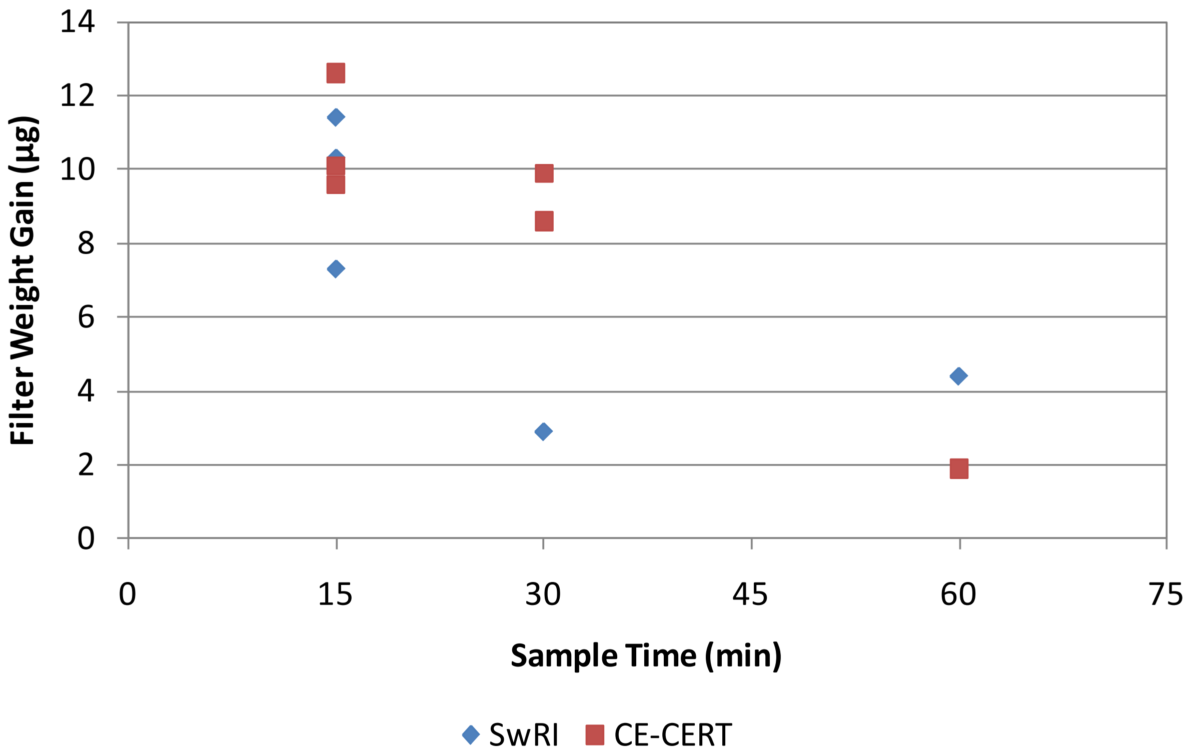


FIGURE 72. CVS FILTER WEIGHT GAIN DURING TUNNEL BLANKS

The filter weight gains during tunnel blank operation were similar for the SwRI and CE-CERT tunnels. The weight gains ranged from 1.9 to 12.6 µg and generally decreased as the sampling time increased. The filter weight gains during the correlation testing were greater than 300 µg making any differences in the tunnel blanks insignificant.

4.11 Investigation of DPF Regeneration

The steering committee requested that screening tests be performed on measurements of active DPF regeneration. Although the majority of the time active DPF regeneration is excluded from in-use measurement as the regulations are currently written there are certain situations where regeneration could be included in a valid NTE event. In addition, if the Horiba system were to trigger filter sampling during DPF regeneration this would still be included in their calibration factor. So even if all NTE events containing active DPF regeneration were considered invalid, the measurement accuracy of the Horiba system during valid NTE events could still be affected through the filter calibration. For this testing the engine was operated at a medium speed medium load condition at steady-state and the DPF was allowed to accumulate PM until the ECM automatically triggered a regeneration. The valves in the bypass were closed forcing a large majority of the exhaust through the DPF although the bypass was not completely sealed. At the point when the ECM indicated it was preparing for an active regeneration the PEMS and CVS filter were triggered to sample. The PEMS sampled 40 seconds on, five seconds off throughout the regeneration, while the CVS filter sampled continuously. Table 19 lists the brake-specific PM results of the PEMS and the CVS.

TABLE 19. PM EMISSIONS RESULTS FROM ACTIVE DPF REGENERATION

	CVS Filter	Horiba	Sensors	AVL
No. of Samples	1	36	31	35
Avg. BSPM, mg/hp-hr	6.8	4.6	7.1	0.2

It is likely that only a small portion of the emissions during the regeneration even included elemental carbon as shown by the fact that the AVL PEMS measured only three percent of the emissions measured by the CVS filter. The Horiba and Sensors PEMS both measured BSPM values on the same order as the CVS filter although the event-by-event emissions were much different. The EEPS also sampled continuously from the CVS through a long residence time secondary dilution tunnel with a nominal secondary dilution ratio of 2. The EEPS number concentration was converted to a mass concentration assuming spherical particles with a density of 1 g/cm³. A comparison of the event-by-event emissions of the three PEMS and the EEPS are shown in Figure 73.

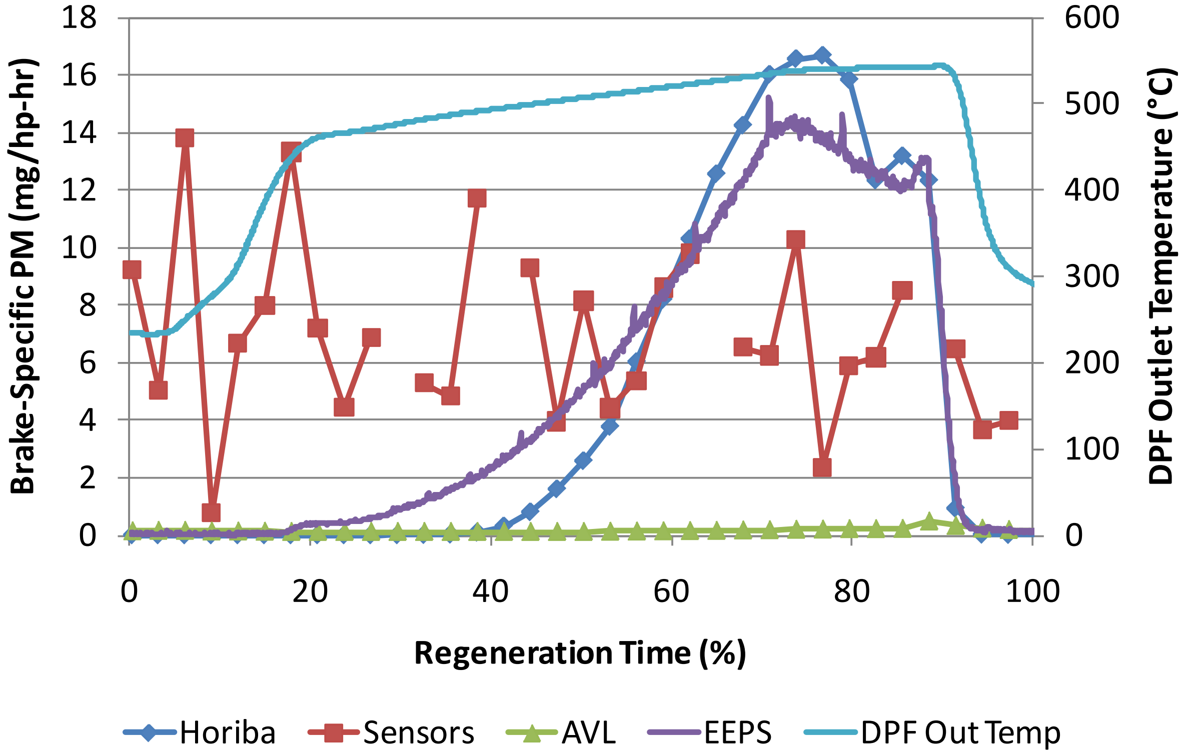


FIGURE 73. BRAKE SPECIFIC PM EMISSIONS DURING ACTIVE REGENERATION

Although the average brake-specific PM value from the Sensors system was very close to the lab value, it is unlikely that the Sensors instrument was properly capturing the behavior of the regeneration. This is because its behavior was insensitive to the active regeneration region as shown in Figure 73. Furthermore, the individual brake-specific emissions seemed to be high, particularly during the first three events and the last two events, where no regeneration occurred. The event-by-event emissions from the Horiba system had similar trend to the mass determined using EEPS number-weighted size distribution measurement, assuming spherical particles with a density of 1 g/cm³. Comparing the Horiba measurements to the CVS filter and the EEPS indicate that it was more accurate than the other PEMS at measuring the regeneration emissions. However, one aspect of the Horiba measurement that was not captured in this experiment, and that is the change in sensitivity of the DCS particle instrument to different size particles. The filter calibration constant for the regeneration event indicated that the DCS was approximately 15 times more sensitive to the particles emitted during the active regeneration compared to the particles emitted during steady-state engine testing. This means that if a steady-state engine cycle was sampled onto the same filter as the DPF regeneration the system would be much less accurate. The Horiba system would over predict the emissions during the regeneration and under predict the emissions during normal engine operation. These findings were presented to the steering committee at the December 11th, 2008 meeting in San Antonio. Although this could be a major issue in the accuracy of the measurement, due to budget limitation, the steering committee did not add DPF regeneration testing to the program given that the regulated aspect of regeneration during in-use testing was vague. No data from the DPF regeneration investigation was included in the model. The AVL MSS was insensitive to regeneration events as shown in Figure 73. This suggests that the majority of mass emitted during regeneration is likely to be volatile materials that will not be detected by the MSS.

4.12 Investigation of Storage and Release

At the same time as the DPF regeneration investigation, the steering committee also requested that screening tests be performed in the area of storage and release of nanoparticles in the aftertreatment system. It has commonly been observed that volatile material emitted by the engine at low temperature will deposit on the DPF only to be released quickly when the engine exhaust temperature climbs. Three different DPF loading conditions were tested:

- Low idle: 650 rpm, 65 Nm
- Medium idle: 1200 rpm, 135 Nm
- High idle: 1800 rpm, 135 Nm.

Idling times of 20, 60, and 90 minutes were tested at each condition. Following the period of low temperature loading, the engine was immediately brought to a high temperature condition to promote the release of the stored particles. Each of the three idling conditions was tested with two high temperature conditions:

- Peak torque: 1200 rpm, 2170 Nm
- Near rated power: 1800 rpm, 1425 Nm

These tests, shown in Figure 74 were conducted as a screening exercise with measurements by the EEPS to determine which combination produced the largest release of nanoparticles to use for the PEMS testing. However none of the tested conditions resulted in any significant particle emissions on a number or mass basis. To ensure that the EEPS was not missing something that might have been captured by one of the PEMS, two tests were run with the PEMS: low idle to peak torque and high idle to peak torque. Only the low idle test is shown here because the results are very similar. The engine was allowed to idle for one hour before going to peak torque for ten minutes; this process was repeated three times consecutively for a cycle length of 3.5 hours. The PEMS only sampled during the peak torque portion of the cycle with the same 40 seconds sample, five seconds off cycling used in the DPF regeneration study.

A spike of just over 2.0E6 particles/cm³ was observed during the transition from idle to peak torque although this appears to be due to acceleration and a possible slight misalignment between the dilution ratio and EEPS measurement rather than a release of particles from the aftertreatment. The spike was less than 1.0E6 for the second and third transitions to peak torque. Figure 75 shows the brake-specific PM emissions measured by the three PEMS during the peak torque portion of the storage and release cycle. All samples are taken during the three repeats of the ten minutes at peak torque and no emissions from the idle portion of the cycle are represented.

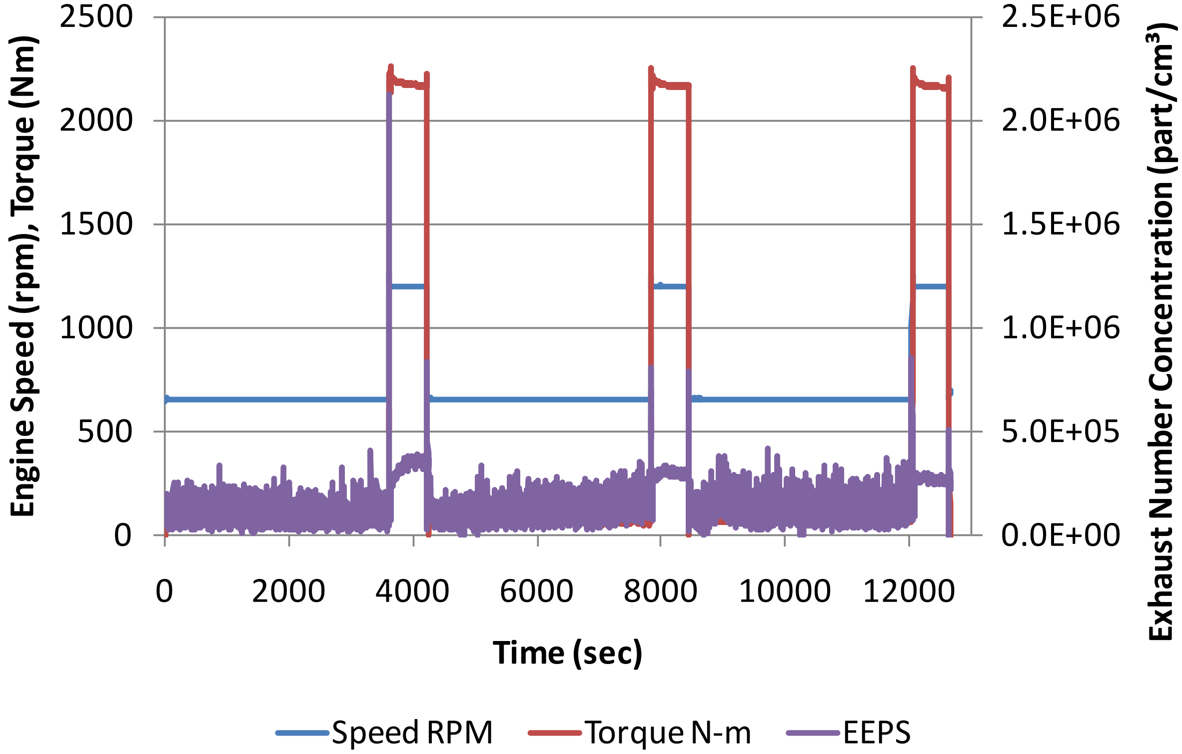


FIGURE 74. TOTAL EXHAUST NUMBER CONCENTRATION DURING STORAGE AND RELEASE

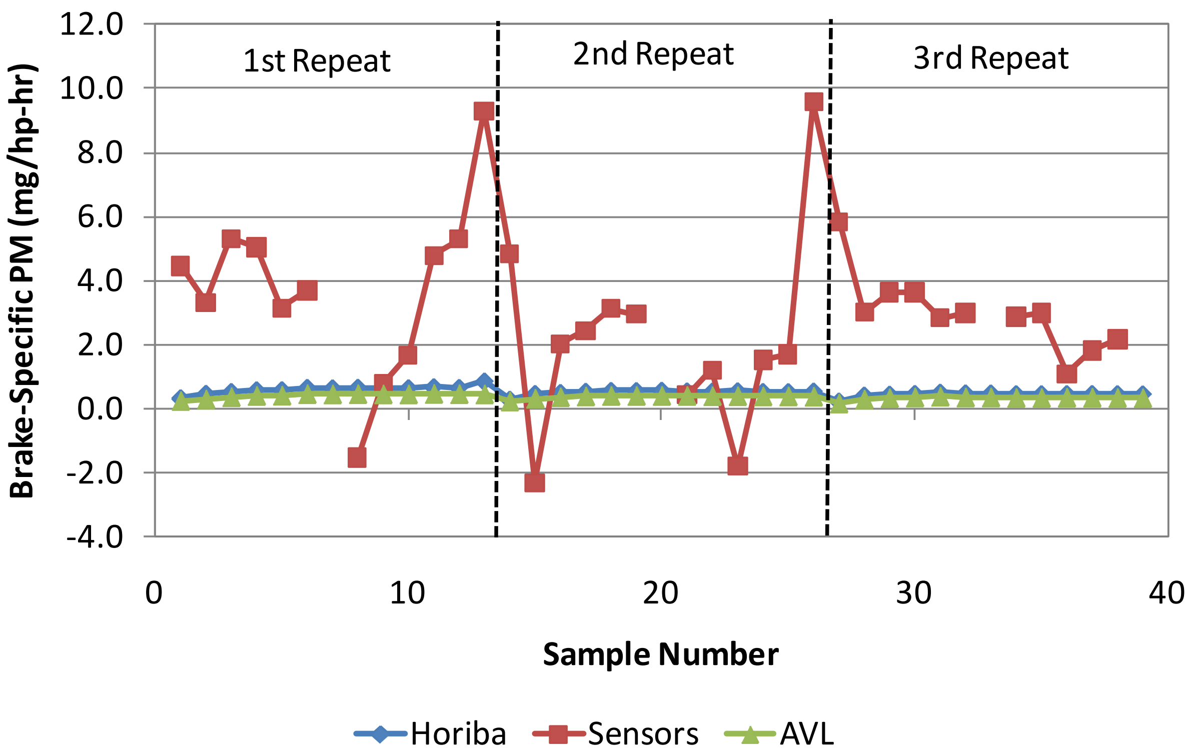


FIGURE 75. BRAKE-SPECIFIC PM EMISSIONS DURING STORAGE AND RELEASE INVESTIGATION

It is unclear why the Sensors were reporting emissions much higher than the other two PEMS. A single CVS filter was sampled for the entire ten minutes at peak torque for each repeat for a total of three filter measurements. The BSPM from the CVS filter was only between 0.3 and 0.4 mg/hp-hr for each of the three repeats. This was lower than any of the PEMS and an order of magnitude lower than the Sensors PEMS. The three negative emissions were attributed to the same crystal which was unusually noisy during the test. A comparison of the average BSPM values for the cycle is shown in Table 20.

TABLE 20. AVERAGE BRAKE-SPECIFIC EMISSIONS DURING STORAGE AND RELEASE CYCLE

	CVS Filter	Horiba	Sensors	AVL
No. of Samples	3	39	36	39
Avg. BSPM, mg/hp-hr	0.38	0.54	2.97	0.41

The effect of storage and release on the PEMS emissions was not clear because of the inability to generate a significant release of nanoparticles, but it was evident that investigating this phenomenon using this experimental configuration was not worthwhile. These findings were presented at the December 11th, 2008 meeting in San Antonio and the steering committee declined to pursue any further work in this area. No data from the storage and release investigation was included in the model.

4.13 Engine Manufacturers Torque and Fuel Error Surfaces

The OEM supplied torque error surface was updated from the gaseous PEMS program and the OEM supplied BSFC error surface was replaced with a fuel flow error surface. Five different engine manufacturers supplied data from 61 different engines. In addition data was used from the four engines tested in the ACES program for a total of 2,099 data points from 65 engines. The ECM torque deltas were normalized by the maximum ECM torque. The torque deltas are shown in Figure 76.

The errors as a percentage of the maximum ECM torque are relatively constant throughout the entire measured range indicating that the error as a percentage of point would increase as the absolute torque decreases. The much smaller data set used for the gaseous measurement allowance program showed constant errors as a percentage of point rather than a percentage of maximum. The plot of ECM fuel flow errors as a percentage of maximum ECM fuel flow is shown in Figure 77.

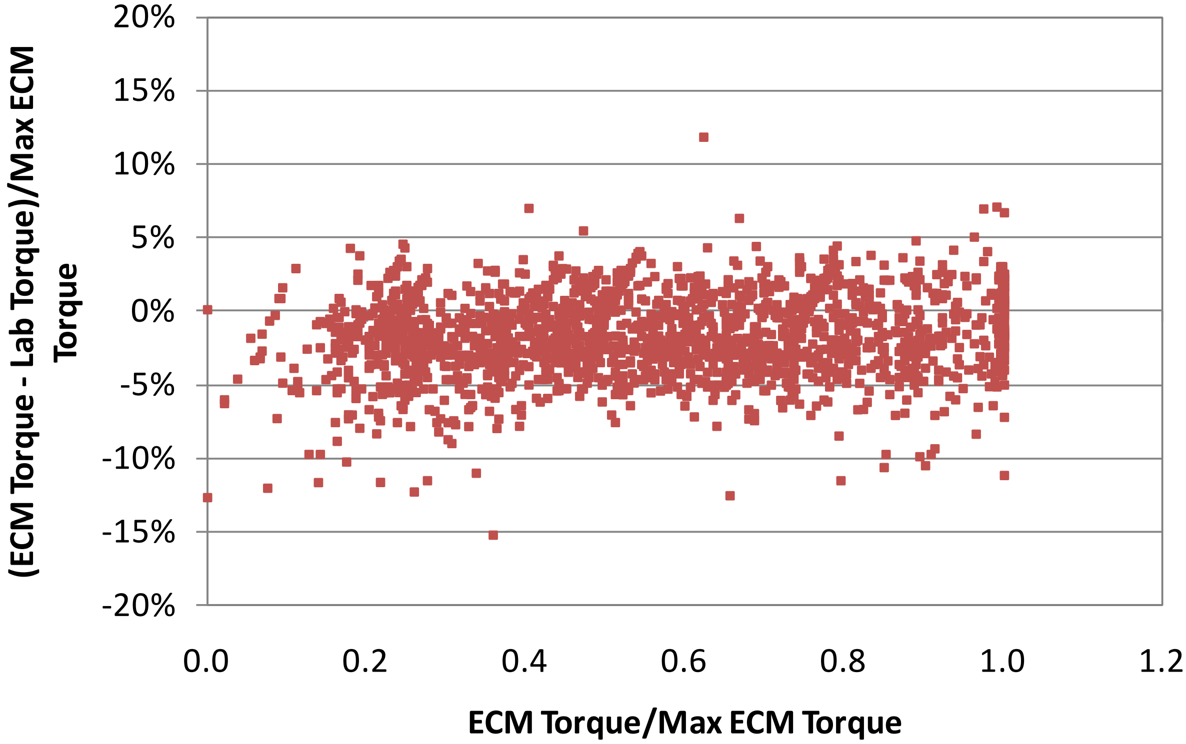


FIGURE 76. OEM SUPPLIED TORQUE ERRORS

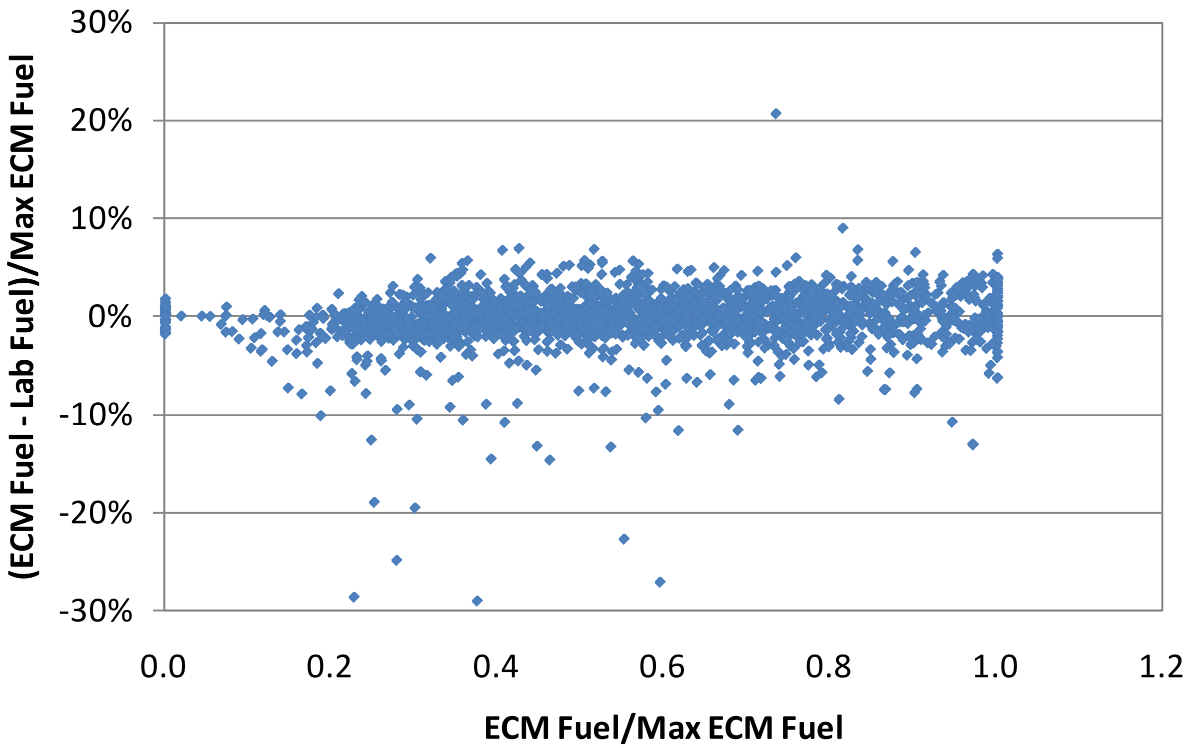


FIGURE 77. OEM SUPPLIED FUEL FLOW ERRORS

The fuel flow errors were also constant in relation to max fuel flow rate above 20 percent fuel flow. Since the fuel flow is expected to remain well above 20 percent during NTE event operation, the smaller errors at low fuel flows were not considered important. Although the OEM supplied torque and fuel flow error surfaces were created as percentages of point for the gaseous measurement allowance, these surfaces were generated as percentages of maximum for the current program. The 1st, 50th, and 99th percentiles were calculated for torque and fuel flow and sampled in the model using a normal distribution. The error surface deltas are shown in Table 21.

TABLE 21. OEM ERROR SURFACE DELTAS FOR TORQUE AND FUEL FLOW

	Percentiles		
Parameter	**1st, % Point**	**50th, % Point**	**99th, % Point**
Torque	-7.6	-1.7	4.1
Fuel Flow	-4.5	-0.1	4.9

5.0 ENVIRONMENTAL TESTING AND RESULTS

A series of tests were conducted to characterize the PEMS response under in-use conditions such as changes in pressure, temperature, and humidity, as well as their response to electromagnetic and radio frequency interference and shock and vibration.

Initially the test plan called for the EPA PM Generator system to be used as the PM source for all environmental testing. The PM generator is capable of producing soot, volatile hydrocarbons, and sulfuric acid to simulate the PM emitted from a diesel engine. However, after the system was operated at SwRI it was discovered that the PM generator was too tall to fit into the altitude chamber. It was likely that it would not be possible to operate the PM generator under atmospheric conditions while the output was subject to a constantly varying pressure. The diffusion rate of the hydrocarbon vials is pressure dependant so it would not have been possible to maintain a constant PM source while varying the pressure inside of the chamber. SwRI proposed using a Jing mini-CAST soot generator in place of the PM generator. The soot generator is only a fraction of the size and much easier to operate compared to the PM generator. The steering committee agreed to allow the soot generator to be used for the altitude testing but requested that the PM generator be used for the temperature and humidity testing.

It was decided to operate the Electromagnetic Interference / Radio Frequency Interference (EMI/RFI) and shock and vibration testing as screening. In this case screening testing meant that the PEMS were operated while sampling zero air to look for potential problems. The results from the screening testing would then be presented to the steering committee to decide whether to proceed with official testing to generate an error surface. The main motivation to conduct the EMI/RFI and vibration testing as screening was the result of the finding of the gaseous measurement allowance program that in most cases a failure mode of the PEMS was observed only as a malfunction of the system in which it could no longer operated. It was not commonly observed that the accuracy of the PEMS was affected while it continued to measure without detected problems.

SwRI's Mechanical and Material Engineering Division (Division 18) performed the environmental testing. The altitude, temperature and humidity testing was performed by Rick Pitman and Mike Negrete. The EMI/RFI testing was performed by David Smith and Herbert Walker. The shock and vibration testing was performed by David Smith, Mike Negrete, and Mark Orlowski.

5.1 Reference Measurement Testing

An eight hour baseline measurement was performed for comparison to the eight hour environmental tests. Unlike the gaseous measurement allowance program it was not possible to compare the accuracy of the PM-PEMS over the measurement period, only the variability. The PM and soot generators provide a particle source, but the correct concentration of the source was unknown.

During the eight hours of testing the PM concentration and dilution ratio was cycled to allow a more accurate assessment of the PEMS performance over a range of operating conditions. Three PM levels and four dilution ratios were sampled for a total of 12 test conditions. Figure 78 shows the schedule of target PM concentration and dilution ratio for one hour of environmental testing.

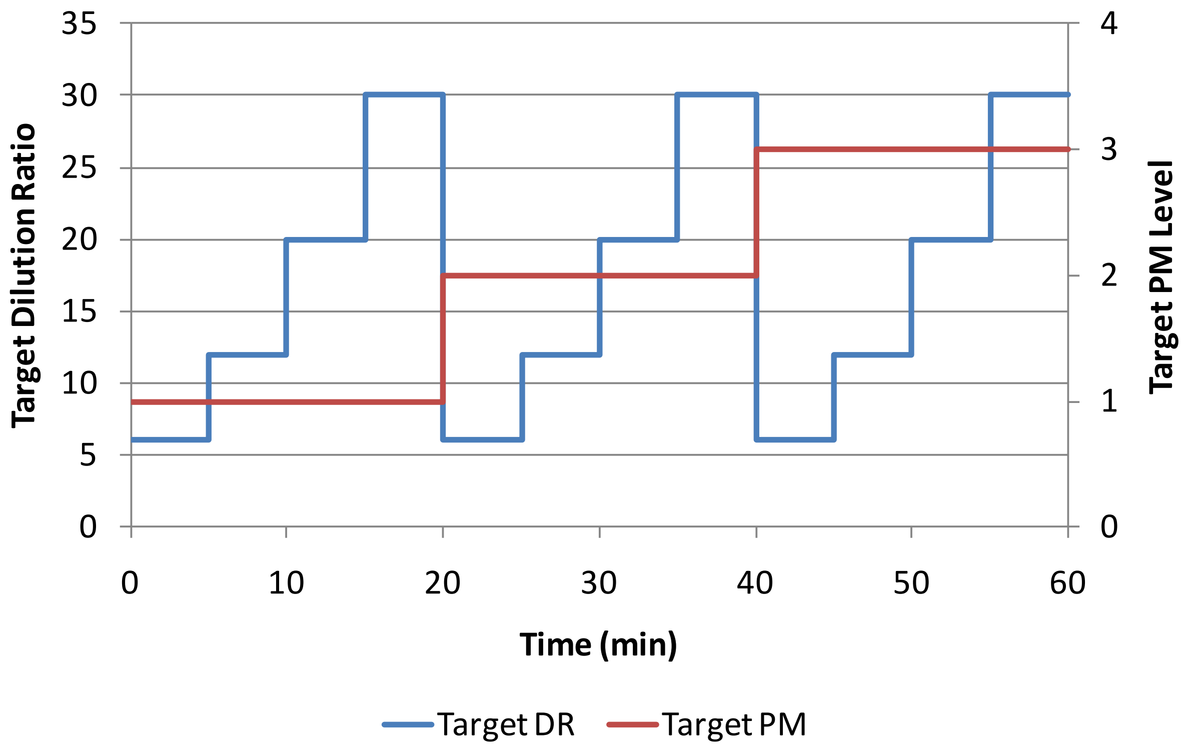


FIGURE 78. TARGET DILUTION RATIO AND PM LEVEL PROFILE FOR ENVIRONMENTAL TESTING

Each level was sampled at dilution ratios of 6, 12, 20, and 30 for the Horiba and Sensors PEMS. The AVL PEMS was maintained at its constant dilution ratio of 5. The PEMS were maintained at a target dilution ratio for five minutes. With 35 seconds remaining, the sample trigger was enabled for 30 seconds. This allowed for four minutes and 25 seconds for stabilization, 30 seconds for sampling, and five seconds after sampling to ensure sampling on all PEMS had stopped before the target dilution ratio was changed. The PEMS were cycled through the four dilution ratios at a single PM concentration level before the process was repeated at the next concentration level. It took one hour to cycle through each combination of dilution ratio and PM concentration. This profile was repeated eight times for a total test time of eight hours. The schematic showing the experimental setup can be seen in Figure 79.

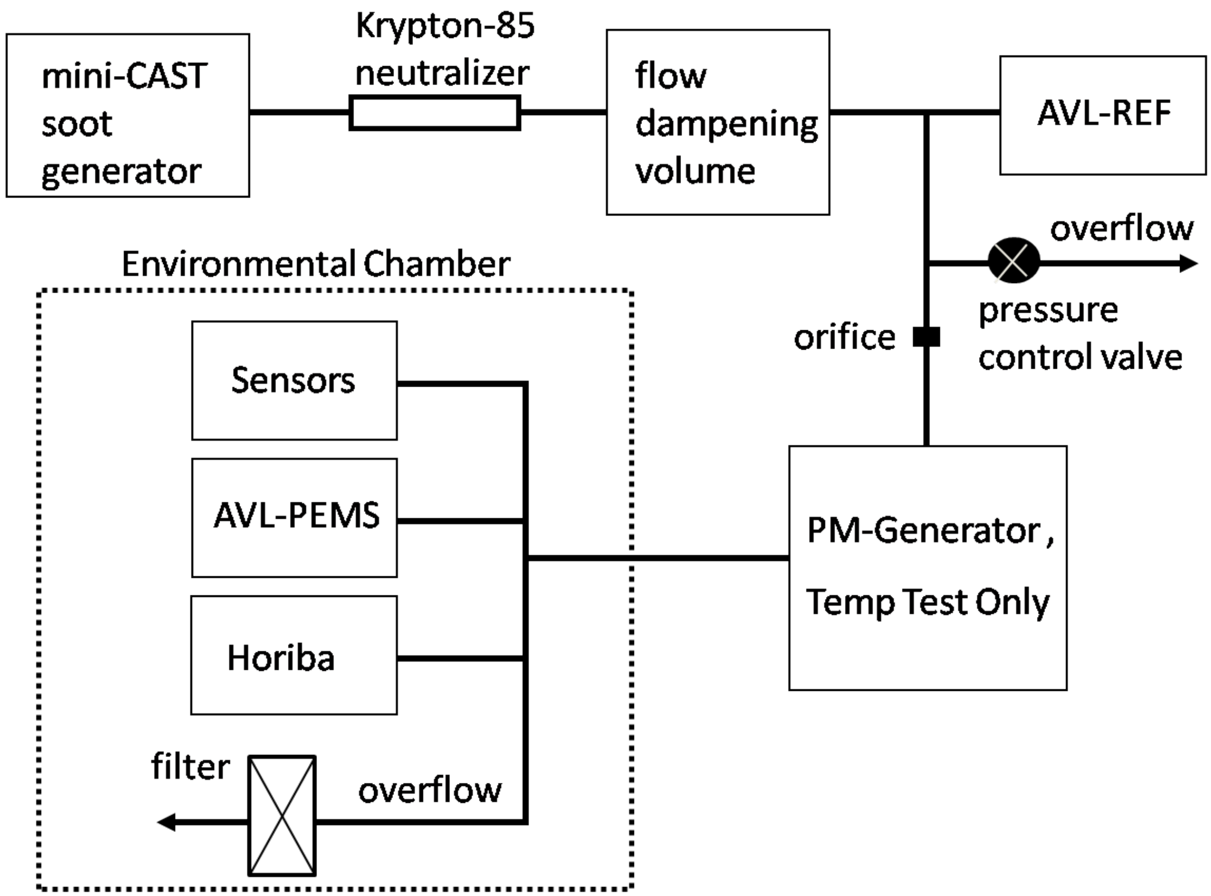


FIGURE 79. EXPERIMENTAL SETUP FOR ENVIRONMENTAL TESTING

The particles from the soot generator passed through a Krypton-85 neutralizer to bring the charge of the particles to a minimum Boltzmann distribution of charge [7] to minimize particle losses due to electric forces. A large volume was placed downstream of the neutralizer to minimize the pressure fluctuations observed by the soot generator and also to smooth out any changes in concentration from the generator. One of the AVL PEMS units was placed outside of the environmental chamber upstream of the orifice and overflow so that it was isolated from the chamber conditions. This PEMS served as a reference to verify that the soot concentration from the generator was stable. The AVL unit was chosen because it could provide a real time measurement of the soot concentration. This was not a guarantee that the total PM concentration from the generator was steady, but typically the volatile emissions from the generator would not fluctuate significantly without some change in the soot concentration.

The mini-CAST soot generator was used as the particle source for the baseline testing. The number mean diameter was approximately 70 nm based on measurement with the EEPS. The three concentration levels were nominal concentration levels of 25, 75, and 125 µg/mol with approximately 30 percent organic carbon based on the OC/EC measurement. Figures 80, 81, and 82 show the concentration measurements during the baseline testing for the Horiba, Sensors, and AVL PEMS, respectively. Figure 83 shows a comparison between the reference MSS and the PEMS MSS which were measuring simultaneously during the baseline testing.

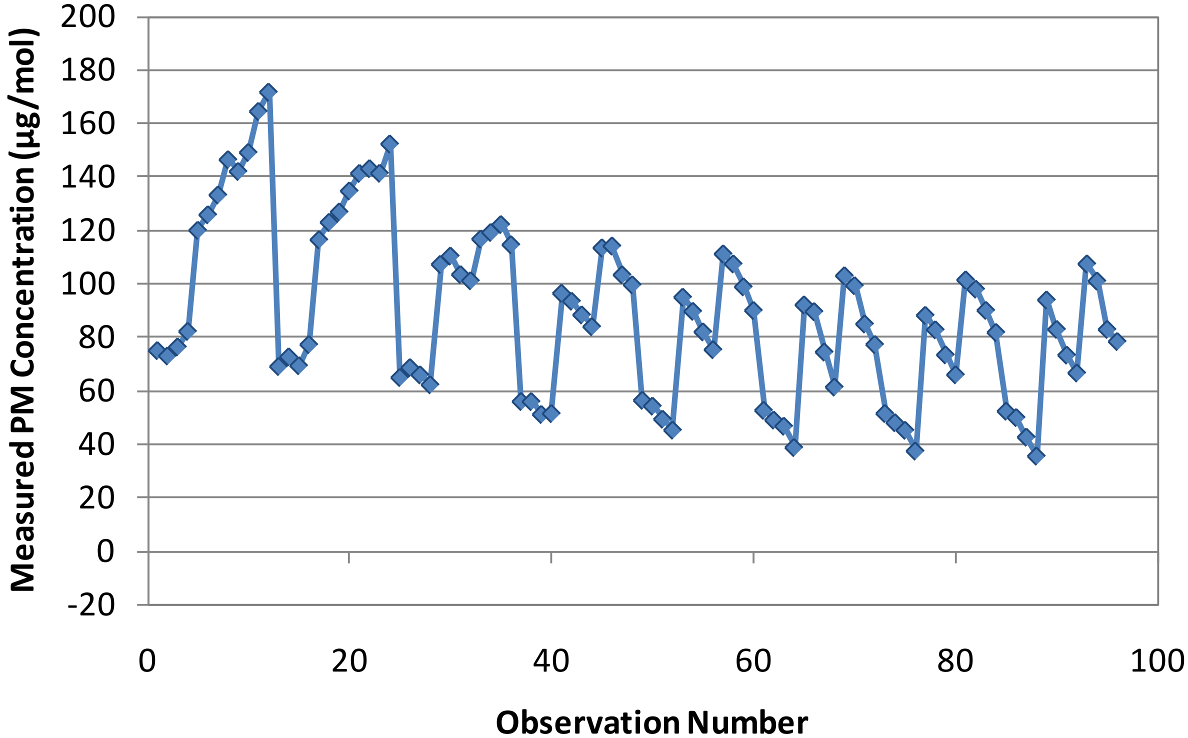


FIGURE 80. HORIBA ENVIRONMENTAL BASELINE MEASUREMENTS

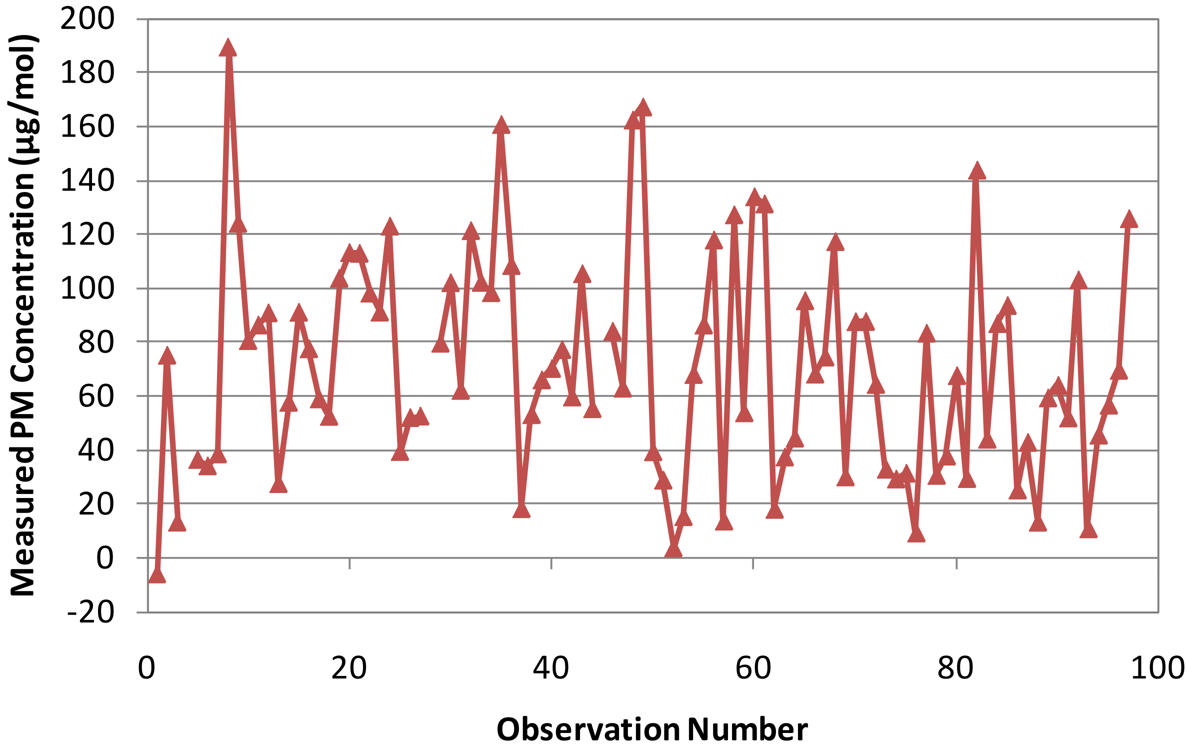


FIGURE 81. SENSORS ENVIRONMENTAL BASELINE MEASUREMENTS

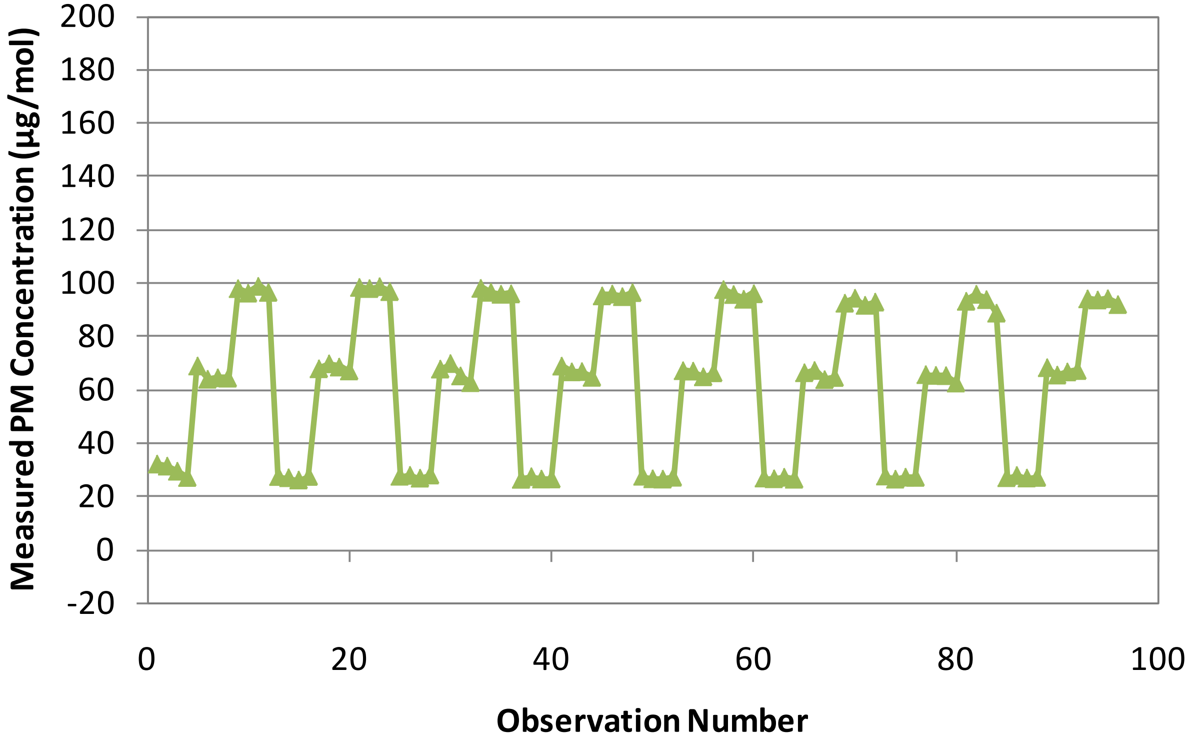


FIGURE 82. AVL ENVIRONMENTAL BASELINE MEASUREMENTS

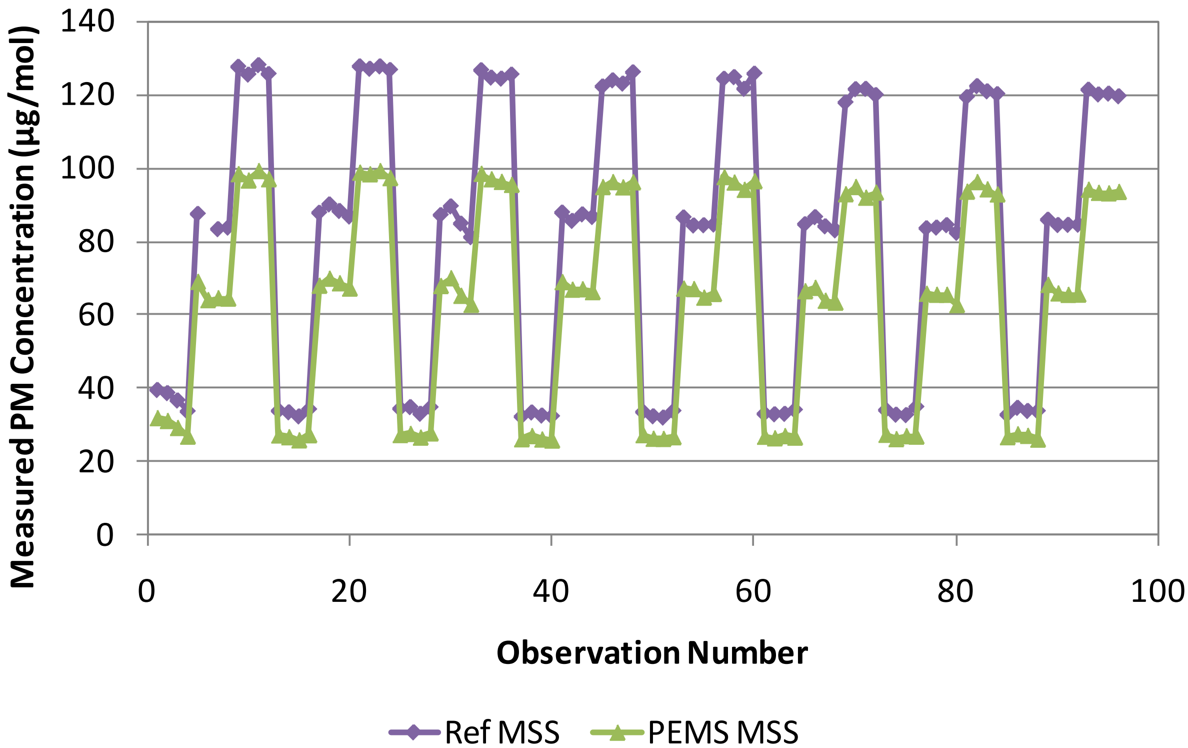


FIGURE 83. REFERENCE MSS ENVIRONMENTAL BASELINE MEASUREMENTS

Although the soot concentration from the generator was likely stable based on the measurements from both AVL PEMS it is not clear whether the total PM concentration remained constant throughout the test. In Figure 80, the Horiba PEMS exhibited a clear downwards trend in measured concentration as the test progressed. The reported PM concentration from the Sensors PEMS in Figure 81 appeared to be somewhat independent of the actual PM concentration sampled. The Sensors data was too scattered to either confirm or disprove the PM trend observed in the Horiba data. In addition to the general downwards trend of the concentration, the Horiba data appeared to suggest that the accuracy of the dilution ratio was playing a role in the measurement. In observations 25 through 96, the reported concentration decreased each time the dilution ratio target increased. This suggests that the Horiba PEMS is has either a positive error on lower dilution ratios or a negative error on higher dilution ratios.

In Figure 83, it is clear that the PEMS and reference AVL units were both able to resolve the differences between the three PM levels clearly even showing similar responses to small changes in concentration. Figure 84 depicts the relationship between the AVL reference measurement and the AVL PEMS measurement.

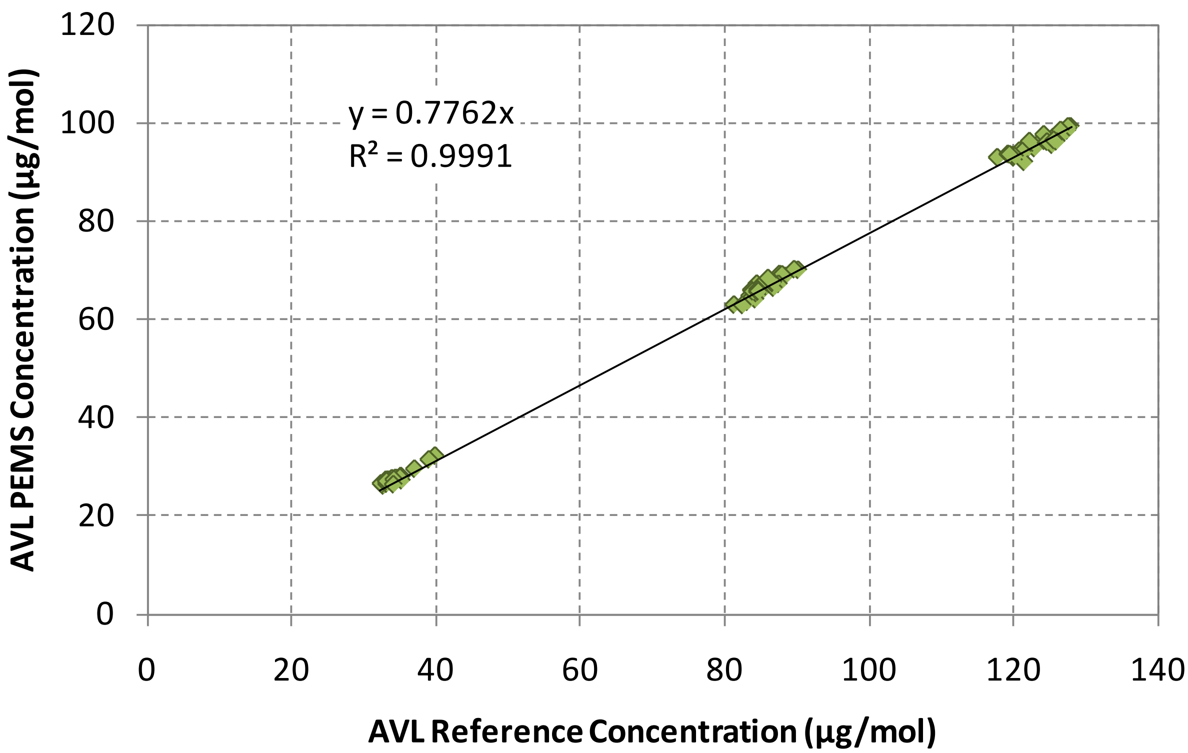


FIGURE 84. REFERENCE AVL VERSUS PEMS AVL FOR ENVIRONMENTAL BASELINE

The correlation coefficient between the two measurements is excellent, better than 0.99. The slope of 0.78 is likely to be a combination of a difference in response of the two instruments and line losses between the two points of measurement.

5.2 Pressure Chamber Testing

The SwRI altitude chamber is capable of simulating altitudes up to 19.8 km. The chamber is 1.5 m in diameter and 2.1 m tall. Typically the simulated altitude chamber at SwRI is operated only under vacuum to simulate altitudes greater than that of San Antonio. The gaseous measurement allowance test plan called for pressures up to 101.87 kPa or 45 meters below sea level. The elevation of San Antonio is approximately 240 meters above sea level with a barometric pressure near 99 (98.4 based on altitude) kPa. In the gaseous measurement allowance program, the altitude chamber underwent significant alterations to achieve positive pressures and still many problems were encountered. The SwRI engineer in charge of the altitude chamber requested that only negative pressures be tested to preserve the integrity of their test equipment. Simply changing the positive pressures to ambient would have resulted in a large portion of the testing being conducted at normal atmospheric pressure. Instead a slight negative pressure of 94.3 kPa (610 m, 2,000 ft) was repeated twice, once at 1.8 hours and once at 7.2 hours. Figure 85 shows the original pressure profile from the test plan as well as the modified profile that was used during testing.

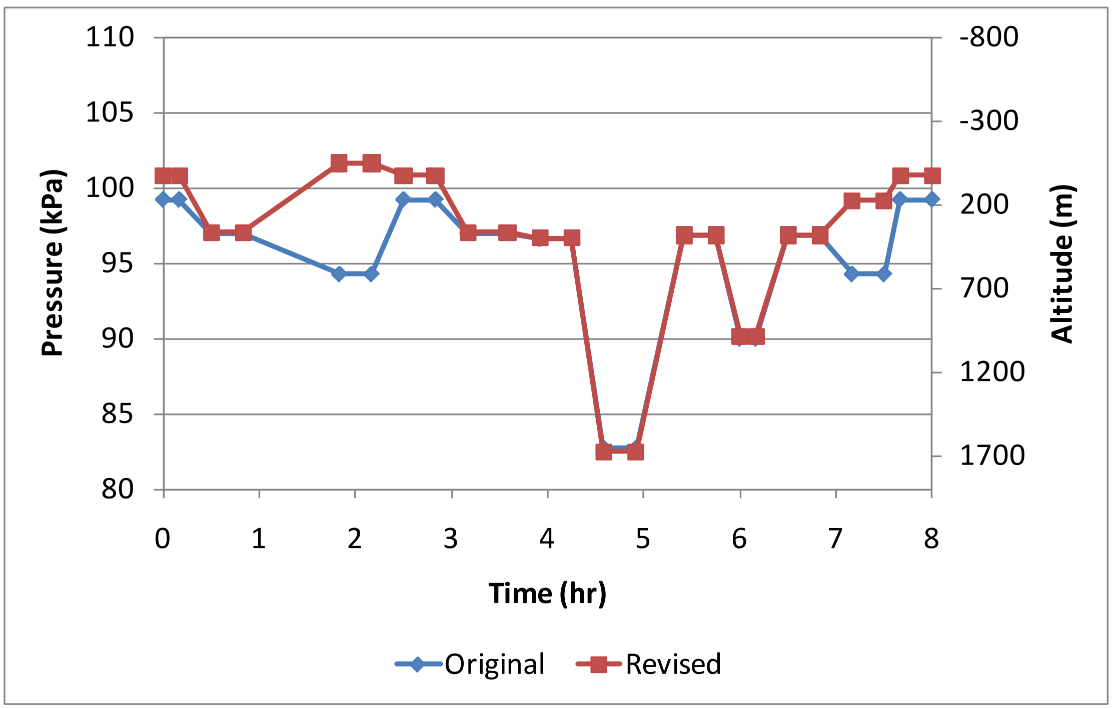


FIGURE 85. ORIGINAL AND REVISED PROFILE FOR ALTITUDE TESTING

Significant efforts were devoted to ensuring that a stable PM source could be generated that was insensitive to pressure. Because the soot generator contains an open flame operating at atmospheric pressure, the properties of the flame, and hence the particle generation, tended to change with the pressure of the outlet. By placing an orifice in the transfer line between the soot generator and the pressure chamber it was possible to operate the soot generator at a higher pressure and maintain a constant pressure through adjustment of an overflow valve upstream of the orifice. Adjustments were only necessary during the pressure ramps to 82.7 kPa and 90.0 kPa. The valve was adjusted to maintain a constant pressure upstream of the orifice. Figure 86 shows the setup outside of the altitude chamber.

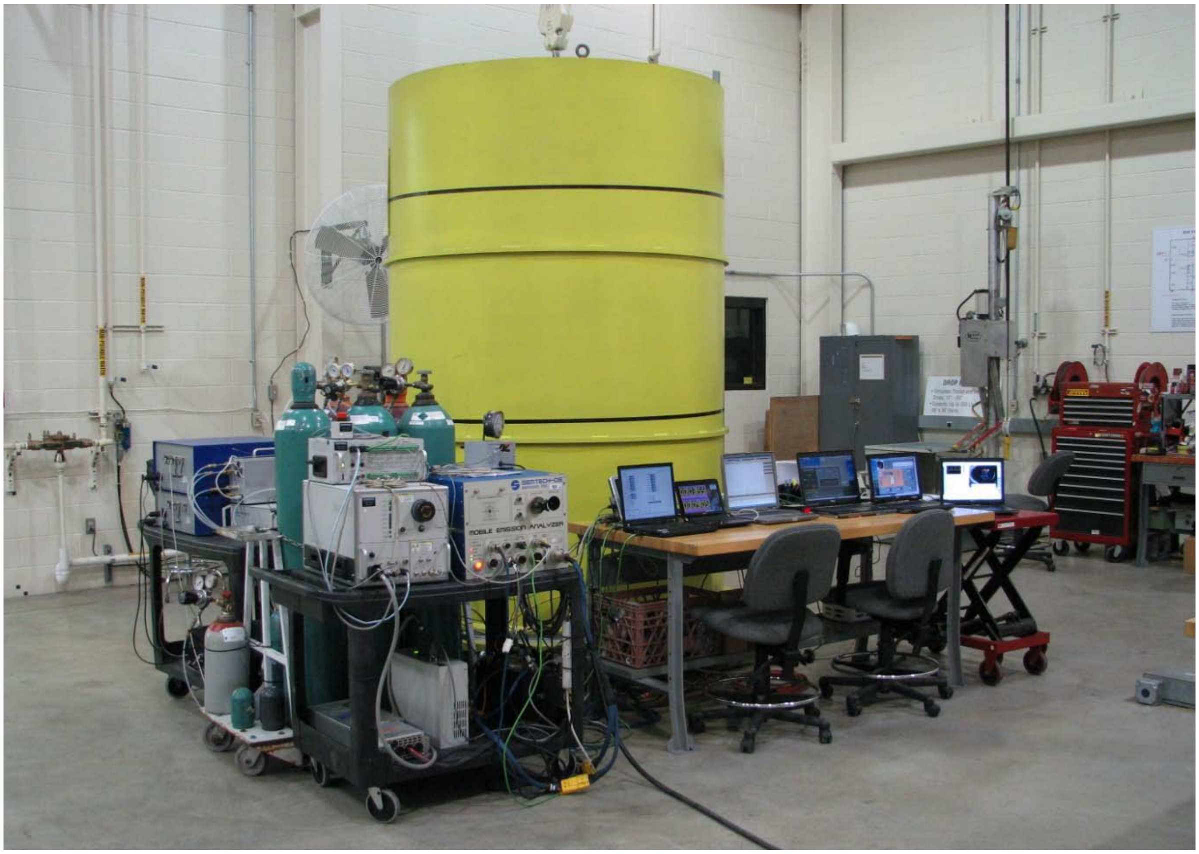


FIGURE 86. ALTITUDE TESTING CHAMBER

During the first practice run, the AVL 3 blew a fuse in its measurement unit. The test was stopped and the fuse was replaced, but immediately blew again indicating an electrical failure within the unit. The unit was replaced with AVL 2 and testing continued with the problem not observed again. Due to space constraints, the Semtech DS and Horiba OBS-2200 gaseous PEMS were located outside of the environmental chamber. Since the purpose of these devices was only communications, it was not considered necessary to test them inside the chamber. The external compressor used for the Horiba dilution air was also installed outside the chamber. A large compressor was supplied by SwRI to provide oil-less dilution air. The steering committee had requested that the Horiba supplied compressor should be used but then agreed to allow the replacement compressor after it was determined that the original compressor could not operate for the entire eight hours without shutting off. A picture of the PEMS installed in the altitude chamber is shown in Figure 87.

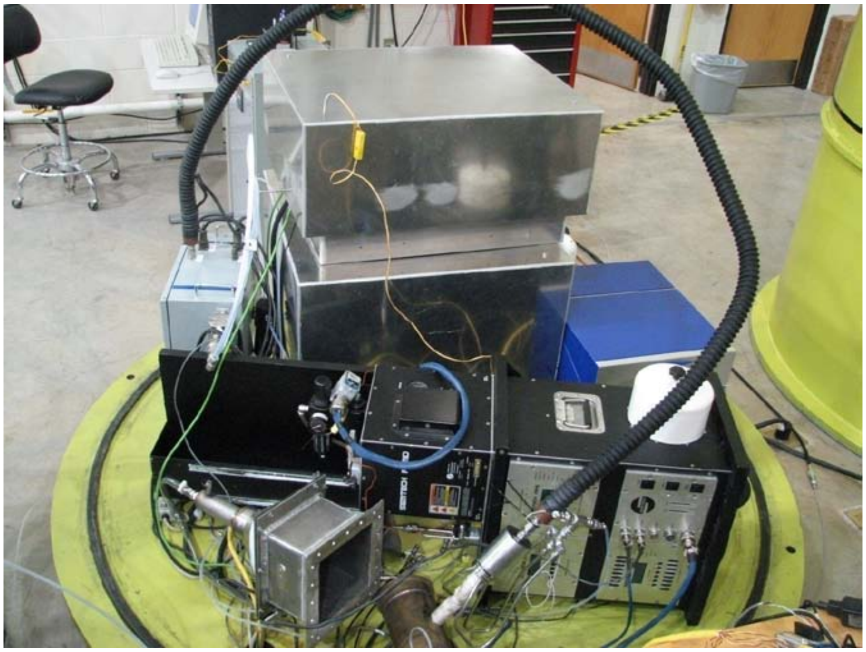


FIGURE 87. PEMS INSTALLED IN THE ALTITUDE CHAMBER

As mentioned previously, analysis of the environmental data was more difficult for the PM-PEMS program compared to the gaseous PEMS program due to the lack of a known reference concentration. For this reason, only the variability of the PEMS measurement in comparison to its average was compared. The individual data points were plotted as well as the average levels to show how far each measurement deviated from the average. Figure 88 shows the concentration measurements by the Horiba.

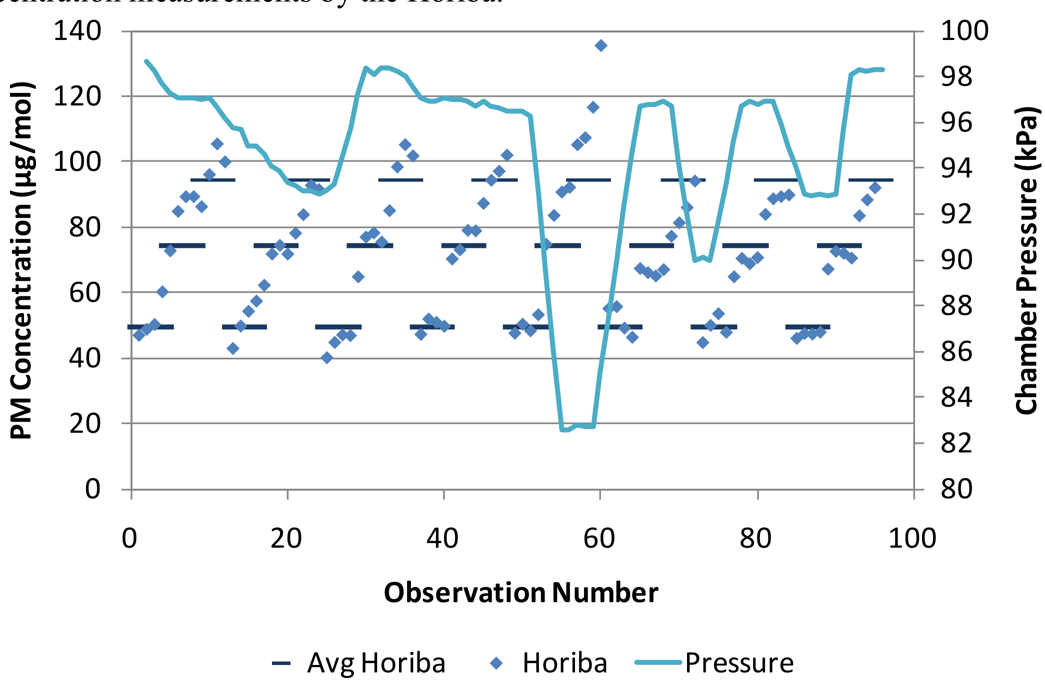


FIGURE 88. HORIBA ENVIRONMENTAL PRESSURE MEASUREMENTS

The Horiba concentration measurements were not consistent for different dilution ratios. In the baseline test it was observed that increasing the dilution ratio in the range of 6, 12, 20, and 30 tended to decrease the reported concentration. In the pressure test, it appears that the measured concentration increases as the dilution ratio increases. The largest deviations from the average occurred during observations 53-60 while the pressure was at its lowest indicating that the ambient pressure does have some effect on the accuracy of the Horiba reported concentration. During the period between observations 53 and 60, the system was unable to maintain its target total flow rate of 30 slpm, as shown in Figure 89.

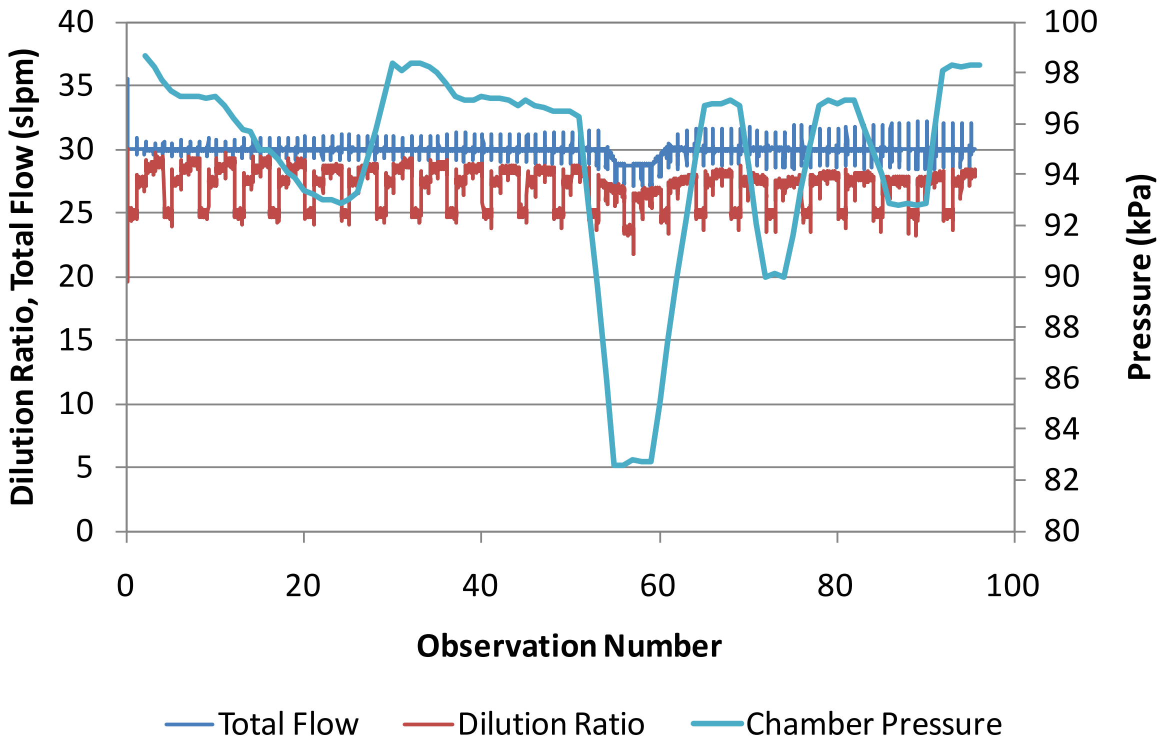


FIGURE 89. HORIBA TOTAL FLOW AND DILUTION RATIO DURING PRESSURE TESTING

The total flow dropped to approximately 28.7 slpm during this period which is below the acceptable tolerance according to the manufacturer, causing the data to be invalidated. The system was however able to maintain proportionality during this part of the test. The short spikes in the total flow is from each switch from sample to bypass mode.

The Sensors data, as shown in Figure 90, exhibited a large amount of variability with some data more than a factor of two higher and lower than the average. With that amount of scatter it was difficult to visually discern an effect of pressure on the measurement.

The AVL data, as shown in Figure 91, was grouped tightly around the average except during the low pressure excursion around observances 53 -60. Because of the excellent repeatability of the measurement, the effect of pressure on the measurement was readily apparent. As the ambient pressure decreased, the measurement decreased as well.

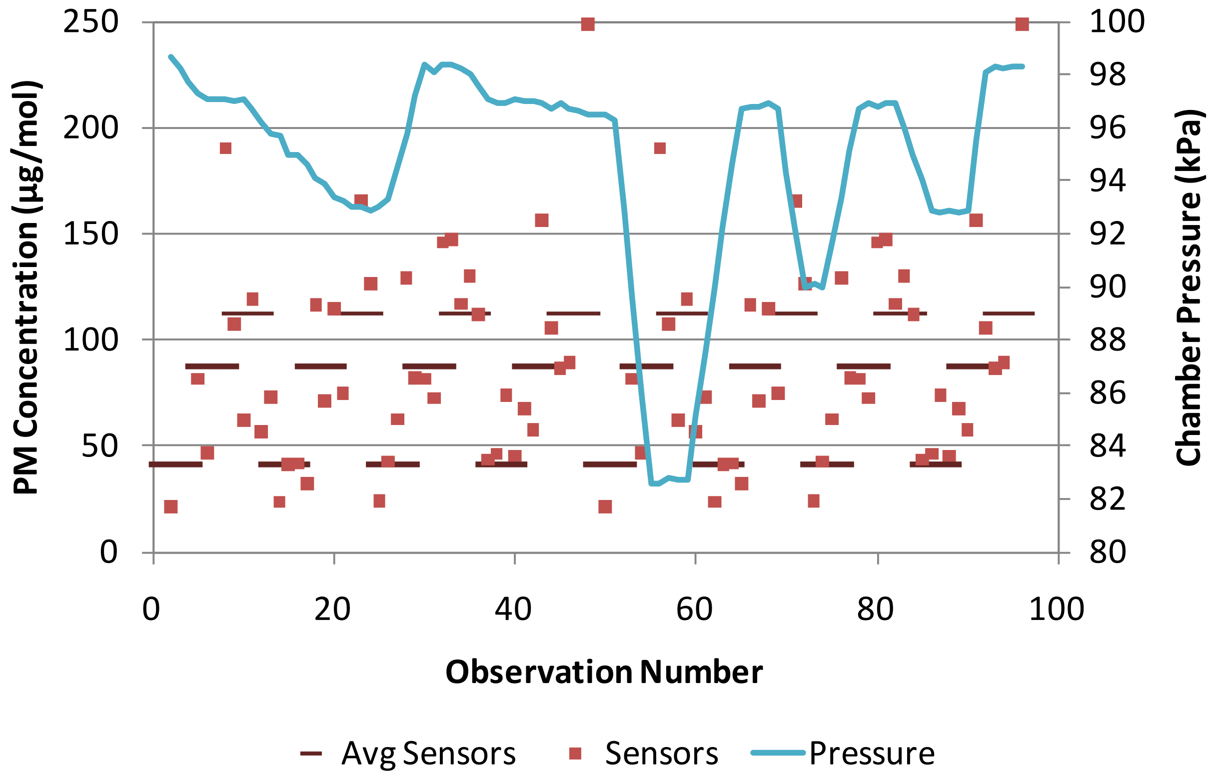


FIGURE 90. SENSORS ENVIRONMENTAL PRESSURE MEASUREMENTS

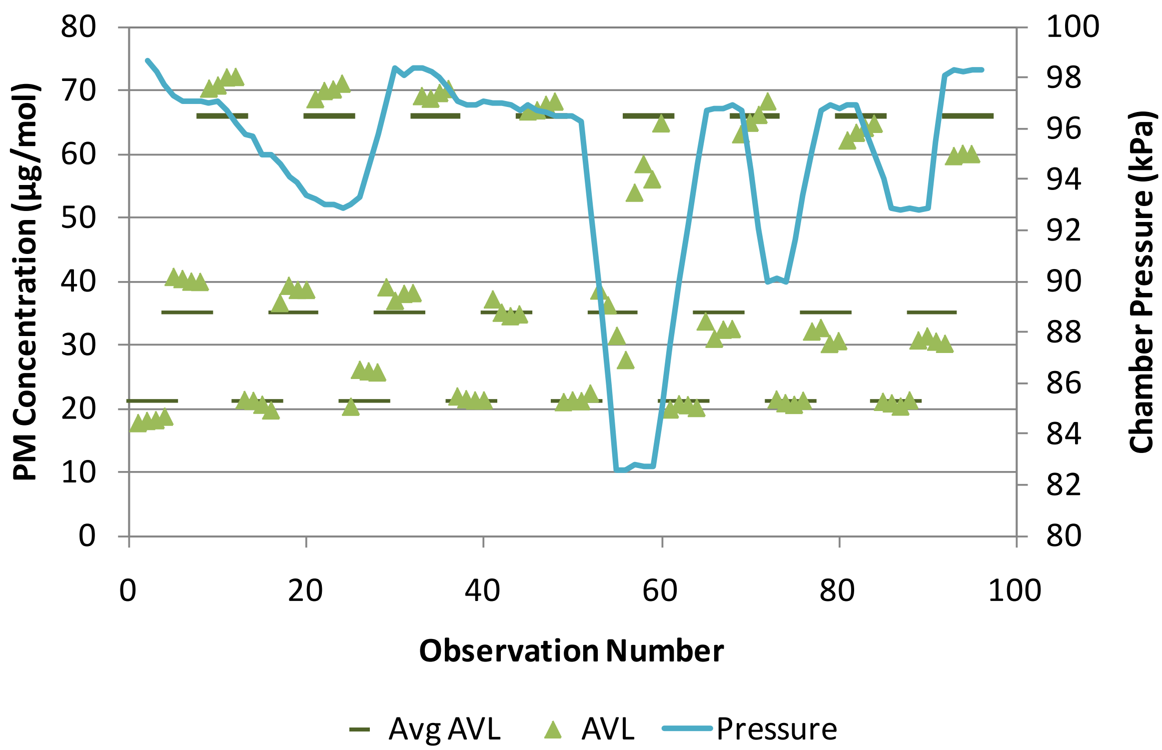


FIGURE 91. AVL ENVIRONMENTAL PRESSURE MEASUREMENTS

To determine whether an error surface would be generated for each PEMS, the MAD from the baseline was compared to the MAD of the pressure test. If the MAD of the pressure test was greater, an error surface was generated to present to the steering committee. The plots of median versus MAD shown in Figures 92, 93, and 94 were presented to the steering committee at the meeting in Indianapolis on July 15th, 2009.

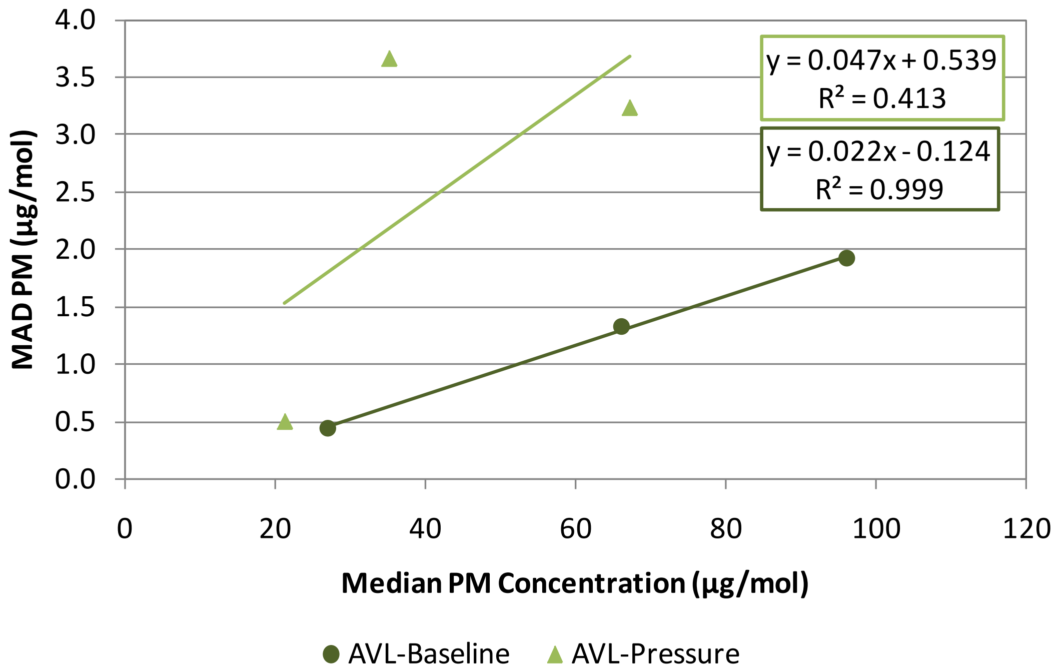


FIGURE 92. AVL PRESSURE MEDIAN VERSUS MAD

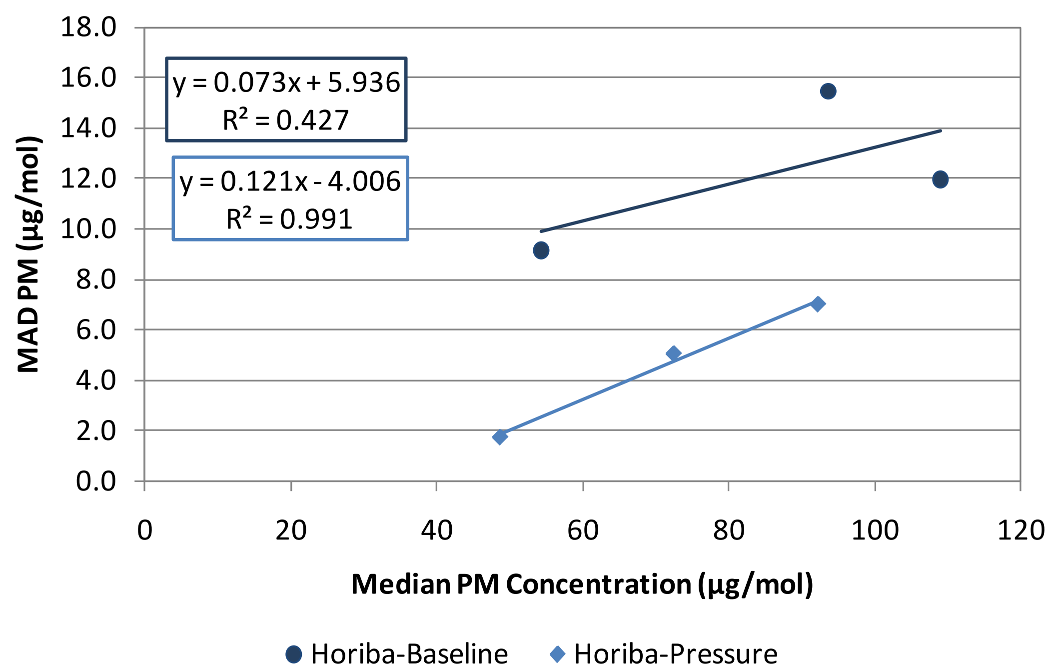


FIGURE 93. HORIBA PRESSURE MEDIAN VERSUS MAD

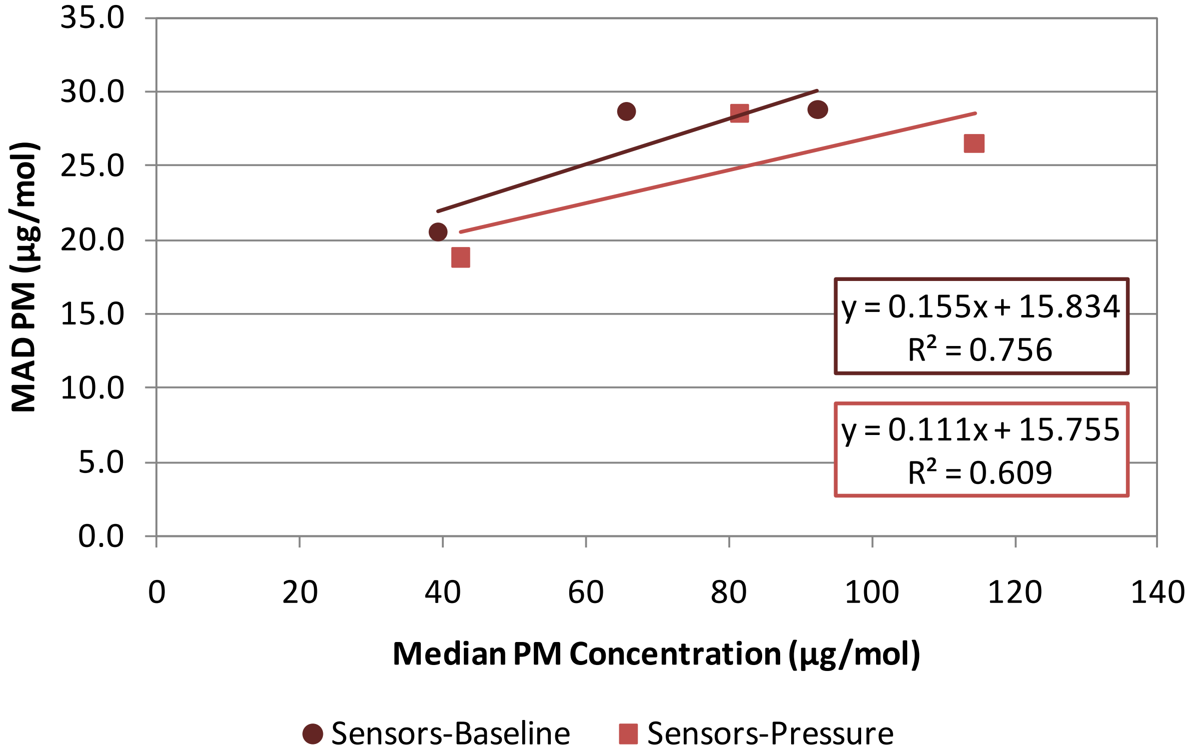


FIGURE 94. SENSORS PRESSURE MEDIAN VERSUS MAD

The MAD values were higher for the baseline compared to the pressure test for both Horiba and Sensors indicating that no additional variability in the measurement could be attributed to changes in pressure using this technique. No environmental error surface was calculated for either Horiba or Sensors. The AVL MAD values were higher for the pressure test compared to the baseline, so an error surface was developed. It should be noted that the variability of the AVL is much lower for the AVL compared to the Horiba and Sensors, however because of the high precision of the AVL measurements during the baseline it was still possible to discern the added variability due to changes in ambient pressure. The environmental pressure error surface was calculated using the same pooled rms technique that was used for the transient error surface. Figure 95 shows the error surface that was generated for environmental pressure on the AVL PM. The error surface was accepted for use by the steering committee during the July 15th, 2009 meeting in Indianapolis.

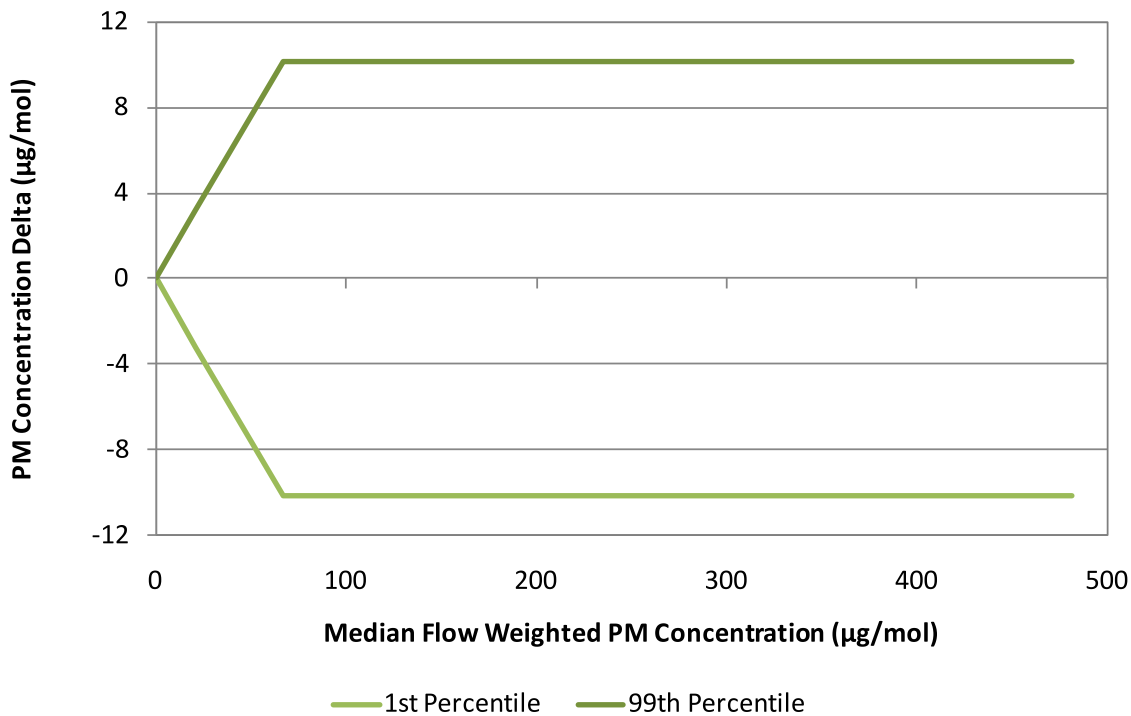


FIGURE95. FINAL ERROR SURFACE FOR ENVIRONMENTAL PRESSURE AVL PM CONCENTRATION

This error surface was similar in magnitude to the AVL transient PM error surface, however it was much smaller than the AVL steady-state PM error surface.

5.3 Temperature and Humidity Chamber Testing

The temperature and humidity chamber testing was designed to characterize the effects of ambient temperature and humidity on the accuracy of PM measurement. The testing chamber has the capability of independently controlling the temperature and moisture content of the air in the range of typically observed levels from ambient conditions. The temperature and humidity profile from the gaseous program was modified based on data acquired during CE-CERT testing. At the June 12th, 2008 meeting in Madison data was presented by Kent Johnson indicating that temperatures near the PEMS instruments could be above 60°C during in-use testing. With this in mind the steering committee elected to add temperatures as high as 50°C to the profile, where the original profile had a maximum temperature of just over 30°C. The original and modified temperature and humidity profiles are shown in Figure 96.

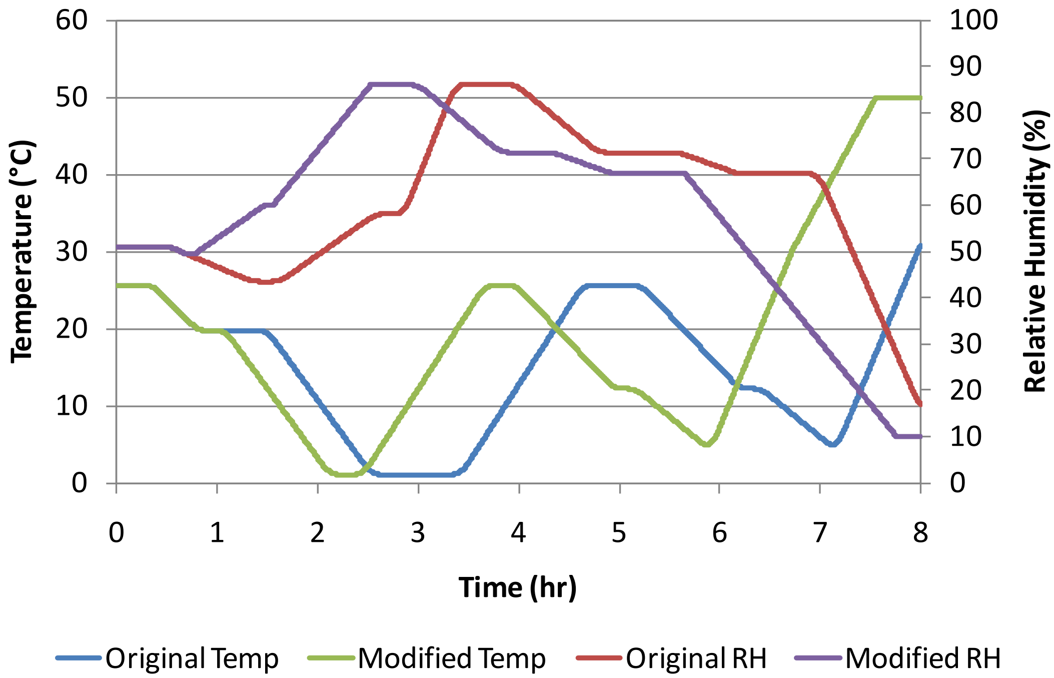


FIGURE 96. TEMPERATURE AND HUMIDITY PROFILE FOR ENVIRONMENTAL TESTING

The temperature chamber was unable to control the humidity under a temperature of 5°C so the humidity was uncontrolled during the portion of the cycle where the temperature was between 2°C and 5°C. The moisture content was quite small during this portion of the cycle, so this was not considered to be a significant issue. Figure 97 shows the PEMS in the temperature and humidity chamber.

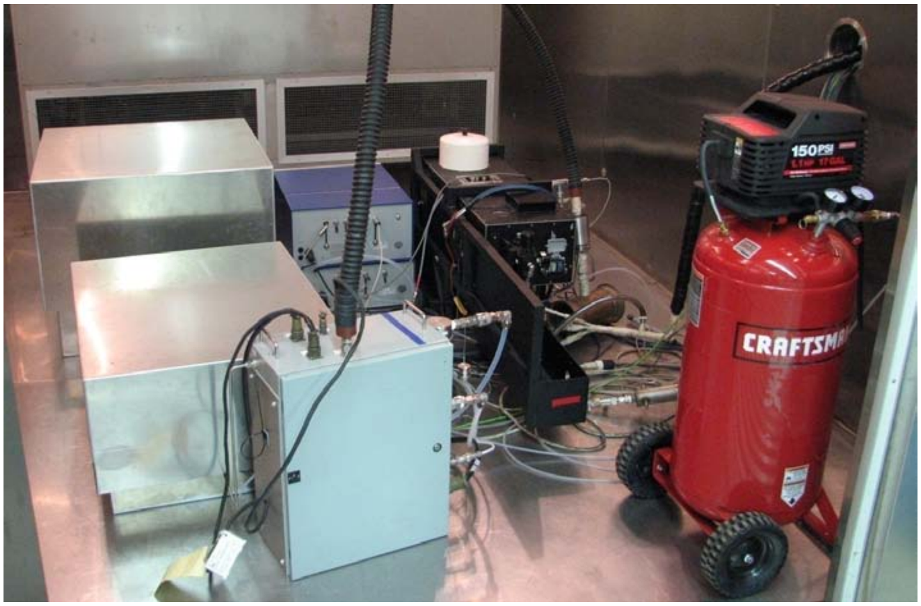


FIGURE 97. PEMS INSTALLED IN THE TEMPERATURE AND HUMIDITY CHAMBER

The compressor pictured was provided by SwRI for use during environmental testing. The original compressor supplied by Horiba was much smaller, but also had difficulty completing eight hours of operation without shutting off. The compressor was included in the temperature chamber so that the dilution air for the Horiba system would be affected by the same changes in temperature and humidity that the dilution air of the Sensors and AVL systems would experience. The PM sample was transported into the chamber using a heated sample line maintained at 60°C. The temperature was set slightly above the maximum temperature of the chamber so that a constant temperature in the sample could be maintained throughout the test. There was a small portion of the end of the transfer line that was not heated, but it was extensively insulated to minimize temperature effects. The EPA PM generator was used in conjunction with the soot generator in this work to provide the particle source. The experimental setup was shown previously in Figure 79. The PM generator is shown in Figure 98.

FIGURE 98. THE PM GENERATOR INSTALLED OUTSIDE THE TEMPERATURE AND HUMIDITY CHAMBER

The Horiba and Sensors gaseous PEMS were installed outside of the chamber along with the PM generator. The PM generator is designed to add volatile hydrocarbons, sulfuric acid, and water vapor to an elemental carbon source. An oxidation catalyst removed any volatile from the soot generator before volatile was added from the diffusion vial ovens. Unfortunately both the sulfur oven and the syringes injecting water malfunctioned during testing and neither was able to be quickly repaired. For the official temperature testing the particle source consisted of elemental carbon from the mini-CAST and volatile hydrocarbon from the PM generator.

Figure 99 shows the individual Horiba concentration measurements along with a comparison of the average concentration measurement for each PM level. The chamber temperature is included for reference as well.

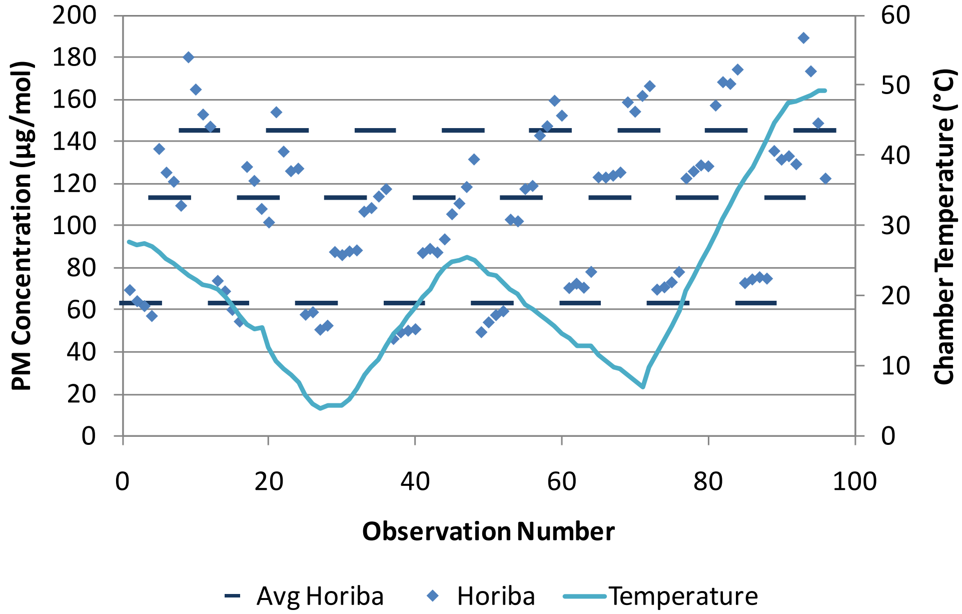


FIGURE 99. HORIBA ENVIRONMENTAL TEMPERATURE MEASUREMENTS

The Horiba data plotted in Figure 99 showed a significant amount of variability although it is unclear from this graph whether the variability is directly related to the changing temperature. For example, the measurements between observation 25 and 35 when the temperature is below 10°C tend to be below the cycle average. However, the second time the temperature drops below 10°C around observation 70, the measurements are above the cycle average. Figure 100 shows the changes in filter dilution air and chamber temperature. The behavior of these variables cannot clearly explain why the PM concentration behaved the way it did in Figure 99.

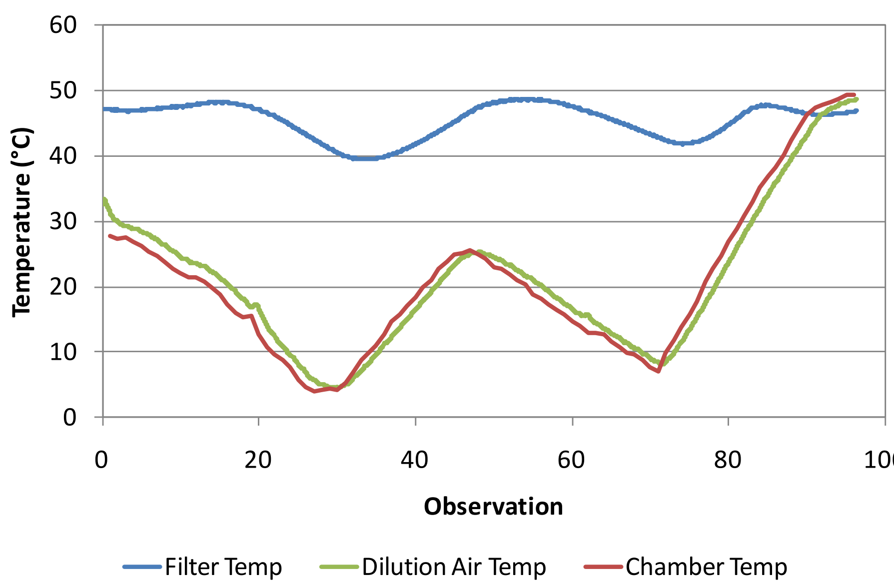


FIGURE 100. HORIBA TEMPERATURES DURING ENVIRONMENTAL TEMPERATURE TESTING

Figure 101 shows the individual Sensor concentration measurements as well as the average concentration for each PM level. The temperature measurements for the Sensors PEMS are shown in Figure 101. The Sensors data displayed a high degree of variation from the mean with no clear trend related to temperature. No valid data was captured for the last hour of operation because the Sensors PEMS was unable to maintain the crystals at a temperature of 50°C when the chamber temperature was above 47°C.

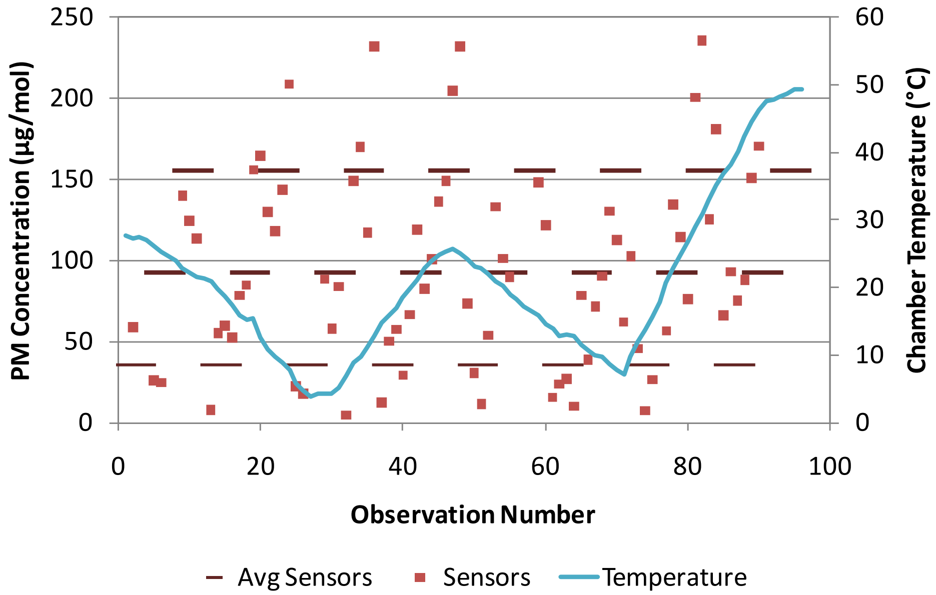


FIGURE 101. SENSORS ENVIRONMENTAL TEMPERATURE MEASUREMENTS

The AVL data, shown in Figure 102, exhibited excellent repeatability in comparison to the other two PEMS. Any temperature dependence by the AVL PEMS was extremely small.

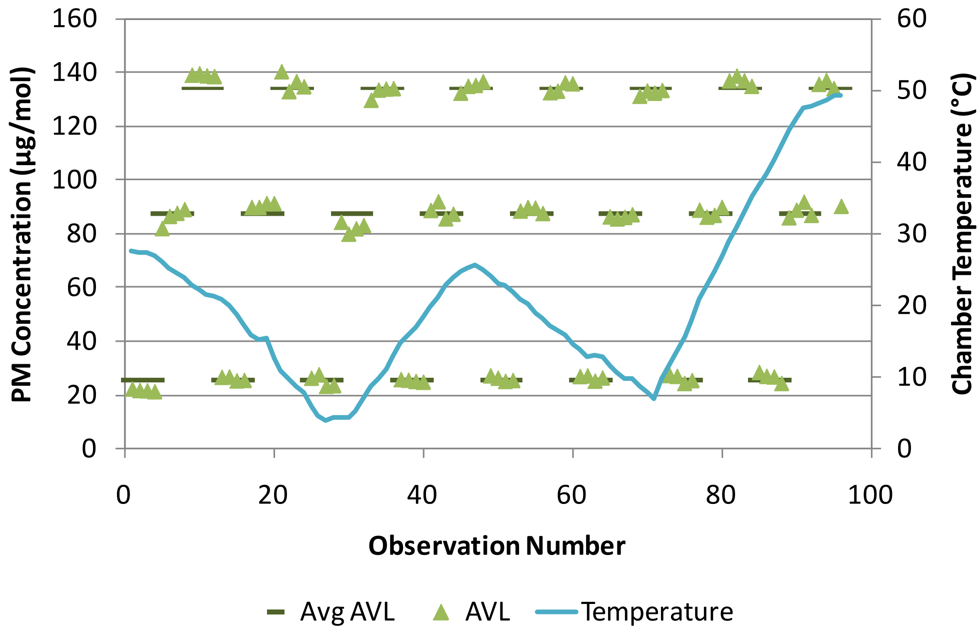


FIGURE 102. AVL ENVIRONMENTAL TEMPERATURE MEASUREMENTS

The temperature data was compared in the same manner as the pressure data with the MAD values plotted in relation to the median, as shown in Figures 103, 104, and 105, for the Horiba, Sensors, and the AVL PEMS, respectively. The MAD of the Horiba baseline is slightly higher than during the temperature test meaning that an error surface was not generated in this case. The Sensors and AVL MAD was higher for the baseline at lower concentrations, but higher for the temperature data for higher concentrations. An attempt was made to calculate an error surface for Sensors, but the pooled rms technique resulted in a slightly higher value for the baseline indicating that an error surface was not necessary. The error surface calculated for AVL using the same technique is shown in Figure 106. The PM median concentrations tested were between 25 and 135 µg/mol. It was necessary to extend the error surface out to nearly 500 µg/mol to encompass the range of concentrations encountered during engine testing. The steering committee elected to cap the error surface at plus and minus 5.3 µg/mol because it was unclear whether the errors would continue to increase outside of the concentrations observed in the temperature and humidity testing. Extending a straight line out to the median concentration of 481 µg/mol would have resulted in a 5th percentile of 18.9 µg/mol.

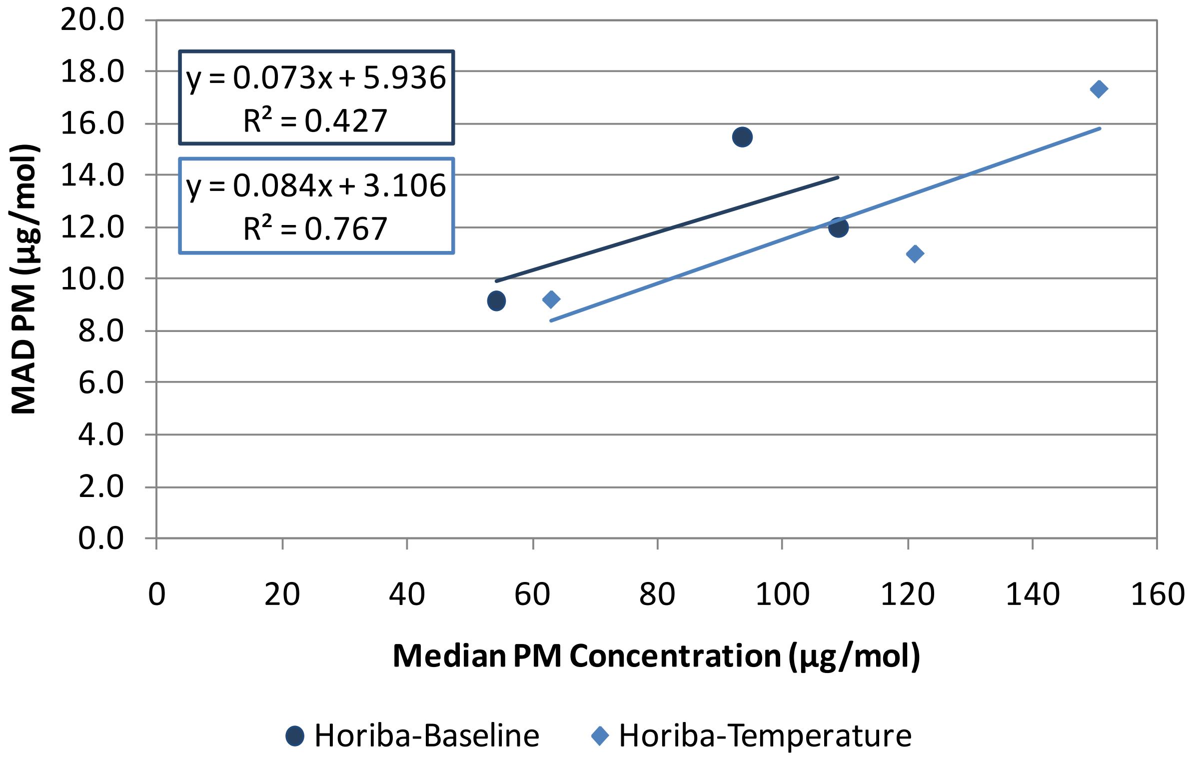


FIGURE 103. HORIBA TEMPERATURE MEDIAN VERSUS MAD

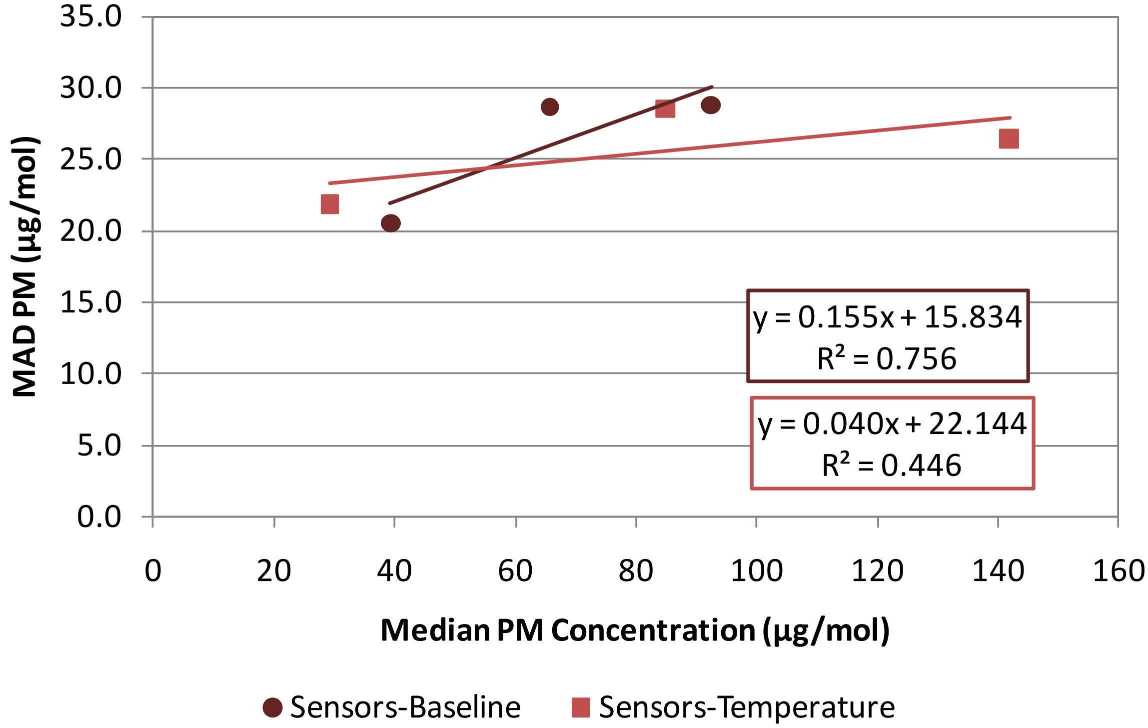


FIGURE 104. SENSORS TEMPERATURE MEDIAN VERSUS MAD

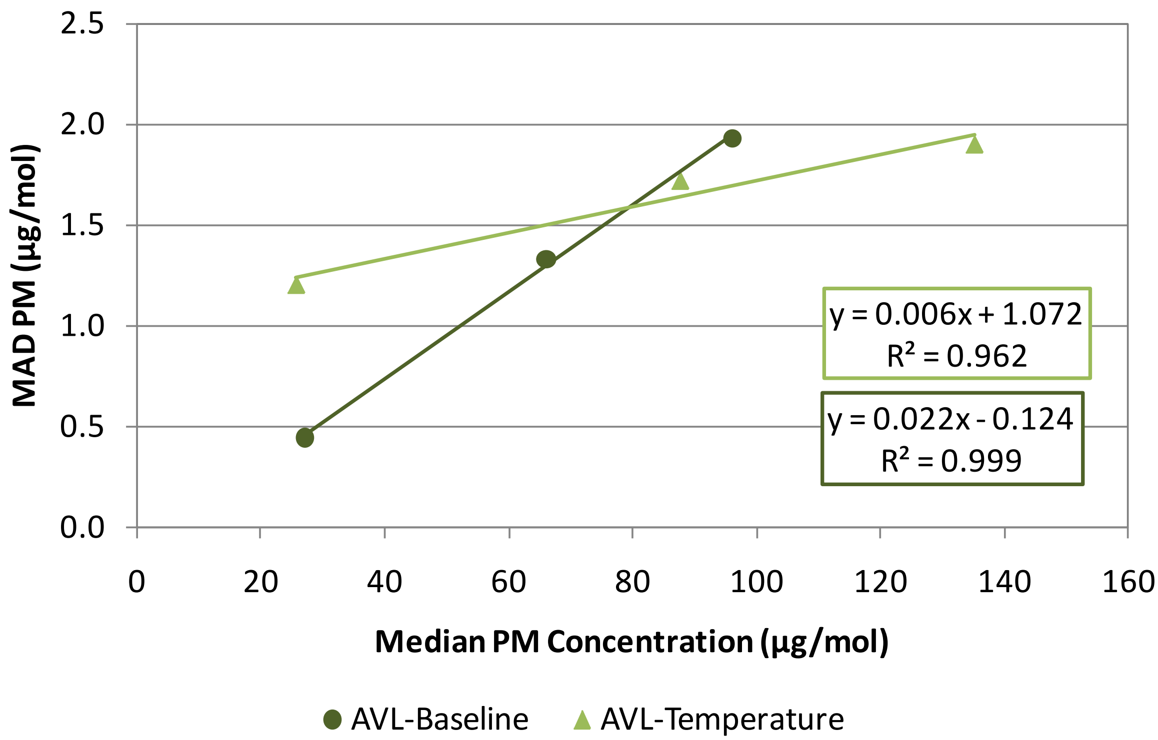


FIGURE 105. HORIBA TEMPERATURE AND HUMIDITY MEDIAN VERSUS MAD

The AVL temperature data is shown in Figure 106 including the individual and average measurements as well as the chamber temperature.

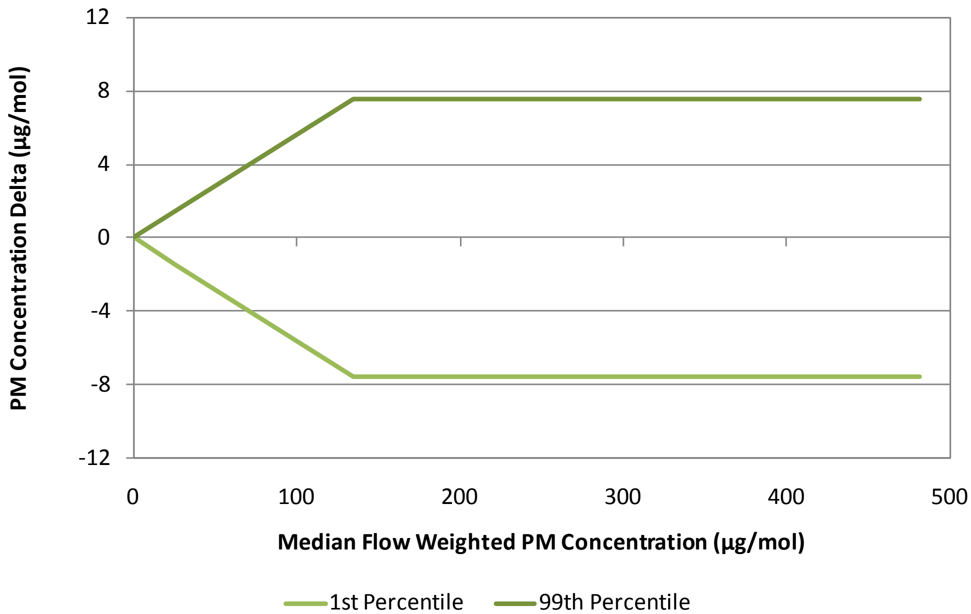


FIGURE 106. FINAL ERROR SURFACE ENVIRONMENTAL TEMPERATURE AND HUMIDITY AVL PM

5.4 Electromagnetic and Radio Frequency Interference Screening

The electromagnetic inference (EMI) and radio frequency interference (RFI) testing was conducted as a screening exercise without the use of PM source. During the gaseous measurement allowance program the majority of the problems encountered caused a malfunction of the PEMS to the point where it would no longer operate. The main purpose of the environmental testing was not to test the durability of the PEMS, but to quantify any errors that might occur during the operation of a PEMS that would cause a measurement error. The same series of tests from the gaseous EMI/RFI testing were conducted as a series of individual screening tests using only HEPA filtered air. Based on the screening results it remained a possibility to conduct a full test cycle using a particle source to generate an error surface.

By providing filtered room air to the PEMS it would still has been possible to detect a wide range of possible measurement accuracy issues, although some problems may only present themselves when a particle sample is present. To shorten the test time, the PEMS were triggered continuously so that time in between tests could be minimized. This meant that the Horiba system was continuously sampling on a filter, and the Sensors system was continuously sampling on a crystal. The Horiba system was able to sample continuously for eight hours or more on the filter since no particle source was loading on the filter. However, the Sensors system had a maximum sample time that was adjusted so that it would cycle through the crystals every 120 seconds. This was desirable since it exercised the operation of all eight crystals however some issues surfaced due to this testing technique. The problems included: both high voltage power supplies turning on at the same time, two crystals sampling at the same time, no crystal sampling even though one was available. Each of these problems occurred infrequently, and it was believed that the problems were a result of leaving the trigger on continuously for long periods of time since none of these issues were observed during engine testing. These were functionality issues that did not appear to have any impact on the accuracy of the measurement.

The EMI and RFI testing, shown in Figure 107, was conducted in a radiation chamber, as shown in Figure 105, with walls covered with large cones of carbon impregnated foam designed to absorb radiation and minimize reflections. Four standard Society of Automotive Engineers (SAE) tests were conducted: Bulk Current Injection, Radiated Immunity, Electrostatic Discharge, and Conducted Transients.

FIGURE 107. AVL PEMS IN THE RADIATION CHAMBER FOR EMI AND RFI TESTING

The Sensors and AVL PEMS were both designed to run off the vehicle's 12 Volt electrical system so both systems were powered using a 12 V automotive battery that was continually charged using a 120 VAC charger supplied by Sensors. The Sensors PEMS was a 12V system so it connected directly to the battery. The AVL system is powered by 120 Volts 60 Hz AC power so a commercially available inverter was provided by AVL to convert the 12 volts DC into 120 volts AC. The Horiba system was designed to operate using a generator, therefore it was still powered using the 120 VAC wall outlets.

5.4.1 Bulk Current Injection

SAE test J1113/4 *Immunity to Radiated Electromagnetic Fields – Bulk Current Injection* was performed to determine the effect of electromagnetic radiation on the electrical cables of the PEMS. The specifications used are detailed in Region 2, Class B of the J1113/4 test protocol. A calibrated current probe was place around the electrical cable and used to inject RF current into the cable. Figure 108 shows a cable running through the bulk current injection probe.

FIGURE 108. BULK CURRENT INJECTION PROBE

The probe was positioned at 120 mm, 450 mm, and 750 mm from the cable connector to test the cable three times. For each test, the frequency of the current was stepped from 1 MHz to 400 MHz using the following step sizes.

1 MHz to 10 MHz – 1 MHz step size
10 MHz to 200 MHz – 10 MHz step size
200 MHz to 400 MHz – 20 MHz step size

These were the maximum allowed step sizes according to the SAE protocol. As with the gaseous program a 5 second dwell time was used to ensure the electromagnetic field had stabilized before switching to the next frequency. The probe was calibrated to deliver 60 milliamps of current as specified in the test procedure. Figure 109 shows the bulk current injection probe being used to test a cable on the Horiba PEMS. Figure 110 and Figure 111 show the sensors and AVL bulk current injection setup, respectively.

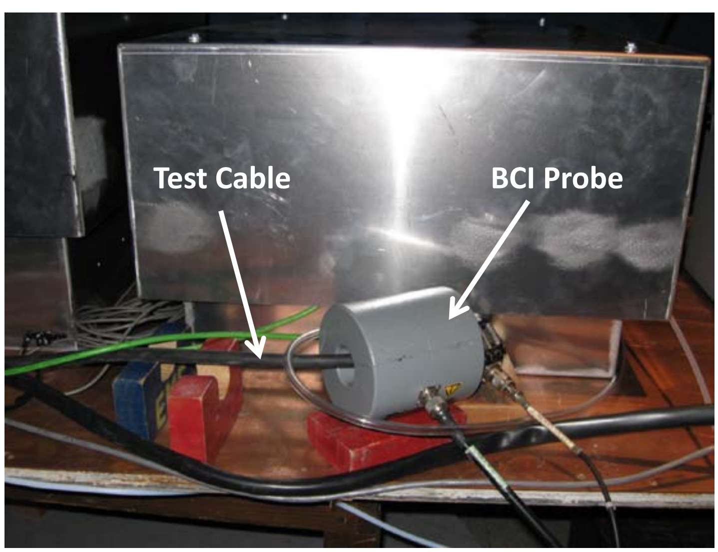


FIGURE 109. HORIBA PEMS SETUP FOR BULK CURRENT INJECTION

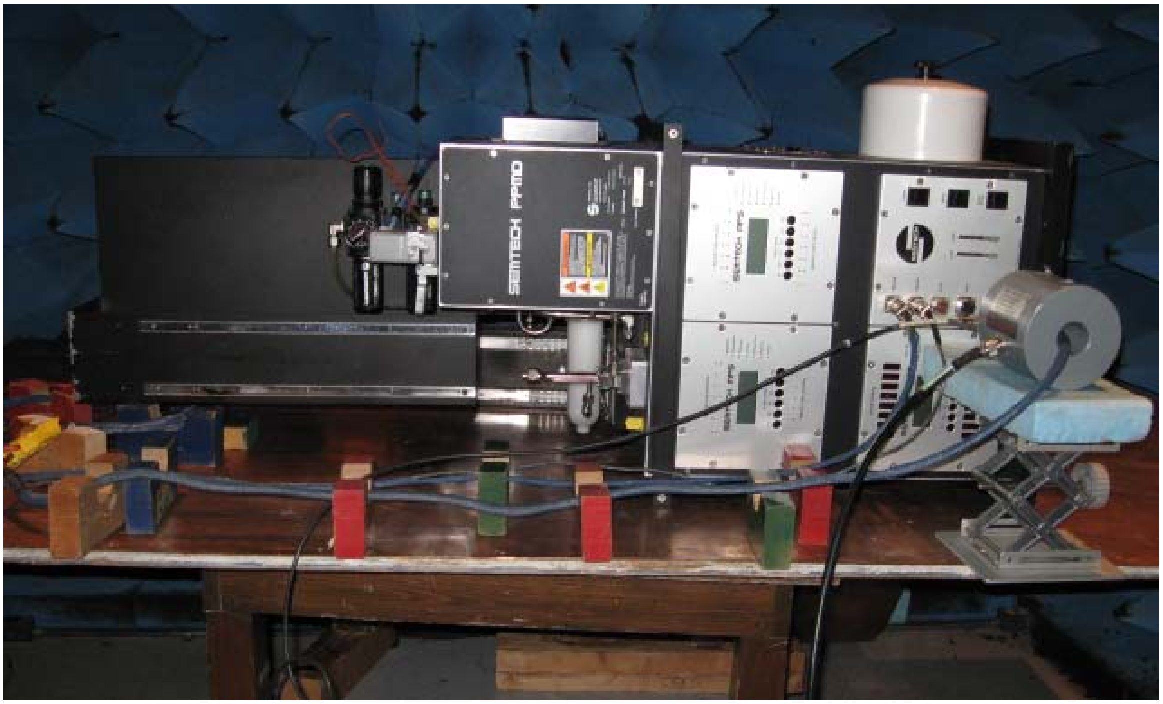


FIGURE 110. SENSORS SETUP DURING BULK CURRENT INJECTION TESTING

FIGURE 111. AVL SETUP DURING BULK CURRENT INJECTION TESTING

The cables tested on the Horiba system were the sample line temperature, sample line heater power, heated enclosure heater power, sample trigger and exhaust flow signal, ethernet connection from the DCS to the electrical enclosure, ethernet connection from the TRPM to 2200, DCS 12 volt power, and two AC power cords. There were two main problems discovered when the bulk current injection was applied to the cables of the Horiba PEMS. When the line supplying power to the heater in the heated enclosure was probed, the reported total flow of the system and started to rapidly fluctuate around the frequency of 10 MHz. This frequency was manually repeated after the sweep and the same behavior occurred. Figure 112 shows the response of several of the Horiba signals to the current injection.

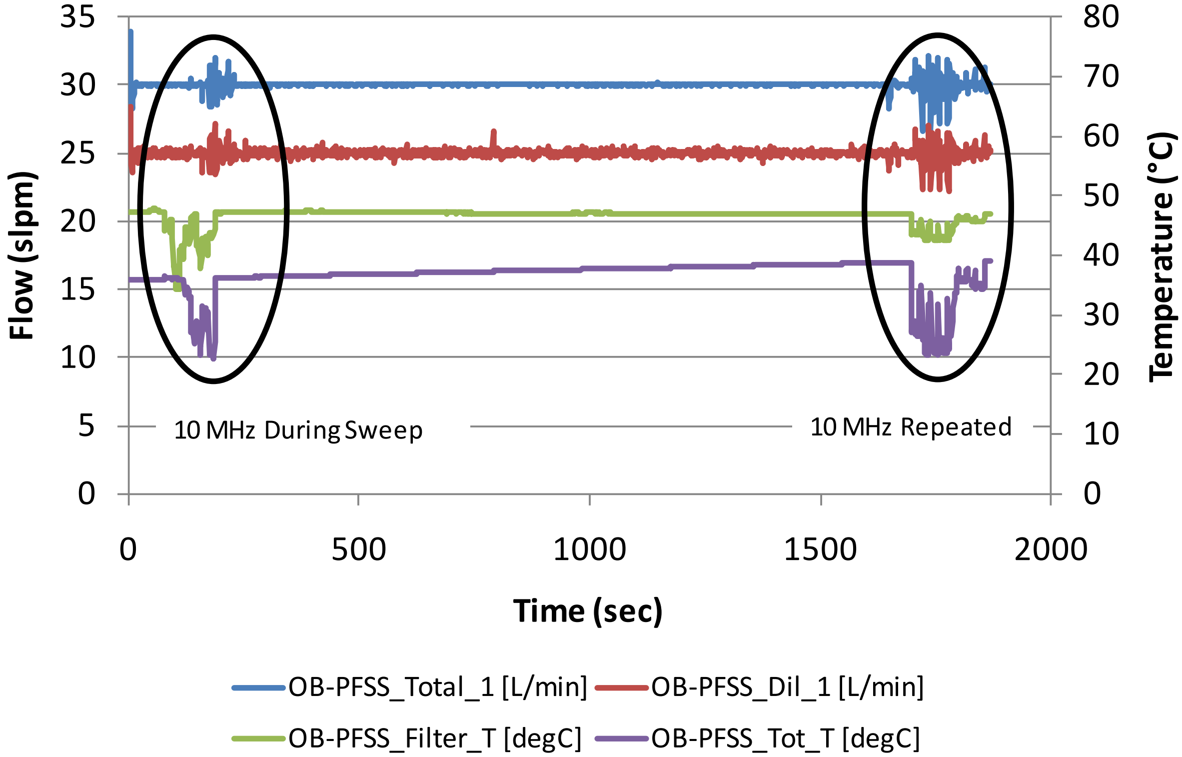


FIGURE 112. HORIBA FLOW DISTURBANCE FROM BULK CURRENT INJECTION

The noise in the system appeared to have originated with several of the temperature and pressure measurements including the filter face temperature and total flow temperature shown here. The total flow temperature and pressures began to fluctuate causing fluctuations in the total flow measurement, which in turn caused the dilution flow to fluctuate in an effort to maintain proportionality. This problem was only observed on the cable supplying heater power to the heated enclosure box.

The communications between the laptop and the PEMS was disrupted when the Ethernet cables were probed. Several times the communications dropped out completely. The problem was intermittent around 40 to 50 MHz and 140 to 160 MHz.

The final major problem experienced by the Horiba system during BCI was a large amount of noise in the exhaust flow signal when the analog signal cable between the OBS-2200 and OBS-TRPM was probed. The exhaust flow is measured by the Horiba gaseous PEMS OBS-2200. The OBS-2200 outputs the exhaust flow measurement as an analog voltage which is then read by the OBS-TRPM Over frequencies between 1 and 40 MHz the exhaust flow signal read as high as 3,000 kg/hr on the OBS-TRPM while the measured value on the OBS-2200 was less than 10 kg/hr. The exhaust flow signal during the BCI sweep is shown in Figure 113.

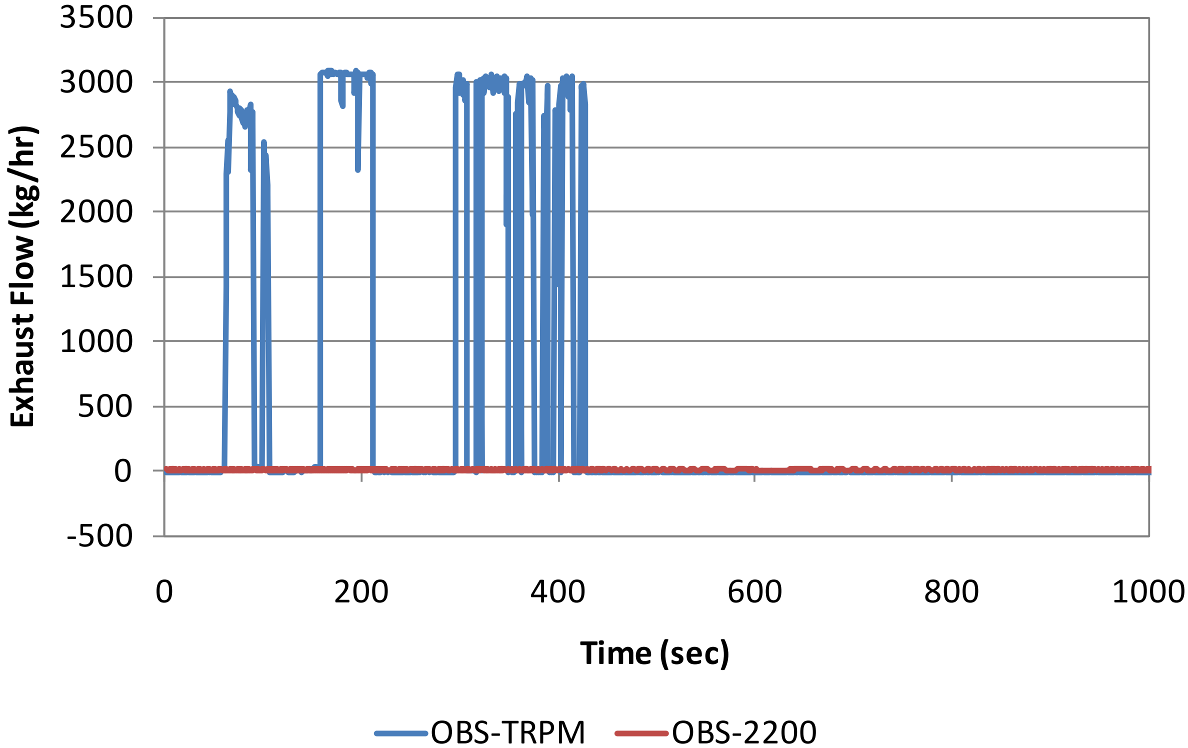


FIGURE 113. HORIBA EXHAUST FLOW NOISE ON ANALOG CABLE DURING BULK CURRENT INJECTION

It was clear that the problem involved only the transmission of the exhaust flow signal as an analog voltage between the two systems, not the actual measurement of the exhaust flow. For in use testing this problem would be easily detectable when the two exhaust flow data from the two different files are compared; however, the TRPM relies on the analog exhaust flow signal for adjusting its dilution ratio for proportional sampling. Errors in the exhaust flow signal would cause the TRPM to lose its proportionality, and therefore any data collected with the same filter sampling would be voided.

The cables tested on the Sensors system were the communication cable from the PPMD to DS, and the DC power. As mentioned previously, many of the problems that were encountered with the Sensors PEMS happened intermittently and could not be reproduced at any specific frequencies. It was assumed that problems involving crystal sampling switching, high voltage power supplies, and fluctuations in the corona current were not induced by the bulk current injection. However, the Sensors system did experience significant communication problems when the serial cable between the PPMD and DS units was probed. The communication was repeatedly disrupted over the entire frequency range causing a loss of data. In nearly every case the communication was recovered once the radiation subsided allowing normal operation to continue.

The cables tested on the AVL system were the communications cable between the measuring and conditioning unit, the analog output to the Semtech DS, and two AC power cords. The BCI induced a significant amount of noise on the analog signal cable between the AVL MSS and the Sensors Semtech DS. The AVL system can log its own data, but the data used officially in this program and during in use testing is the data logged by the Semtech DS. Two signals are carried on the analog output wire: the measured concentration and the dilution ratio. These two numbers are multiplied together for the final reported concentration. The measured concentration did not see significant noise, but the dilution ratio signal was strongly influenced by radiation in the range of 1-3 MHz and 40 MHz. A comparison of the MSS measured dilution ratio and the dilution ratio recorded by the Semtech DS is shown in Figure 114.

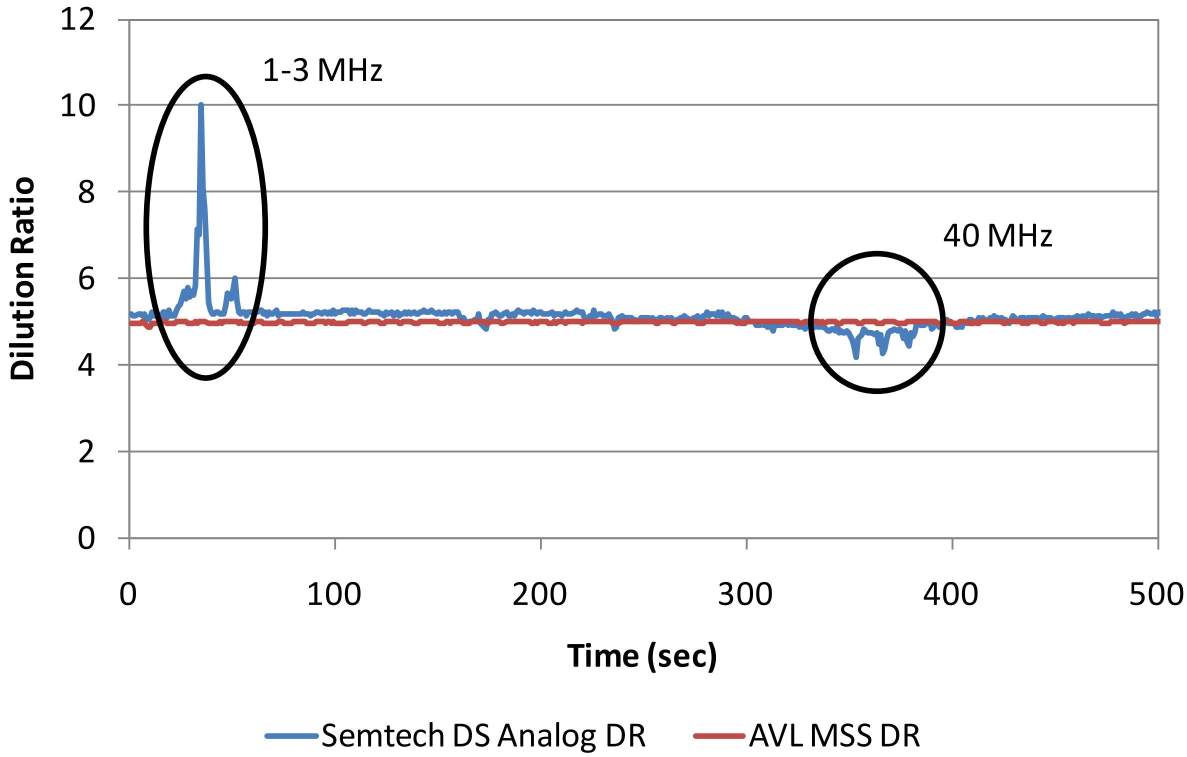


FIGURE 114. BCI NOISE ON AVL ANALOG OUTPUT CABLE

The dilution ratio doubled from 5 to 10 during current injection at 1-3 MHz. The data in the plot was recorded during the frequency sweep, and the problem was replicated manually afterwards. Since the true dilution ratio was still recorded in the MSS log file, the correct reported concentration could be recovered after testing.

5.4.2 Radiated Immunity

The response of the PEMS to continuous narrowband electromagnetic fields was measured using SAE test J1113/21 *Electromagnetic Compatibility Measurement Procedure for Vehicle Components – Part 21: Immunity to Electromagnetic Fields, 10 kHz to 18 GHz, Absorber-Lined Chamber.* The exact specifications of the tests performed were drawn from Region 2, Class B of the J1113/21 protocol. Several different antennae were used to generate electromagnetic radiation over the frequency range of 10 kHz to 1 GHz. The electromagnetic susceptibility experts at SwRI recommended ending the test at a frequency of 1 GHz rather than 18 GHz due to the very small probability of detecting any susceptibility above 1 GHz. This same approach was used in the gaseous PEMS program. The carbon impregnated foam walls of the radiation chamber was designed to absorb any radiation so that the PEMS would only see the direct radiation generated by the antenna. The following step sizes were used during the frequency sweeps:

- 10 kHz to 100 kHz – 10 kHz step size
- 100 kHz to 1 MHz – 100 kHz step size
- 1 MHz to 10 MHz – 1 MHz step size
- 10 MHz to 200 MHz – 2 MHz step size
- 200 MHz to 1 GHz – 20 MHz step size

The SAE standard field intensity of 50 volts/meter was used with both vertical and horizontal electromagnetic radiation orientations. Figure 115, Figure 116, and Figure 117 show the Horiba, Sensors, and AVL radiated immunity testing setup, respectively.

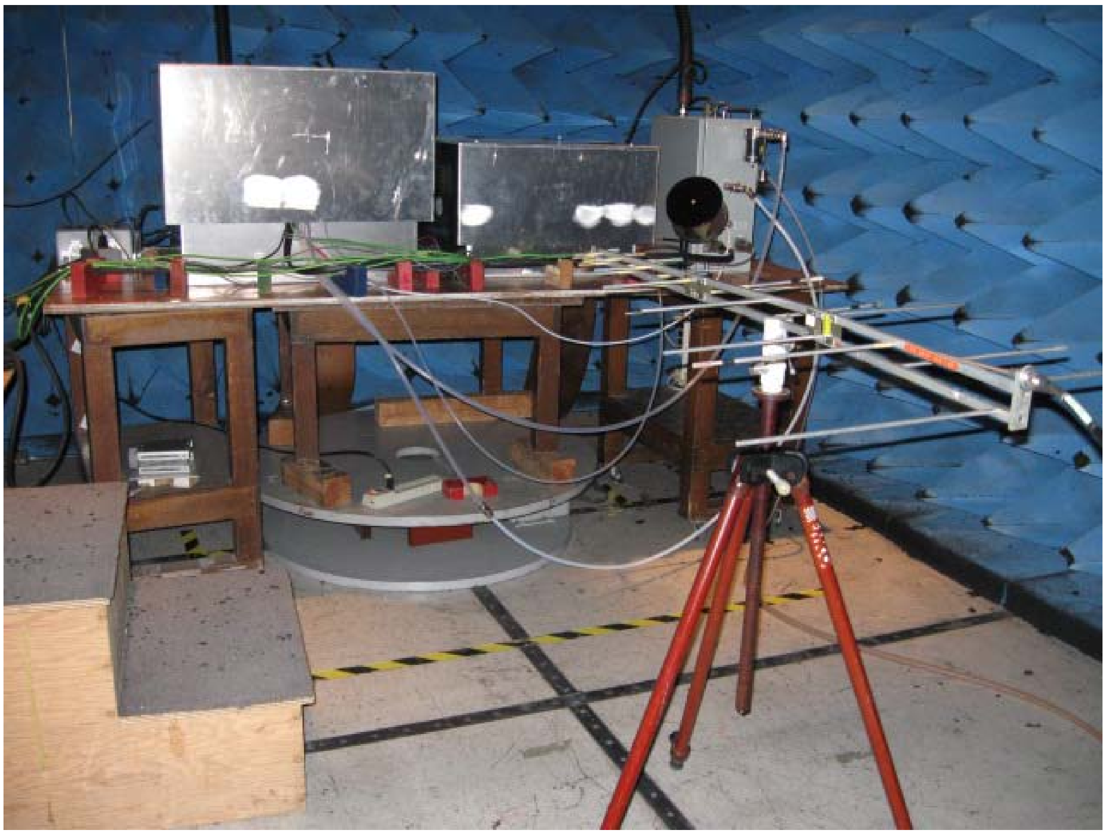


FIGURE 115. HORIBA PEMS SETUP DURING RADIATED IMMUNITY TESTING

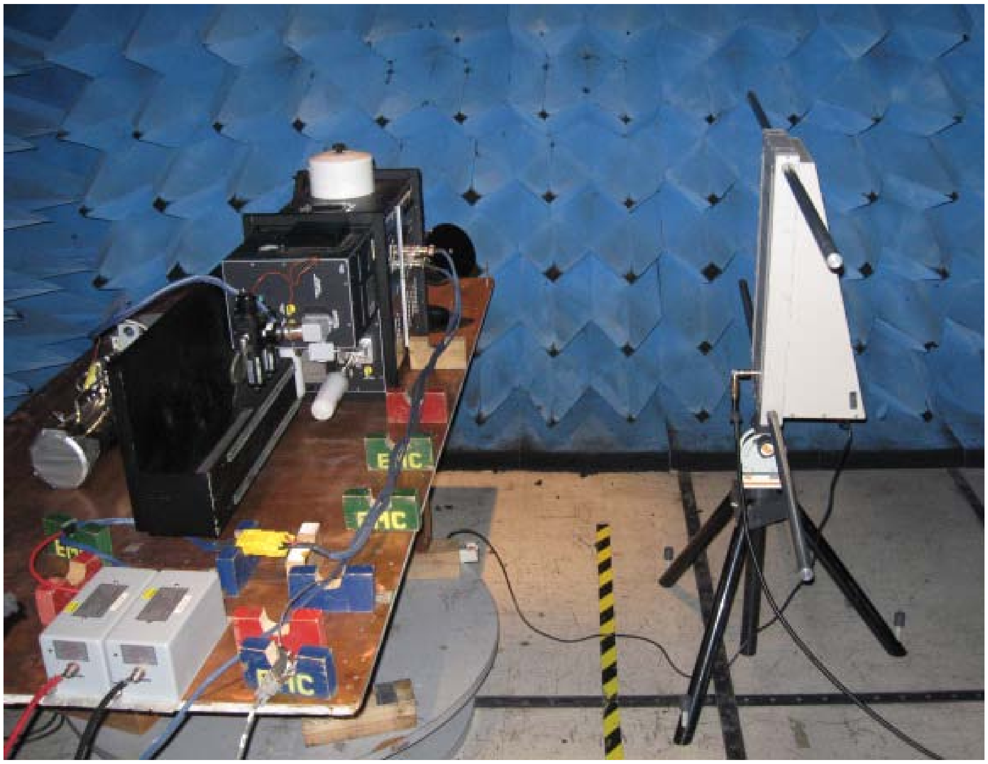


FIGURE 116. SENSORS PEMS SETUP DURING RADIATED IMMUNITY TESTING

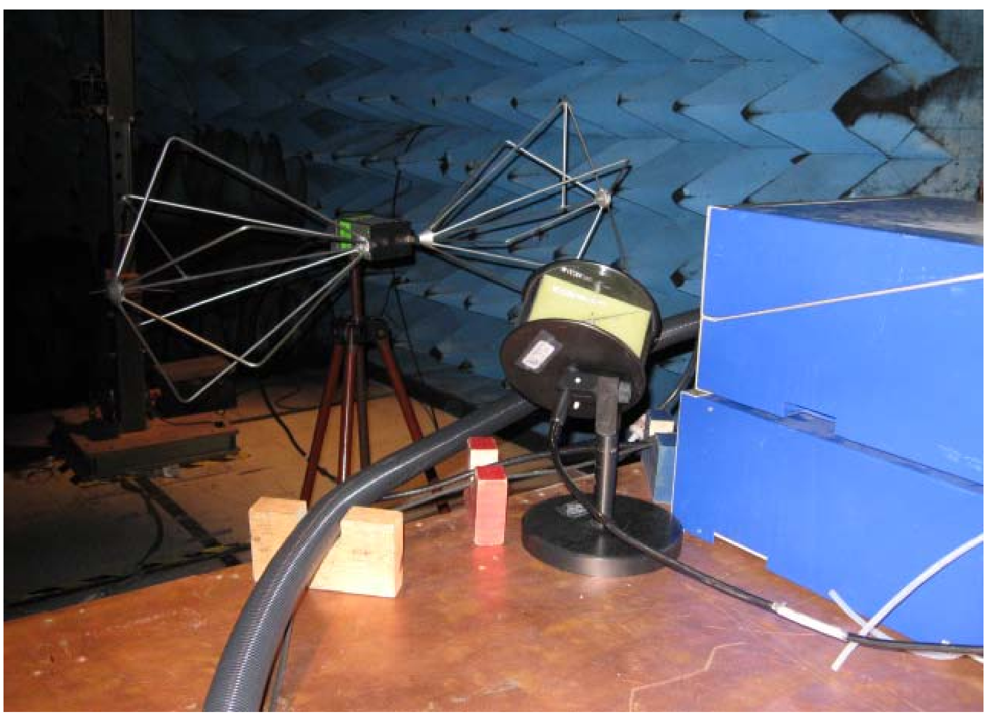


FIGURE 117. AVL PEMS SETUP DURING RADIATED IMMUNITY TESTING

The Horiba PEMS experienced several problems related to the radiated immunity test including a loss of communications between the laptop and the instrument. This problem occurred at several different frequencies for both horizontal and vertical polarizations. Because the data is logged on the laptop any loss of communication is also a loss of data. This would result in a voided test since the filter calibration relies on collecting data the entire time the filter is sampling. A problem was also observed with the control of the dilution ratio, as shown in Figure 118. During EMI and RFI testing the Horiba dilution ratio was maintained constant at 6.

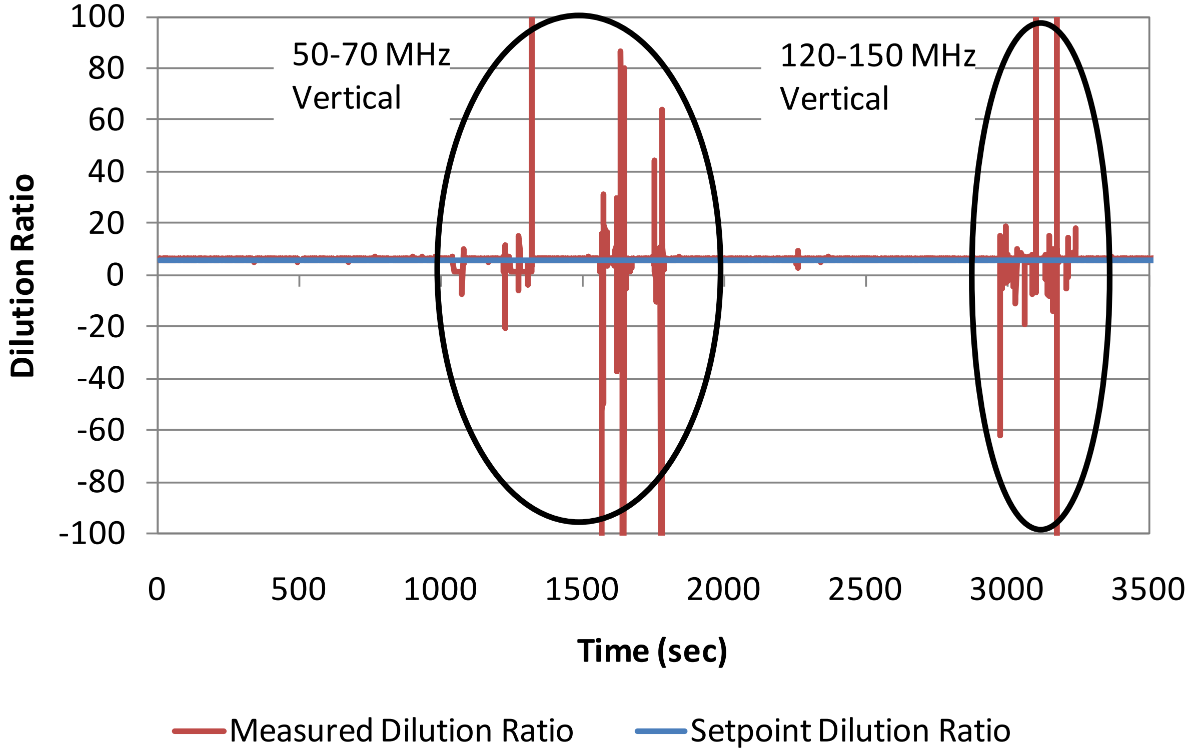


FIGURE 118. HORIBA DILUTION RATIO FLUCTUATIONS DURING RADIATED IMMUNITY

The dilution ratio varied between 338 and -938 but only a smaller portion of the graph is shown for more detail. The external flowmeter on the end of the sample flow indicated that these rapid changes in flow were real and not just reported. The problem with the exhaust flow analog output signal first encountered during the bulk current injection testing was also observed during radiated immunity.

The AVL system reported a supply voltage error in the range of 200 MHz to 1 GHz of horizontal radiation. The inverter powered down at 300 MHz shutting down the system completely.

5.4.3 Electrostatic Discharge

SAE test J1113/13 *Electromagnetic Compatibility Measurement Procedure for Vehicle Components—Part 13: Immunity to Electrostatic Discharge* was performed to test the PEMS response to Electrostatic Discharges (ESDs) on surfaces and connectors. The exact procedure used was taken from Region 2, Class B of the J1113/13 standard. Approximately 40 ESDs were supplied to each PEMS at various connector ports, exposed screws, and general surfaces. The test included both direct contact discharges as well as indirect discharges with the electrostatic discharge gun placed near the surface of interest. The ESD gun is shown in Figure 119.

FIGURE 119. ELECTROSTATIC DISCHARGE SIMULATOR

The ESD gun was calibrated using an electrostatic voltmeter to deliver 4000 volts per discharge. Neither the Horiba nor the AVL PEMS exhibited any susceptibility to the ESD tests. The Sensors unit shut off completely with an ESD near the auxiliary connector port to which an external flow meter connects for audit purposes. This problem was confirmed with a second ESD. No issues possibly related to measurement accuracy were found with any of the PEMS.

5.4.4 Conducted Transients

The response of the PEMS to voltage disturbances in the 12 volt power supply cable was checked using SAE test J1113/11 *Immunity to Conducted Transients on Power Leads.* The tests were conducted using specifications found in Region 2, Class B of the J1113/11 protocol. A Schaffner NSG 5000 Automotive Electronics Test System was installed in between the 12 volt power supply and the PEMS. The Schaffner Electronics Test System delivered voltage perturbations to the PEMS of varying magnitudes and durations. The voltage spikes ranged from -200 to 100 volts and lasted anywhere between 250 ns and 200 ms. The tests included quick voltage recovery, slow voltage recovery, repeated voltage bursts, and load dump. The conducted transients tests were not performed on the Horiba PEMS, because the Horiba system was intended for use with an external generator and does not use 12 volt power. The Schaffner Test System can be seen in Figure 120 with the Sensors PEMS and Figure 121 for the AVL PEMS.

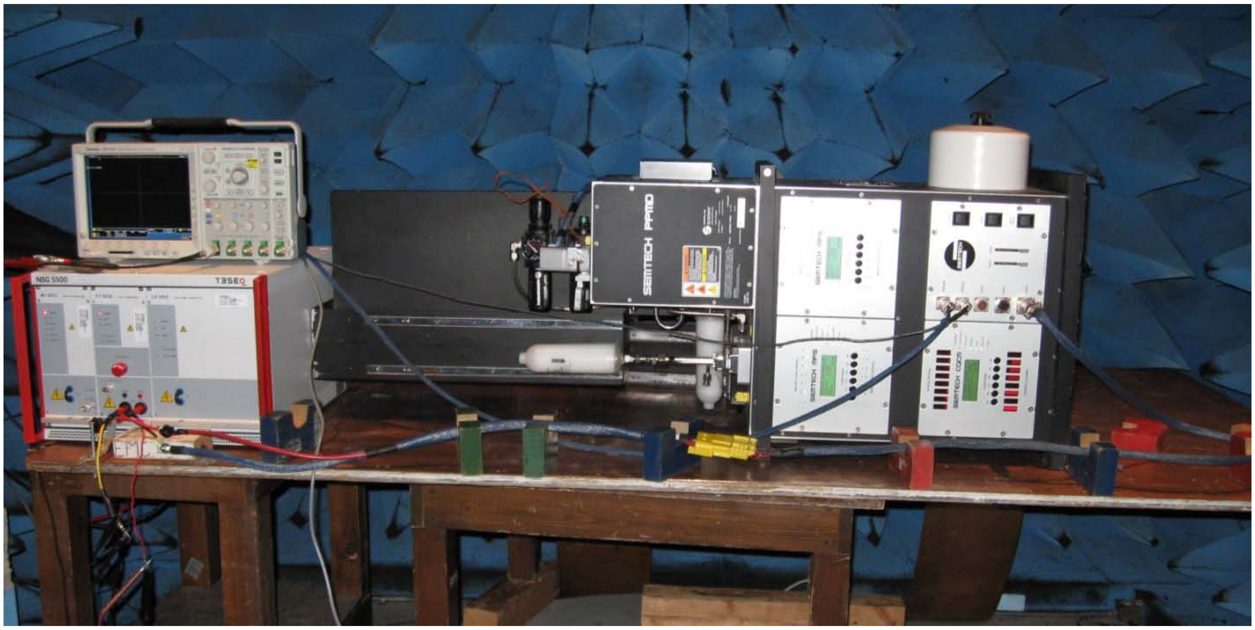


FIGURE 120. SENSORS SETUP DURING CONDUCTED TRANSIENTS TESTING

FIGURE 121. AVL SETUP DURING CONDUCTED TRANSIENTS TESTING

The Sensors PEMS powered down during a -100 volt spike with quick recovery and again powered down when the magnitude of the spike was reduced to -50 volts and then -25 volts. The slow recovery voltage spikes also caused the PEMS to power down with the shortest dwell time of 40 ms causing the unit to shut down. Longer dwell times were not tested.

The quick recovery voltage spike caused the AVL inverter to power down, although it appeared to be working properly when it was restarted. However, during the slow recovery voltage spikes, the inverter shut down again, started smoking and stopped working. The test was not repeated with another inverter to prevent further damage.

The findings from the EMI and RFI testing were presented to the steering committee during the May 20th, 2009 in San Antonio. The steering committee declined to pursue further testing to develop any EMI and RFI error surfaces. The steering committee requested that Horiba investigate the issue of bulk current injection noise in the analog exhaust flow cable and that Sensors investigate the issue of exhaust flow errors during radiated immunity testing.

5.5 Vibration Testing

Figures 122, 123, 124, 125, 126, and 127, show the setup for Sensors vibrational testing using different configurations. The vibration testing was conducted as a screening exercise similar to the method used for the EMI and RFI testing. The PEMS were operated on HEPA filtered room air while being subjected to vibration. The response of the PEMS to the screening exercise was used to determine whether further testing was needed to generate an error surface for vibration. Each PEMS was mounted on an Unholtze-Dickie Shaker Table which was capable of vibrating the PEMS on all three axes separately by adjusting the orientation of the PEMS. The system used a large table to vibrate horizontally. By rotating the orientation of the PEMS, this table was able to simulate longitudinal and transverse horizontal vibration. The shaker was rotated into a vertical position and a smaller platform was attached to provide vertical vibration. Due to considerations for non-road in-use testing, the steering committee requested that the PEMS also be rotated at a 45 degree incline on each axis as well. The horizontal vibration platform was large enough to include all of the pieces of any one type of PEMS at a time. The vertical platform and 45 degree stand were each capable of installing only a single piece of the instrumentation at a time.

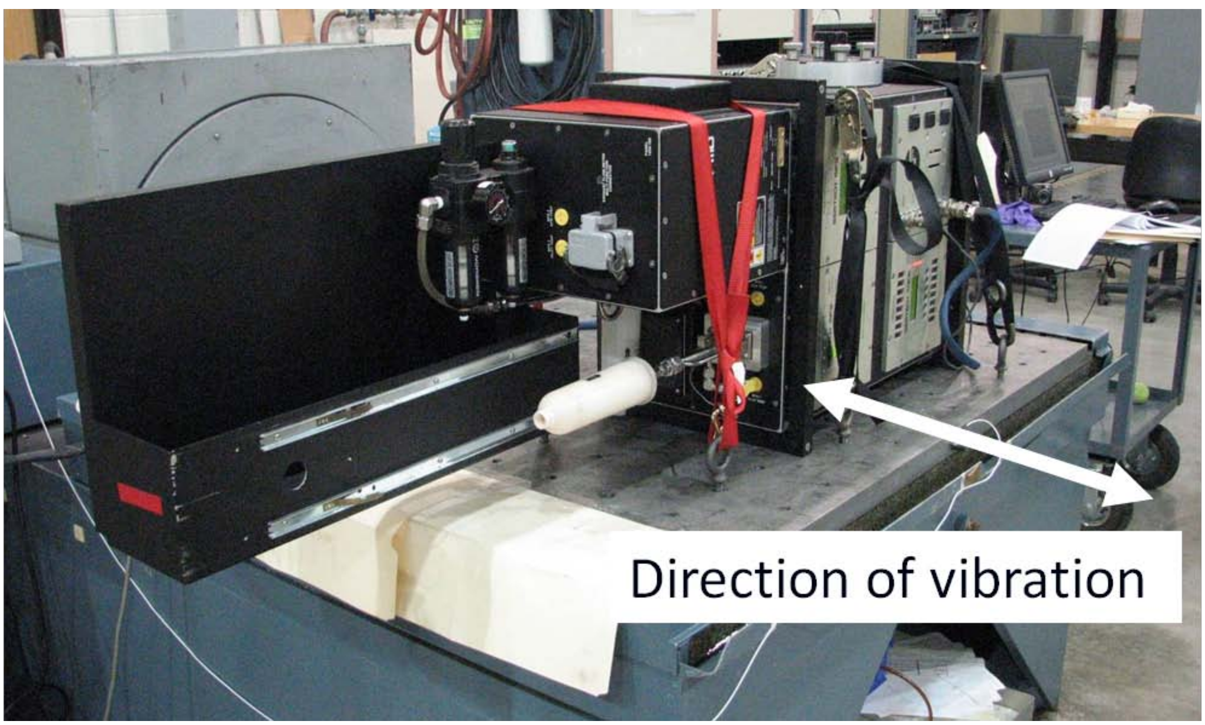


FIGURE 122. SENSORS PEMS MOUNTED FOR TRANSVERSE HORIZONTAL VIBRATION

FIGURE 123. SENSORS PEMS MOUNTED FOR LONGITUDINAL HORIZONTAL VIBRATION

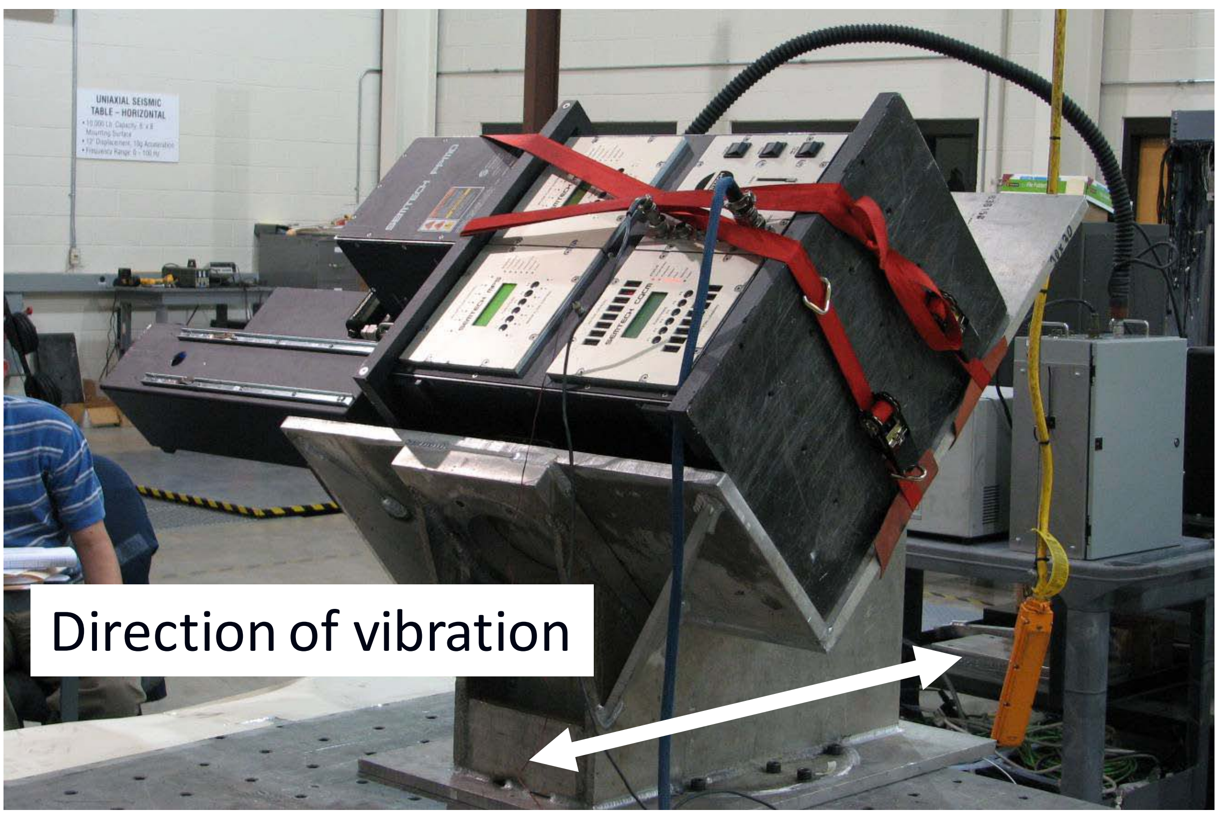


FIGURE 124. SENSORS PEMS MOUNTED FOR TRANSVERSE 45° VIBRATION

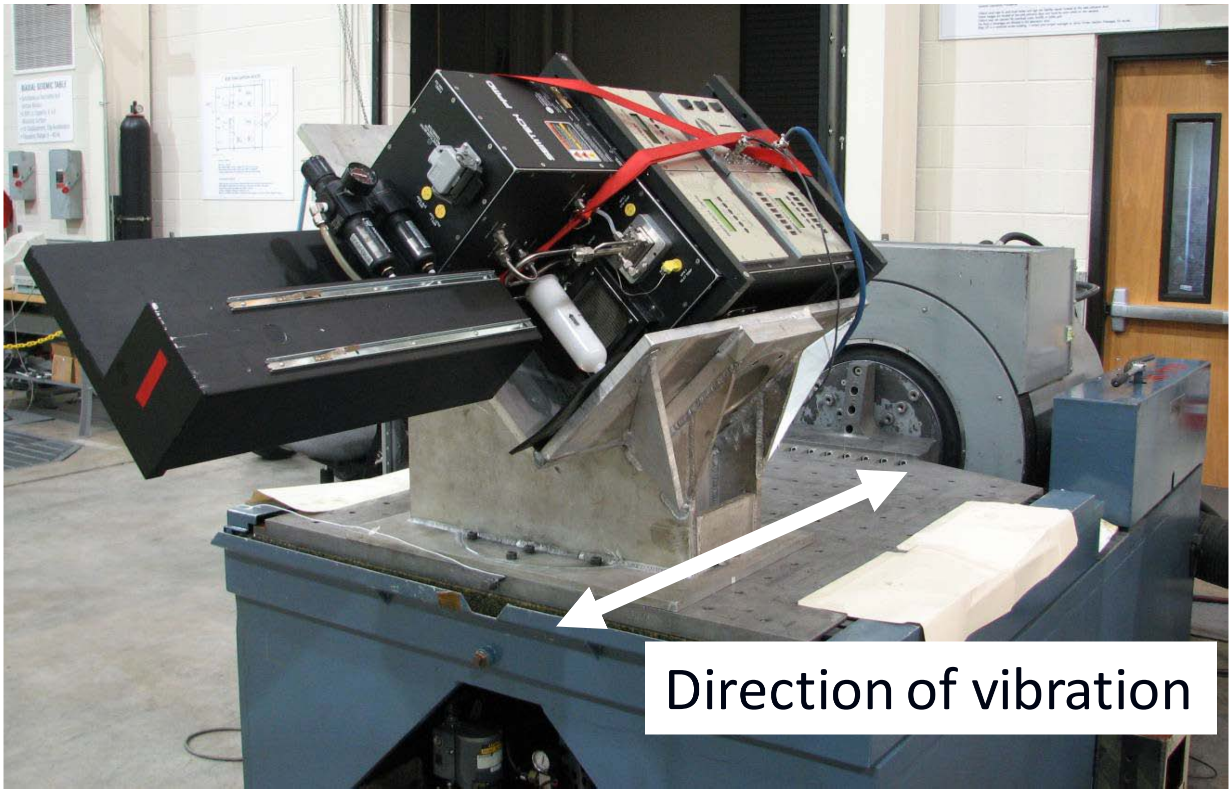


FIGURE 125. SENSORS PEMS MOUNTED FOR LONGITUDINAL 45° VIBRATION

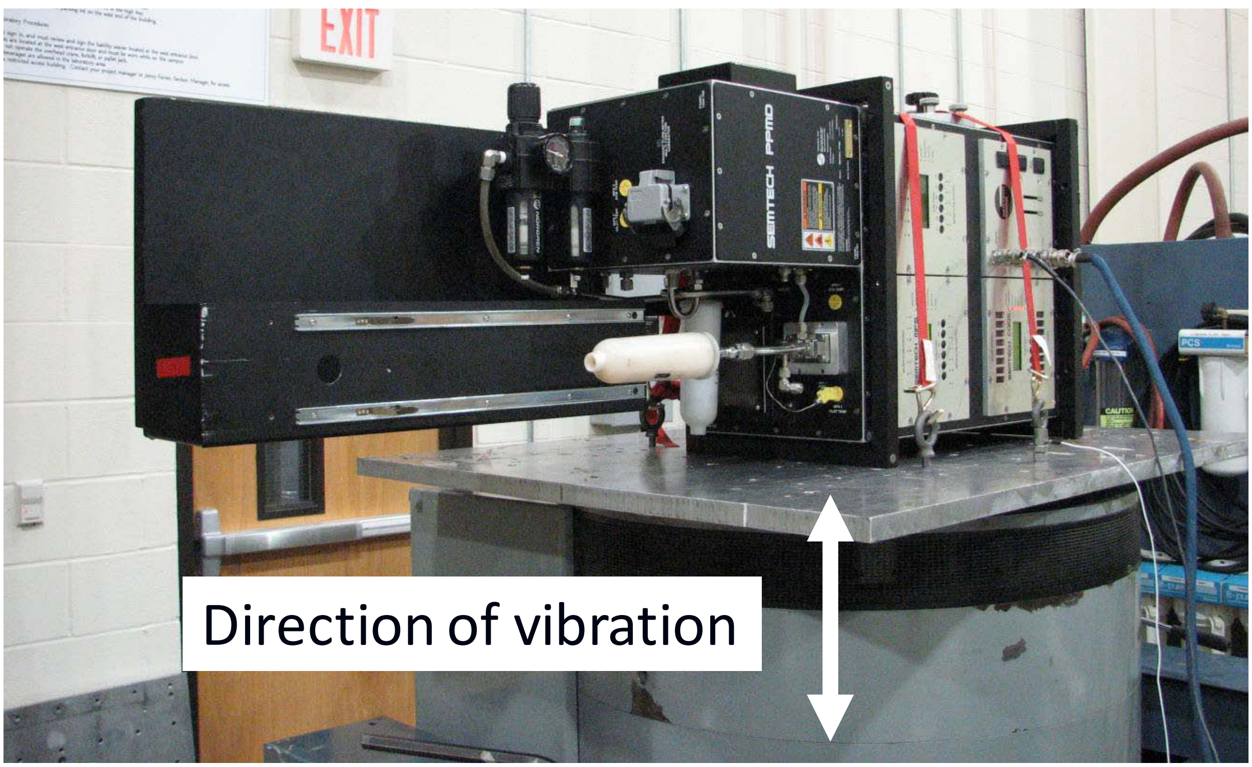


FIGURE 126. SENSORS PEMS MOUNTED FOR VERTICAL VIBRATION

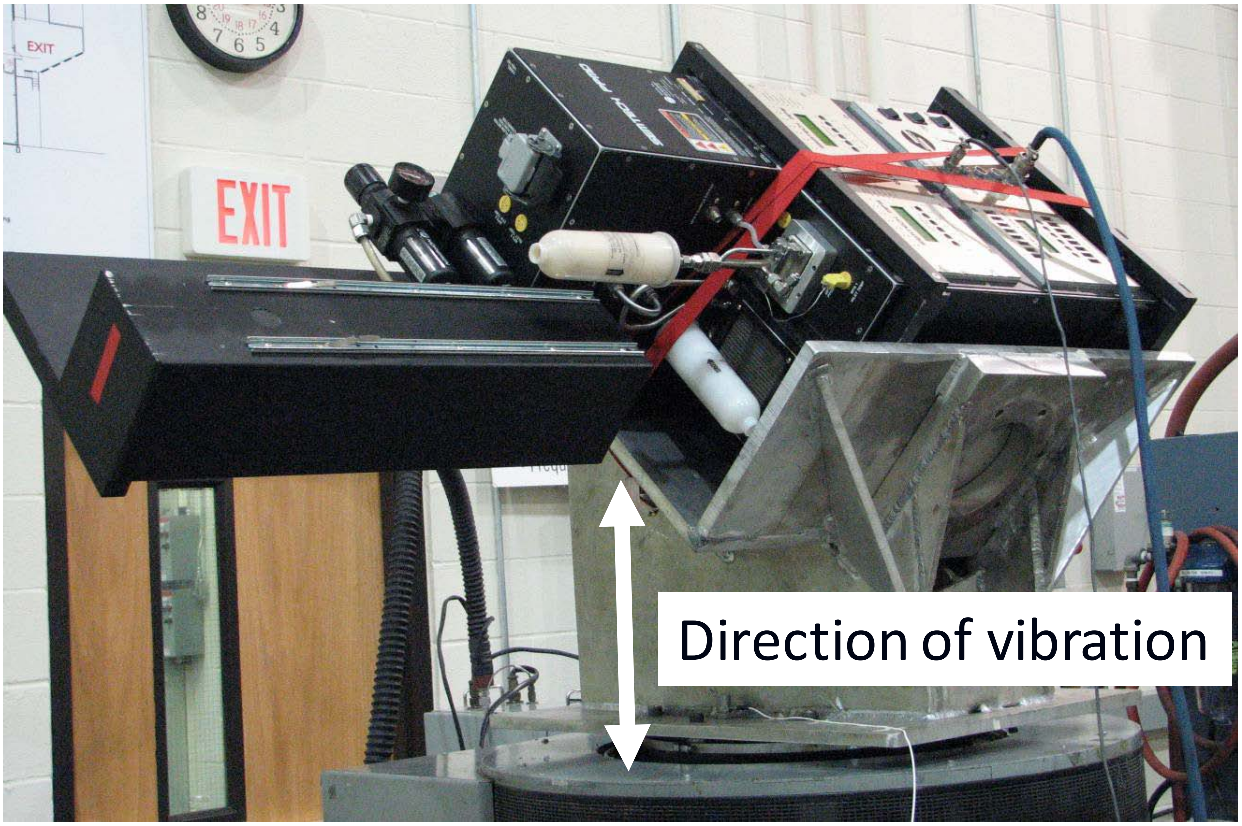


FIGURE 127. SENSORS PEMS MOUNTED FOR 45° VERTICAL VIBRATION

The power spectral density (PSD) from the Mil Standard 810, U S Highway Truck Vibration Exposure was used in this testing. To prevent damage to the PEMS, the PSD was only operated at 25%, 50%, and 75% of the energy specified in the Mil Standard 810. After a few tests at the 75% level, the energy levels were reduced to 10%, 25%, and 50% to maintain the integrity of the instruments. In addition each energy level was only tested for 5 minutes to minimize the chances of damaging the instruments. Figure 128 shows the PSD used for vertical vibration testing and Figure 130 shows the PSD used for horizontal testing.

Figure 130 shows the Horiba PEMS vibration positions for different configurations. Because the OBS-TRPM included three separate boxes, some of the vibration testing had to be performed on individual boxes. The DCS, HE, and MEEE were all able to fit on the horizontal vibration table however only a single box could fit at a time on the 45 degree angle stand. The DCS and MEEE were tested on this stand; the HE box was not tested at 45 degrees, because it was felt that no errors would be detected in a box housing only a filter holder and a cyclone. A particle source would need to be present to detect problems in this portion of the system. The vertical vibration platform was able to hold both the DCS and the MEEE, so these two boxes were tested simultaneously while the HE was again not tested. Any piece of the system that was not being tested on the vibration stand was positioned directly next to the stand so that all flow and electrical cables could still connect to the system normally.

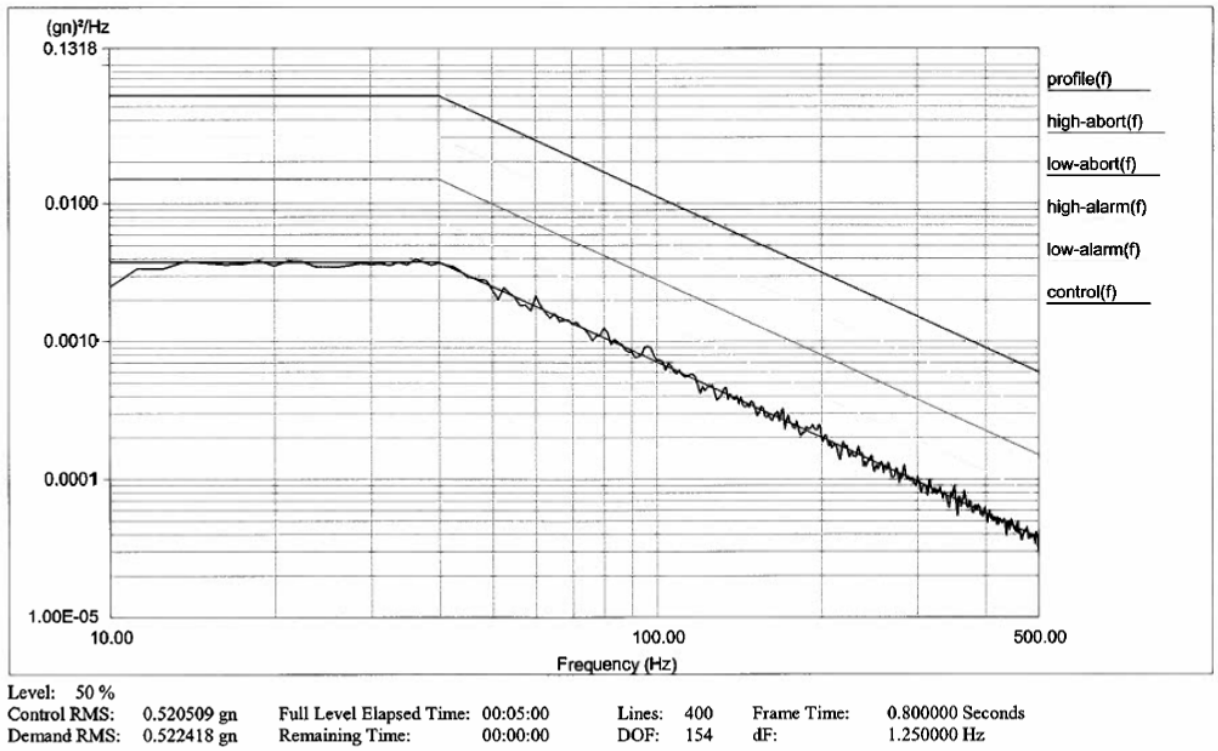


FIGURE 128. POWER SPECTRAL DENSITY FOR VERTICAL VIBRATION TESTING

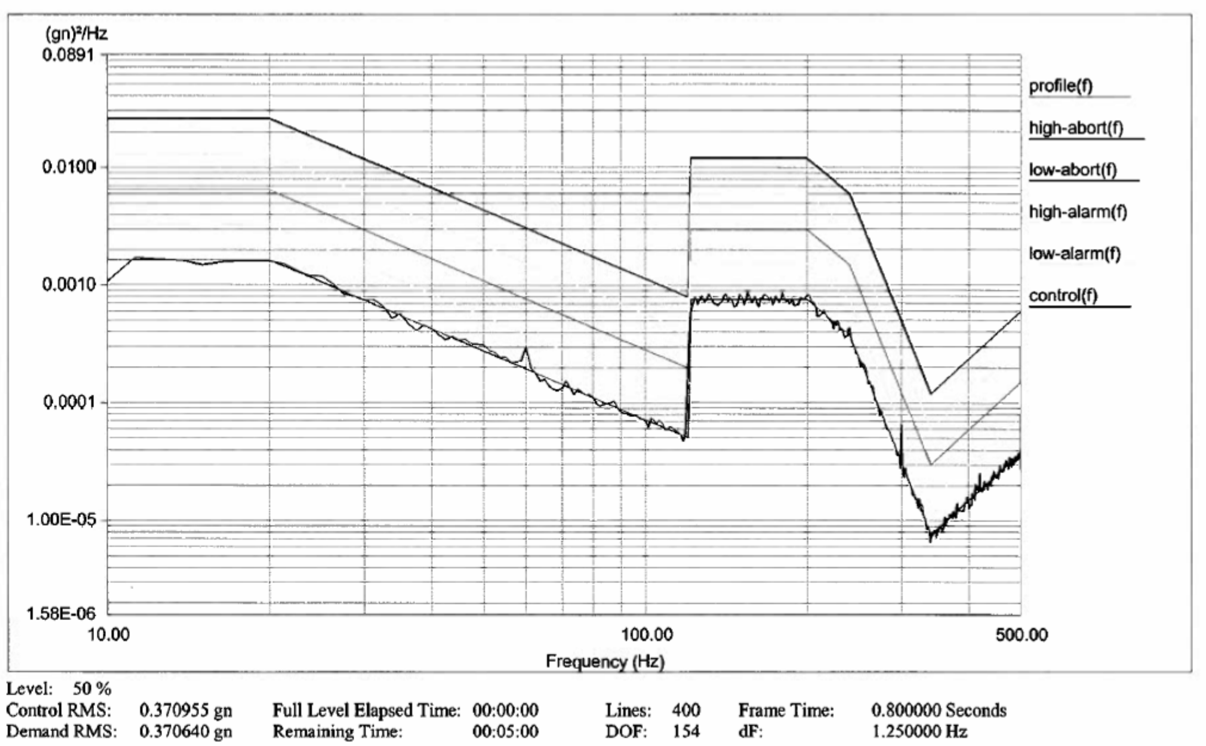


FIGURE 129. POWER SPECTRAL DENSITY FOR HORIZONTAL VIBRATION TESTING

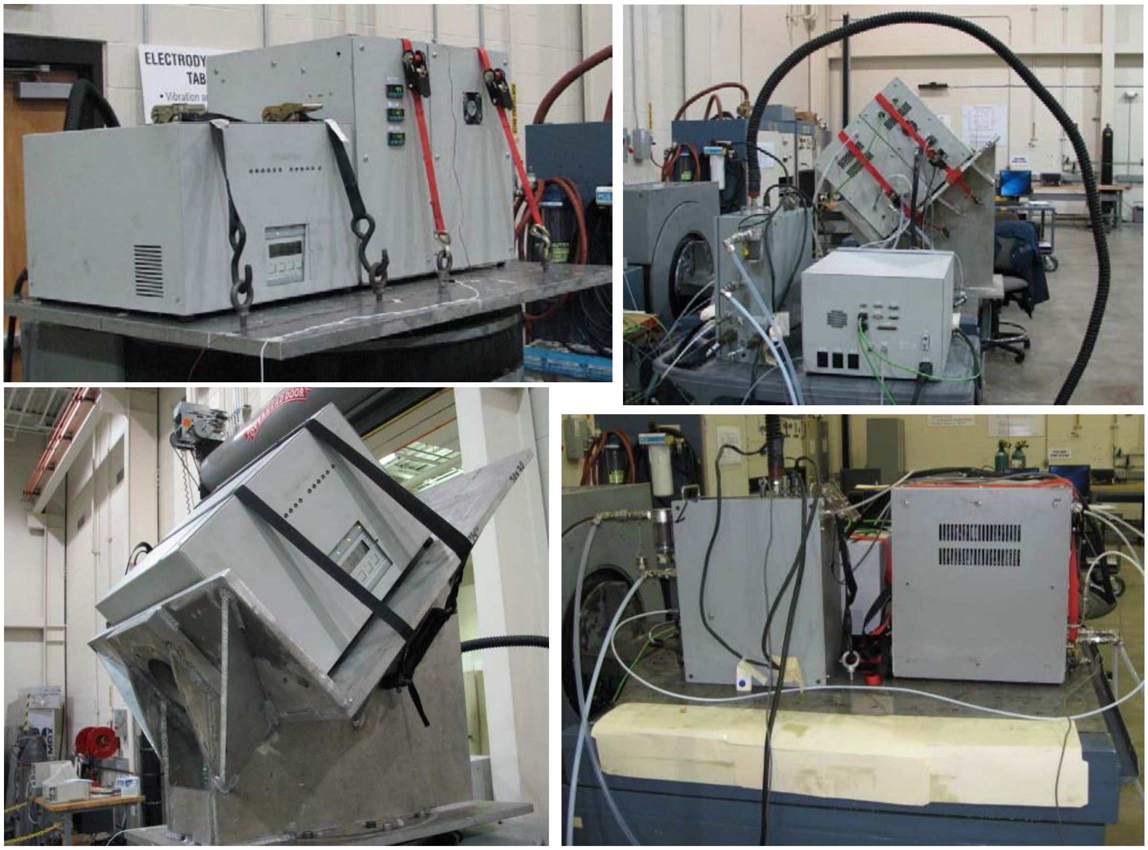


FIGURE 130. HORIBA PEMS VIBRATION POSITIONS

The Horiba PEMS experienced a mechanical failure during testing at the 75% energy level of the transverse horizontal vibration. A bracket holding a filter inside the Mechanical Enclosure (ME) box broke causing a flow line to become blocked. The test was stopped and the bracket was replaced with one from another unit. The testing was resumed until it was discovered that one of the pressure transducers used to measure the flow was not working properly causing an error in the reported flow. This problem was believed to have originated from the broken bracket because the line that was closed off was attached to this pressure transducer. The pressure transducer was replaced with one from the other unit and the system functioned properly. All future tests were conducted at 10%, 25%, and 50% energy for all PEMS to prevent further damage. The only other damage incurred by the Horiba was a rubber foot on the bottom of one of the boxes was sheared off. The measured dilution flow exhibited a higher degree of fluctuations during the vibration testing than was normally observed although the differences were not significant.

The Sensors PEMS was operated without the exhaust flow meter and sample elbow attached to the unit. As can be seen in Figure 127, the two pieces were removed to allow a HEPA filter to be placed on the inlet. Although it would have been desirable to leave these pieces attached it was considered more important to provide clean air to ensure a zero particle level. The Sensors PEMS experienced no mechanical failures during vibration testing although several functionality issues did occur. The exhaust flow measurement became noisier with vibration although the magnitude of the noise was relatively small. In the EMI and RFI testing values as high as 1000 kg/hr were observed, but in vibration testing the exhaust flow never went above 50 kg/hr.

The Sensors PEMS experienced problems maintaining its total flow rate during vibration in the vertical direction. This problem was related to the automatic drain valves on the moisture traps in the dilution flow line. These traps are designed to open automatically when enough downwards force is applied from accumulated moisture in the reservoir; however the vertical vibration was causing the valves to repeatedly open allowing a portion of the flow to escape. Figure 131 shows an example of the total flow dropping while experiencing vertical vibration.

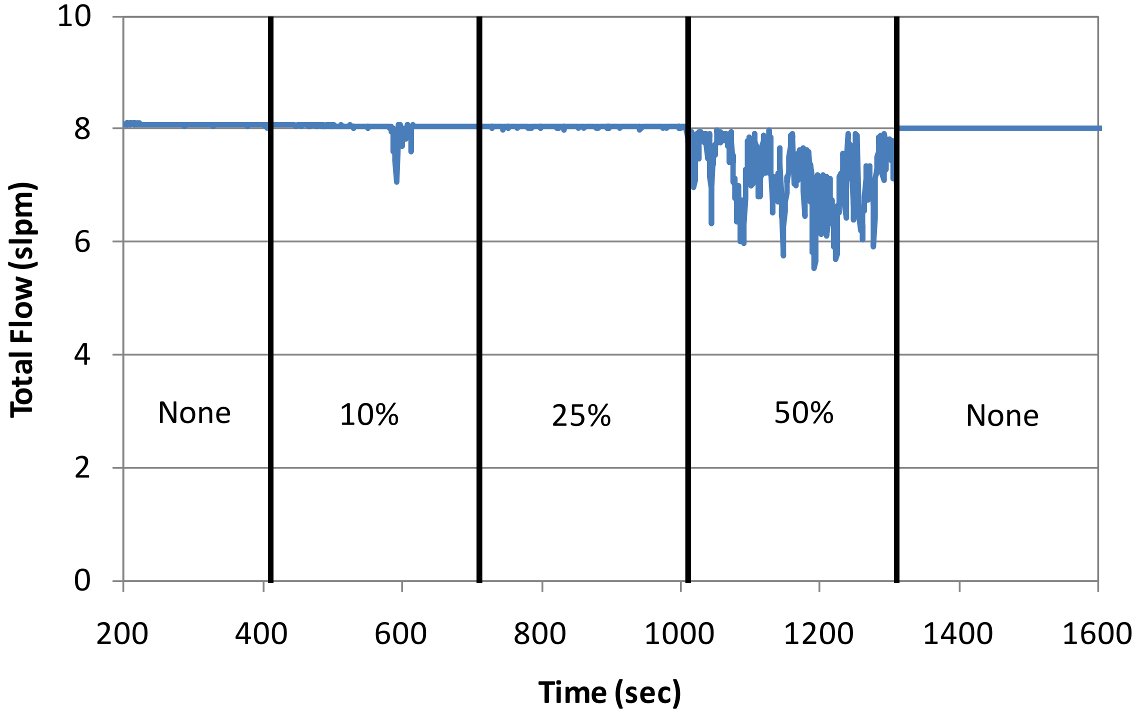


FIGURE 131. SENSORS TOTAL FLOW DURING VIBRATION TESTING

It was possible to test both of the AVL boxes simultaneously for the horizontal and vertical vibration, however they were tested separately for the 45 degree angle vibration. Figure 132 shows the AVL PEMS vibration testing using different configurations.

No mechanical problems were encountered with the AVL unit during vibration testing although the measurement did exhibit vibration induced noise. The measured soot concentration fluctuated with increasing amplitude as the vibration increased for all orientations tested. The peak measurement recorded was about plus and minus 5 µg/mol with more typical values swinging between plus and minus 2.5 µg/mol. A typical measurement is shown in Figure 133.

FIGURE 132. AVL PEMS VIBRATION POSITIONS

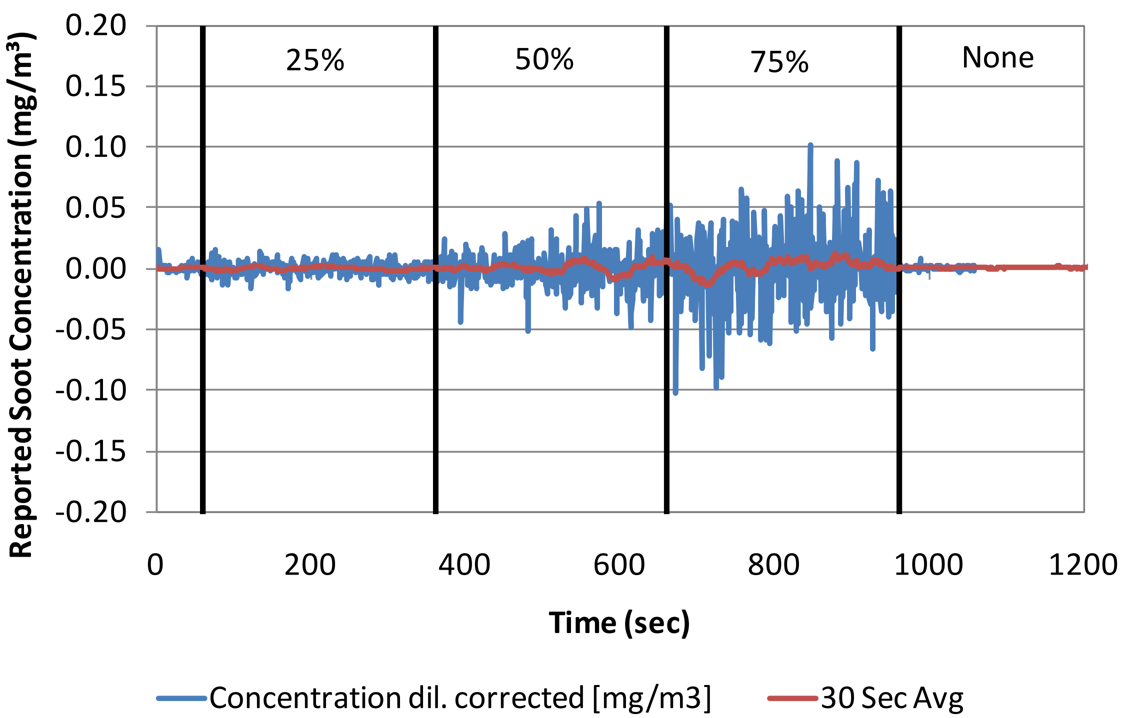


FIGURE 133. AVL SOOT MEASUREMENT NOISE DURING VIBRATION TESTING

This particular data was from the 45 degree angle longitudinal vibration. The noise in the measurement has no bias indicating that it will average out over larger periods of time. The 30 second average is shown since this is likely the measurement error that would be observed during an NTE event. The maximum error of the 30 second average was -0.009 mg/m^3 which is relatively insignificant based on PM concentrations expected at the threshold. However, it is unclear from this testing whether the noise could be greater if a particle source was present. The results from the vibration testing were presented to the steering committee at the September 22nd, 2009 meeting in Riverside. The steering committee declined to perform additional tests to create an error surface for vibration since the AVL system was excluded from being an official PM-PEMS.

6.0 MODELING RESULTS

The main objective of this portion of the project was to use Monte Carlo techniques (e.g. random sampling) in an error model to simulate the combined effects of all the agreed-upon sources of PEMS error incremental to lab error on the components of the brake-specific (BS) PM emissions. This was accomplished by creating "error surfaces" for the Monte Carlo simulation to sample, based upon the results of a variety of lab experiments. The constructed model was simulated for thousands of trials (i.e., iterations) using data taken from a reference data set of 141 unique NTE events. The model results were used to determine the brake-specific additive measurement allowances for PM by three different calculation methods for three different PEMS model units.

The error surfaces were generated from the results of each of the engine dynamometer and environmental chamber laboratory tests. The engine-lab-test error surfaces covered the domain of error versus the magnitude of the signal to which the error was to be applied (i.e., 1st to 99th percentile error vs. concentration, flow, torque, etc.). The environmental-test error surfaces for shock and vibration, and electromagnetic and radio frequency interference (EMI/RFI) was not included because no error surfaces were generated. The environmental test error surfaces for pressure and temperature were characteristically different because they covered the domain of the environmental-test cycle time versus the magnitude of the signal to which the error was to be applied (i.e., error at a selected time vs. concentration).

6.1 Convergence Results from MC Runs

This section contains a summary of the checks to determine if the convergence criteria were met for the simulation runs. Section 2.9 on *Convergence and Number of Trials* contains a detailed description of the convergence methodology and the procedures followed to check for convergence for the reference NTE event trials. This procedure was applied to the simulation data obtained for each of the three PEMS units and all applicable calculation methods.

Figure 134 through Figure 140 contain plots of the 90% confidence interval widths at the 95th percentile delta differences (expressed as a percent of the BSPM emissions NTE threshold) versus the ideal BSPM emissions for the 141 individual reference NTE events. This is done for each of the three PEMS units and the applicable calculation methods. A summary of the results is given in Table 22. Of interest was whether or not the simulations converged within 1% of the threshold value. As can be seen in the plots, a majority of the reference NTE events did not converge within 1% of the BSPM threshold. However, a majority did converge within 2% of the threshold. For the three PEMS units and calculation methods, the maximum percent of the confidence interval widths ranged from 1.82% for the AVL Method 1 to 2.76% for Sensors Method 1. Upon examination of the delta BSPM distributions for the various reference NTE events, those that had a high percentage above the BSPM threshold at the 95th percentile generally had low input PM concentration levels.

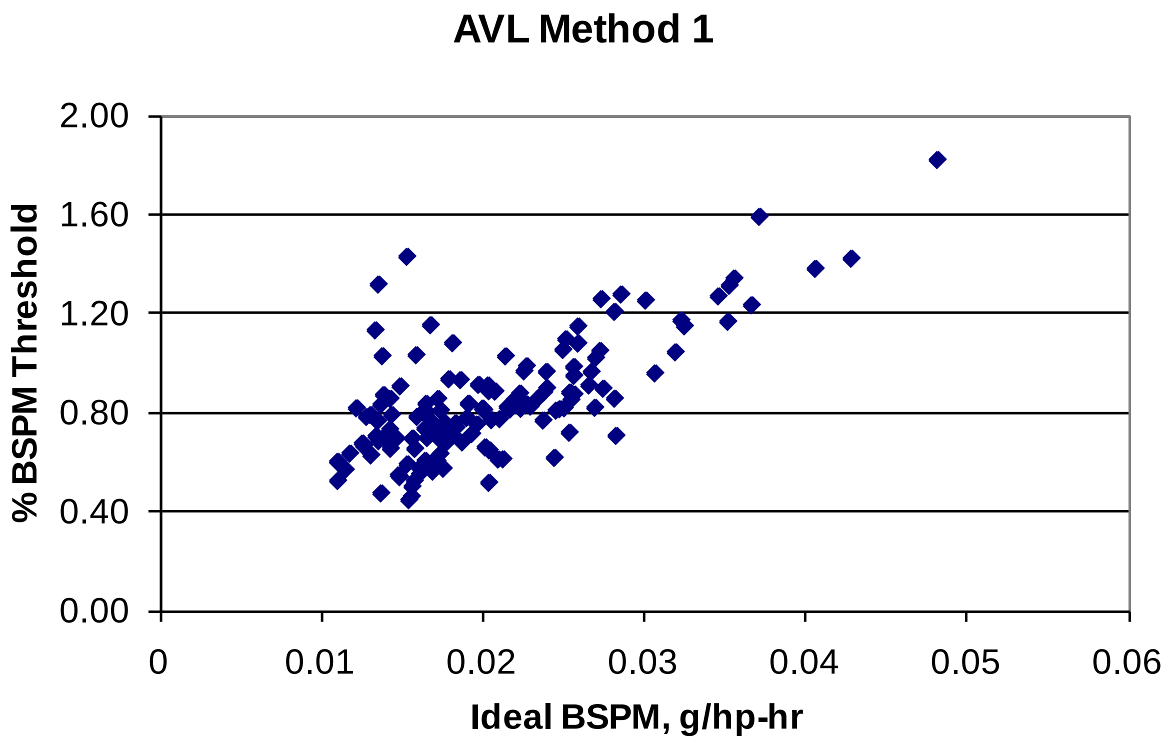


FIGURE 134. CONVERGENCE FOR AVL METHOD 1 AS A PERCENT OF BSPM THRESHOLD

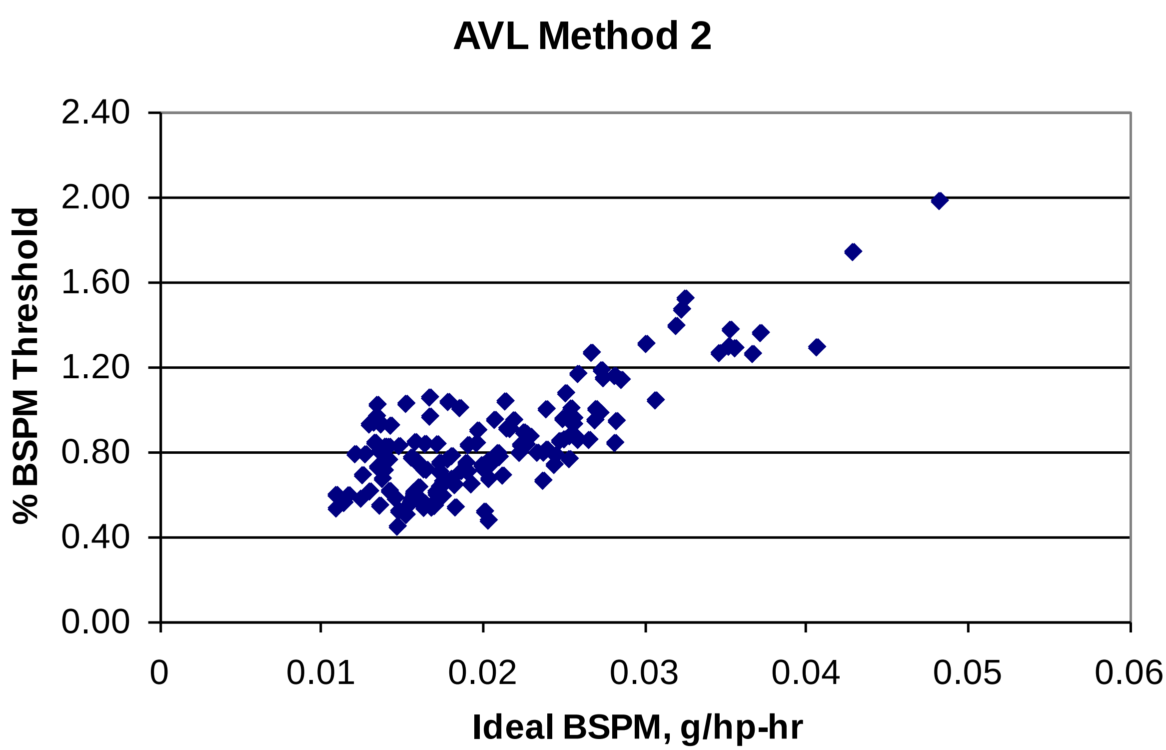


FIGURE 135. CONVERGENCE FOR AVL METHOD 2 AS A PERCENT OF BSPM THRESHOLD

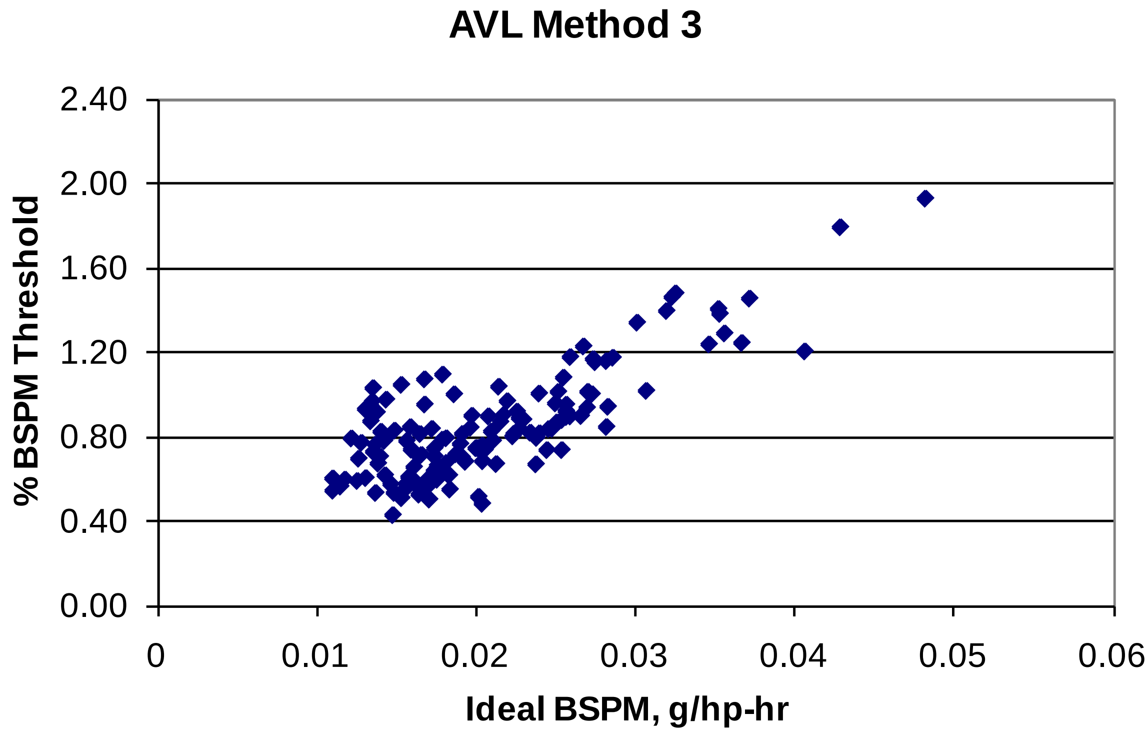


FIGURE 136. CONVERGENCE FOR AVL METHOD 3 AS A PERCENT OF BSPM THRESHOLD

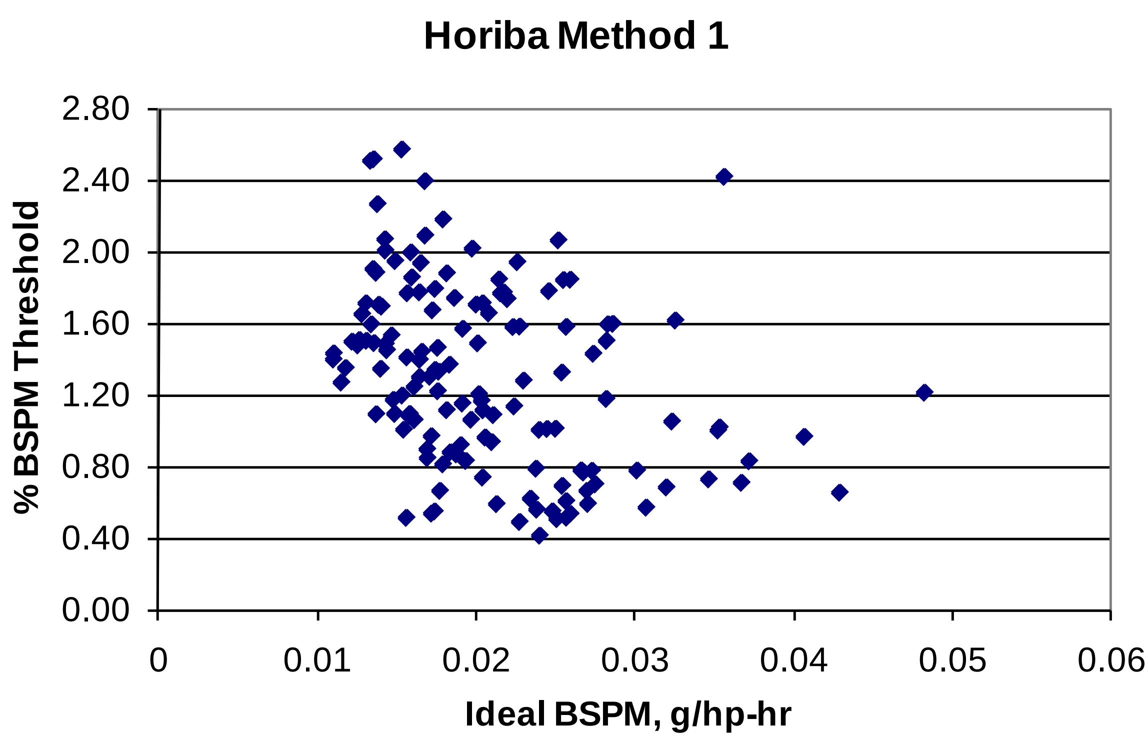


FIGURE 137. CONVERGENCE FOR HORIBA METHOD 1 AS A PERCENT OF BSPM THRESHOLD

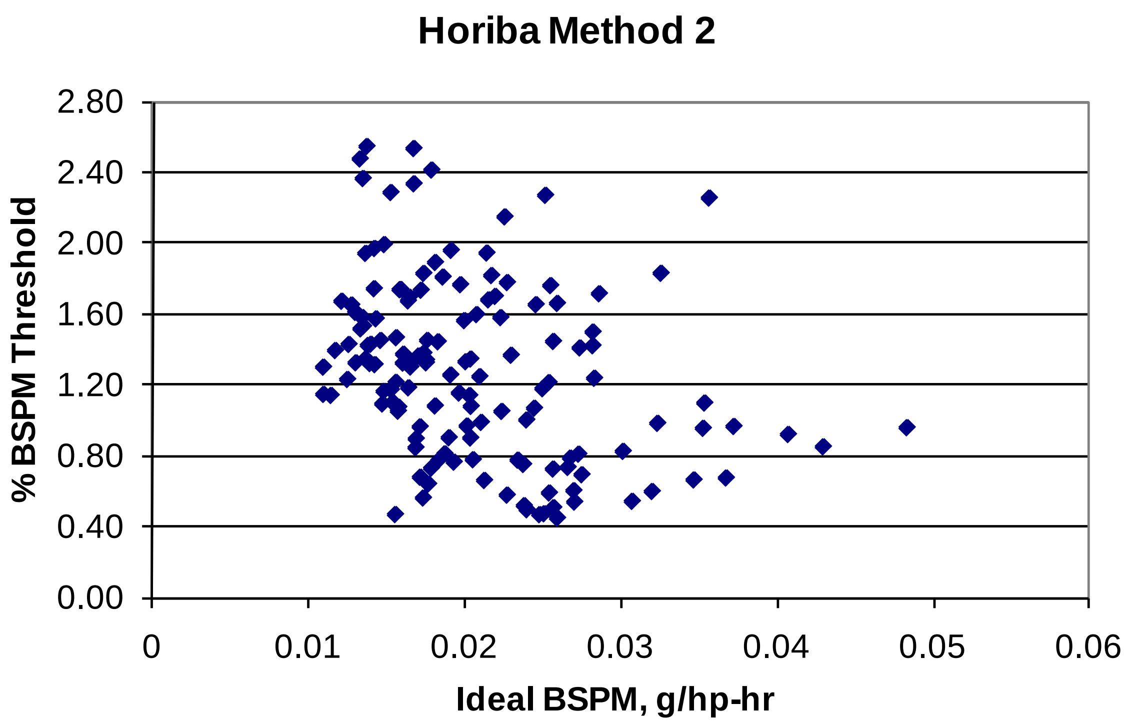


FIGURE 138. CONVERGENCE FOR HORIBA METHOD 2 AS A PERCENT OF BSPM THRESHOLD

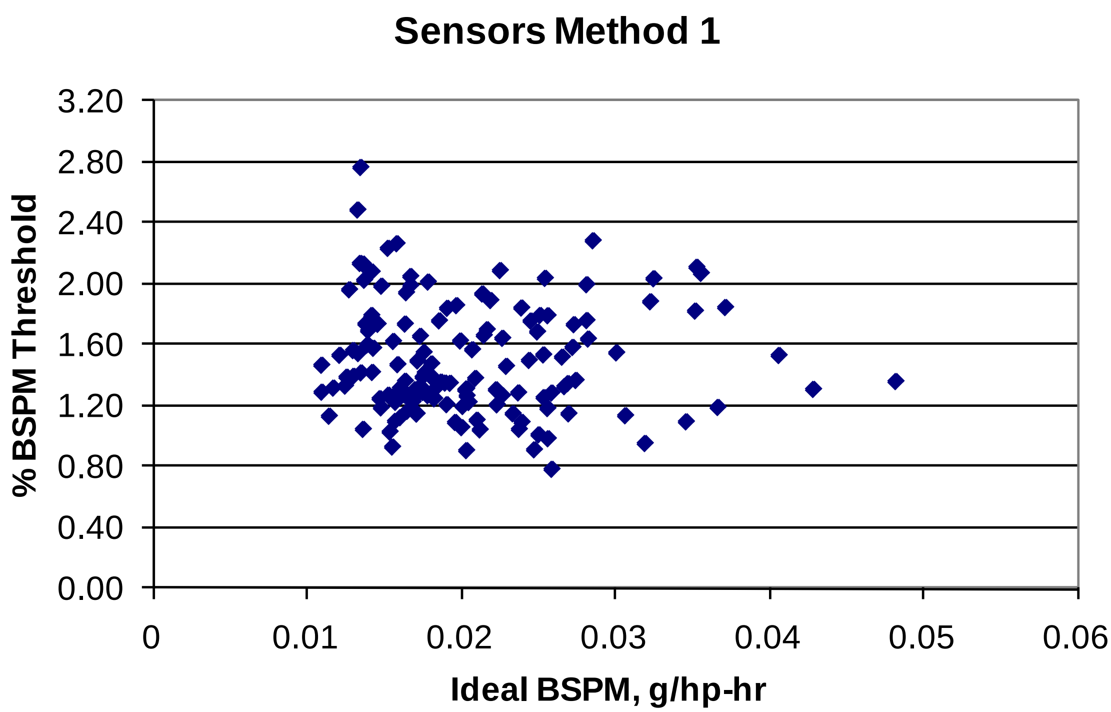


FIGURE 139. CONVERGENCE FOR SENSORS METHOD 1 AS A PERCENT OF BSPM THRESHOLD

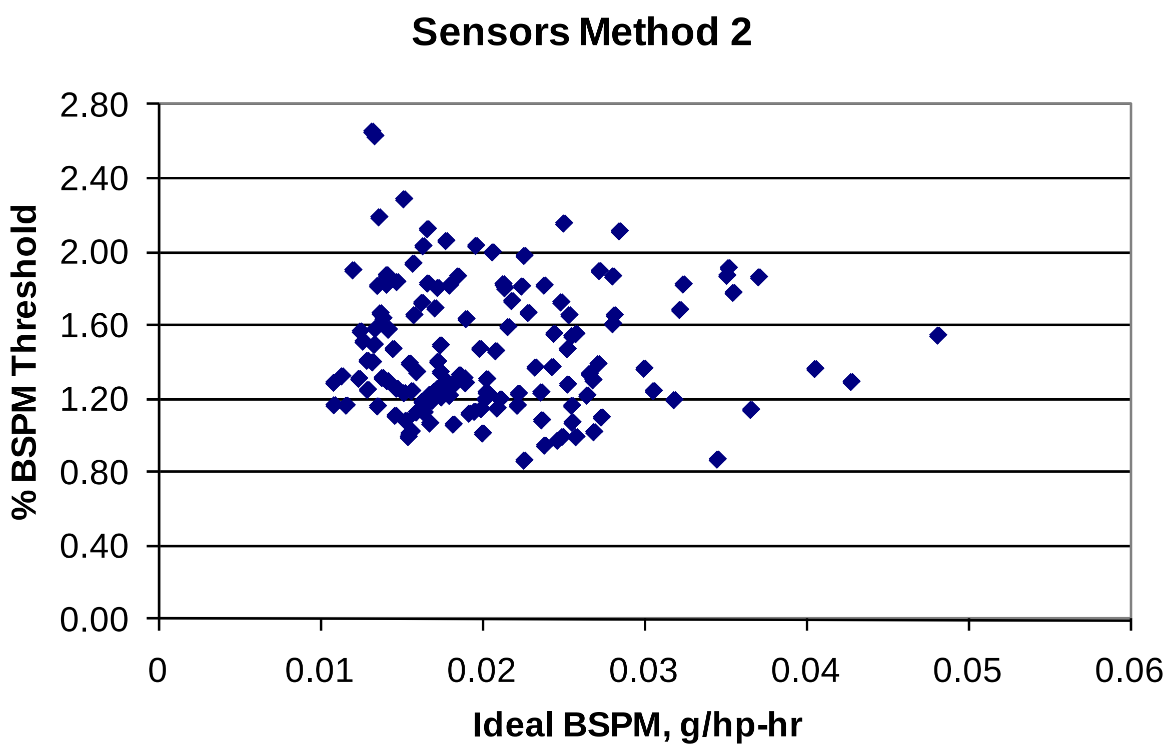


FIGURE 140. CONVERGENCE FOR SENSORS METHOD 2 AS A PERCENT OF BSPM THRESHOLD

TABLE 22. SUMMARY OF NUMBER OF REFERENCE NTES MEETING 2% CONVERGENCE

PEMS Unit	Method	Min	Max	No. NTEs within 2% Convergence	% NTEs within 2% Convergence
AVL	1	0.4467	1.8211	141	100%
	2	0.4446	1.9766	141	100%
	3	0.4240	1.9215	141	100%
Horiba	1	0.4158	2.5663	129	91%
	2	0.4414	2.5447	131	93%
Sensors	1	0.7883	2.7664	125	87%
	2	0.8613	2.6544	131	93%

6.2 Sensitivity Based on Bias and Variance

This section contains a summary of the error surfaces that contributed the most to the bias of the generated BS emissions. The sensitivity charts developed in Crystal Ball help identify the error surfaces (assumptions) that are sensitive to changes in variation with respect to their effect on the three delta BS emissions. Another type of sensitivity examined in this study was concerned with the effects of potential "bias" in error surfaces and their effects on the forecast values. In order to study these effects a new error surface assumption was added to the MC Monte Carlo simulation model for each of the original 31 error surfaces.

This assumption was sampled as a discrete binary distribution (i.e., on or off) during the simulation. For each trial of the simulation, 31 original error surfaces and 31 'on/off' error surfaces were sampled according to their defined sample distribution. If the 'on/off' error surface produced an 'off' condition, the delta emissions from that particular error surface were not added to the BS emissions computations for the BS emissions 'with errors'. Similarly, if the 'on/off' error surface produced an 'on' condition, the delta emissions from that particular error surface were added to the BS emissions calculations.

During every trial of the simulation, the exclusions due to the 'off' conditions resulted in various combinations of the error surface delta emissions being added to the BS emissions 'with errors' computations. Over the course of a MC simulation with thousands of trials, the sensitivity of a particular error either 'on' or 'off' was assessed by examining the change in the forecast delta emission. Therefore, in a single MC simulation of a reference NTE event sensitivities due to variance and/or bias were explored.

Simulation results from the reference NTE events produced sensitivity values for all 95th percentile delta emissions by all three PEMS units and applicable calculation methods. Table 23 through Table 29 summarize the error surfaces in which either the contribution-to-variance normalized sensitivity value or the 'on/off' bias check for the error surface was at least 5% in magnitude compared to all the other error surfaces. If the label in the error surface contains the words 'Delta' then it represents a check for bias; otherwise, the error surface indicates a check for variance. Table 23 through Table 25 lists the sensitivity and bias descriptive statistics for the delta BSPM emissions for the AVL PEMS for Methods 1, 2 and 3, respectively. For all three methods, the largest mean normalized variance was from the bias effect due to error surface #1, SSPM.

TABLE 23. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR AVL BSPM METHOD 1

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	141	11.34	7.59	35.25
2	TR PM	4	7.00	6.42	7.34
20	SS Exhaust Flow	4	5.57	5.32	6.05
31	Torque Warm-up	10	-6.64	-11.22	-5.32
35	Torque Engine Manufacturer	1	-6.27	-6.27	-6.27
	Delta Exhaust Flow Pulsation	3	5.78	5.56	5.99
	Delta SS PM	141	-74.37	-83.67	-21.02

TABLE 24. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR AVL BSPM METHOD 2

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	141	21.48	7.44	60.56
2	TR PM	38	9.20	5.53	12.31
31	Torque Warm-up	8	-6.82	-10.77	-5.24
35	Torque Engine Manuf	1	-6.12	-6.12	-6.12
45	SS CO2	4	-6.89	-7.82	-5.32
	Delta SS PM	141	-63.27	-83.77	-20.95

TABLE 25. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR AVL BSPM METHOD 3

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	141	20.91	7.71	60.50
2	TR PM	36	9.27	5.17	12.52
31	Torque Warm-up	9	-6.62	-10.77	-5.14
35	Torque Engine Manuf	1	-6.12	-6.12	-6.12
45	SS CO2	4	-6.96	-7.89	-5.40
	Delta SS PM	141	-64.04	-83.76	-20.93

Table 26 and Table 27 list the sensitivity and bias descriptive statistics for the delta BSPM emissions for the Horiba PEMS for Methods 1 and 2, respectively. For both methods, the highest mean normalized variances were from the bias and variance due to error surface #1, SS PM.

TABLE 26. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR HORIBA BSPM METHOD 1

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	138	41.86	6.65	80.39
2	TR PM	10	5.84	5.04	7.18
20	SS Exhaust Flow	26	8.94	5.00	7.80
31	Torque Warm-up	100	-8.34	-15.96	-5.08
35	Torque Engine Manuf	29	-5.72	-8.07	-5.00
	Delta Exhaust Flow Pulsation	31	6.67	5.07	10.01
	Delta SS PM	83	-32.05	-83.42	73.96

TABLE 27. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR HORIBA BSPM METHOD 2

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	138	39.55	6.99	80.30
2	TR PM	10	5.89	5.00	7.42
31	Torque Warm-up	95	-8.19	-15.04	-5.03
35	Torque Engine Manuf	24	-5.72	-7.65	-5.08
42	Fuel Rate Engine Manuf	7	5.52	5.07	6.34
45	SS CO2	54	-6.60	-9.83	-5.09
	Delta SS PM	89	-42.60	-83.42	75.48

Table 28 and Table 29 list the sensitivity and bias descriptive statistics for the delta BSPM emissions for the Sensors PEMS for Methods 1 and 2, respectively. For both methods, the highest mean normalized variance was from the bias and variance due to error surface #1, SSPM.

TABLE 28. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR SENSORS BSPM METHOD 1

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	138	46.92	6.57	78.61
2	TR PM	100	8.48	5.00	12.31
20	SS Exhaust Flow	8	6.11	8.06	7.56
31	Torque Warm-up	30	-8.28	-11.57	-5.02
35	Torque Engine Manuf	10	-5.60	-6.06	-5.14
	Delta Exhaust Flow Pulsation	9	7.01	5.56	8.79
	Delta SS PM	120	-31.19	-86.58	75.35

TABLE 29. ERROR SURFACE SENSITIVITY TO BIAS AND VARIANCE FOR 141 REFERENCE NTE EVENTS FOR SENSORS BSPM METHOD 2

Error Surface No.	Error Surface	No. Ref NTE Events	Avg. Contribution to Normalized Variance, %	Min Contribution, %	Max Contribution, %
1	SS PM	138	45.92	6.68	77.78
2	TR PM	101	8.48	5.03	12.52
31	Torque Warm-up	24	-7.84	-12.01	-5.08
35	Torque Engine Manuf	5	-5.61	-6.06	-5.01
42	Fuel Rate Engine Manuf	4	6.18	5.72	6.53
45	SS CO2	10	-6.84	-9.77	-5.15
	Delta SS PM	127	-28.96	-86.67	75.75

The contribution to normalized variance and bias sensitivities from Table 23 through Table 29 are illustrated pictorially as box plots in Figure 141 to Figure 147 for BSPM by PEMS unit for Methods 1, 2 and 3. Only the error surfaces with at least 35 of the 141 reference NTE events (1/4 of the events) are included as box plots. The mean normalized variance for each of the plotted error surfaces is noted by a "+" symbol in the boxes. The error surface with the largest mean normalized variance is plotted at the left of the chart. The error surface with the second largest mean normalized variance is plotted second from the left, and so on. Figure 142 and Figure 143 demonstrate the high sensitivity to the negative bias for error surface #1, PM SS. Figure Figure146 and Figure 147 show a large variance effect due to PM SS. Table 30 and Table 31 show a summary of the error surface sensitivity to bias and variance for the different PEMS using Method 1 and Method 2. Table 32 shows a similar summary using Method 3 for the AVL PEMS only.

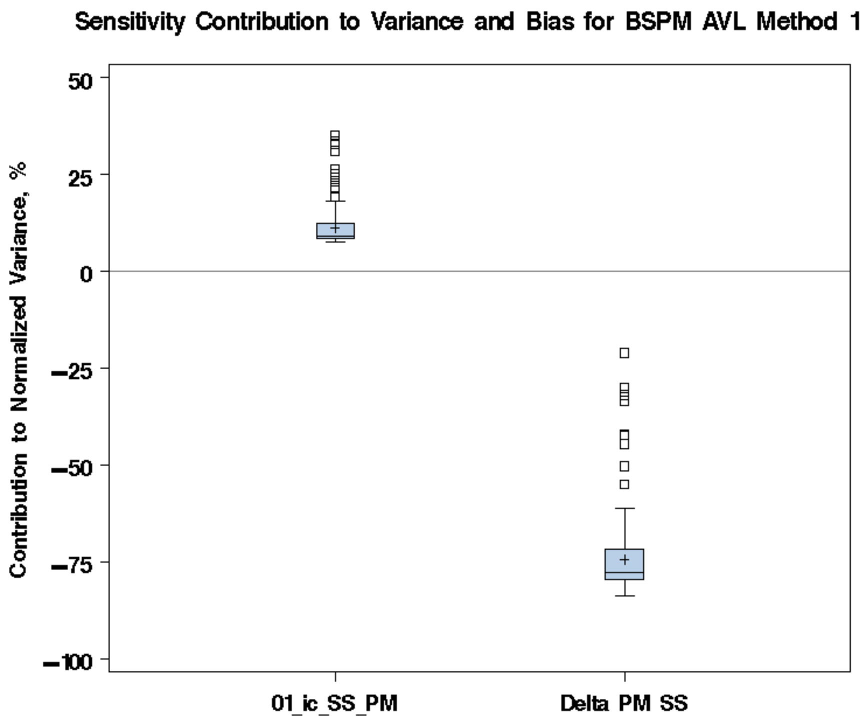


FIGURE 141. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR AVL BSPM METHOD 1

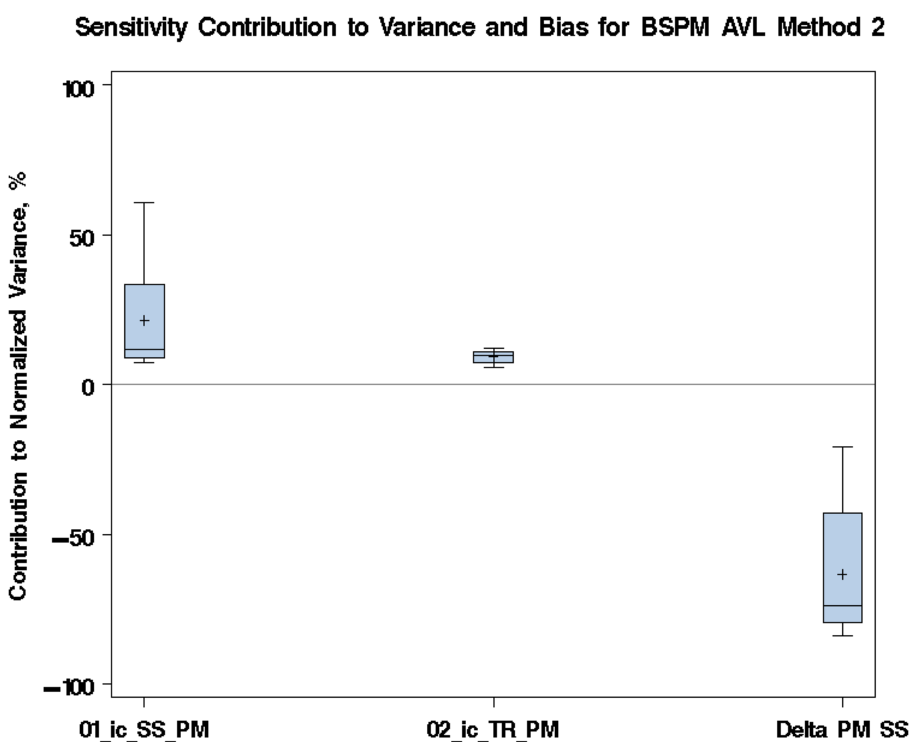


FIGURE 142. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR AVL METHOD 2

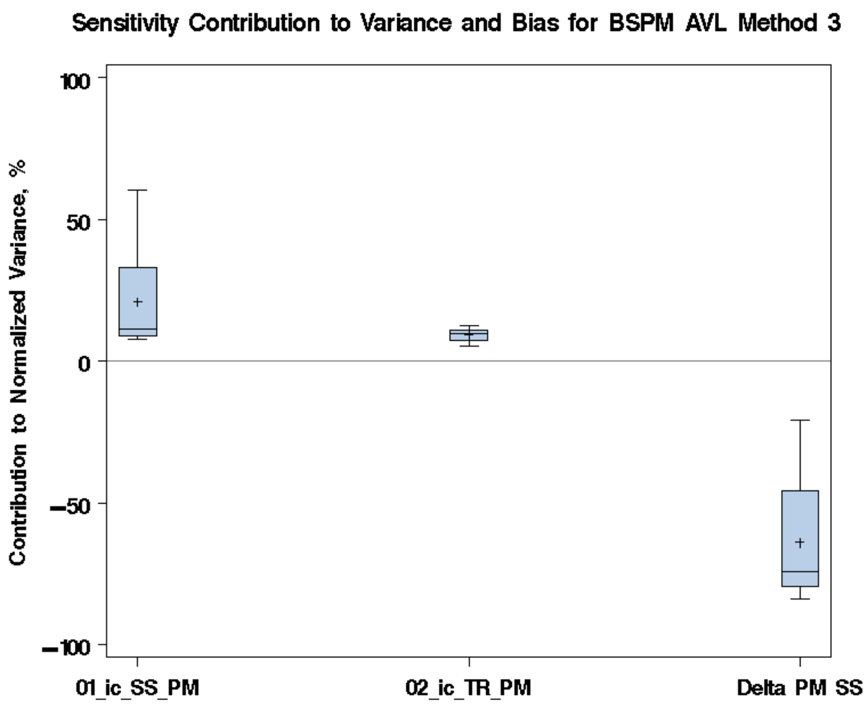


FIGURE 143. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR AVL METHOD 3

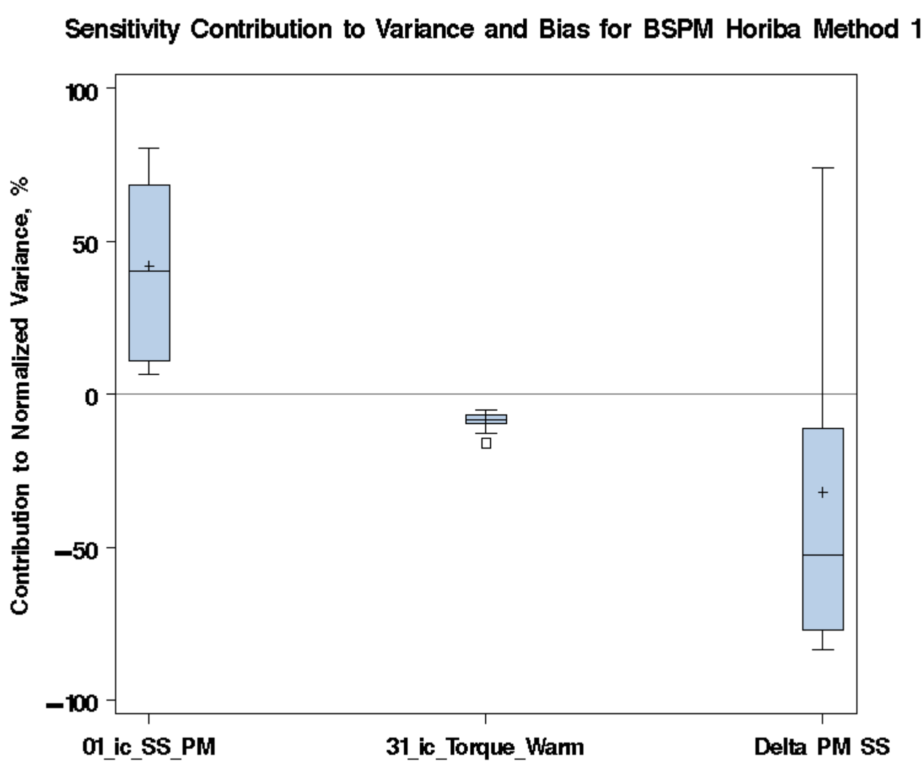


FIGURE 144. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR HORIBA BSPM METHOD 1

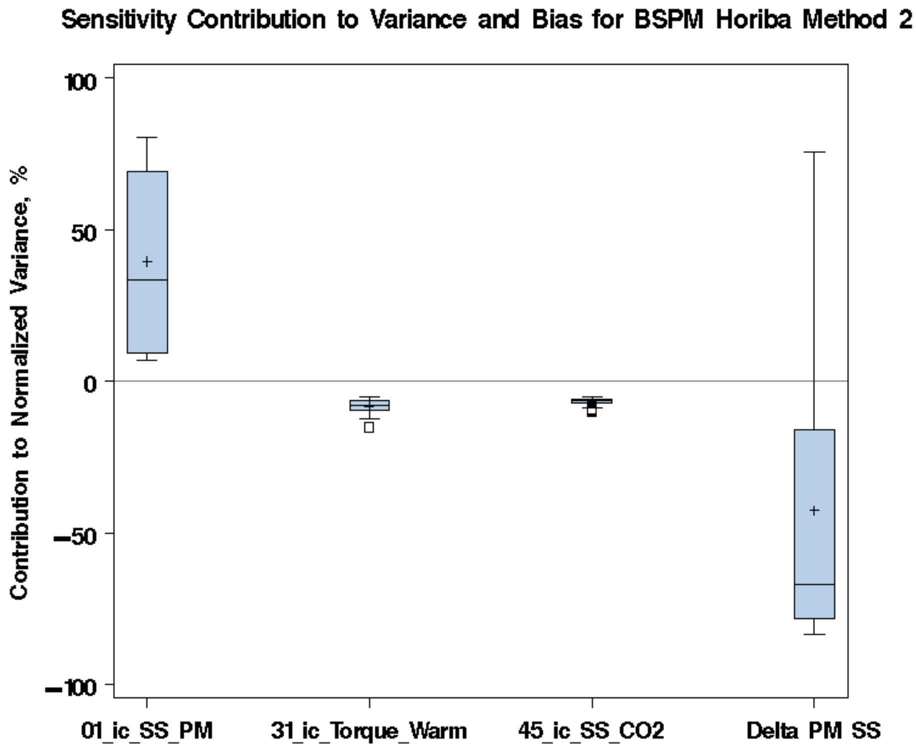


FIGURE 145. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR HORIBA BSPM METHOD 2

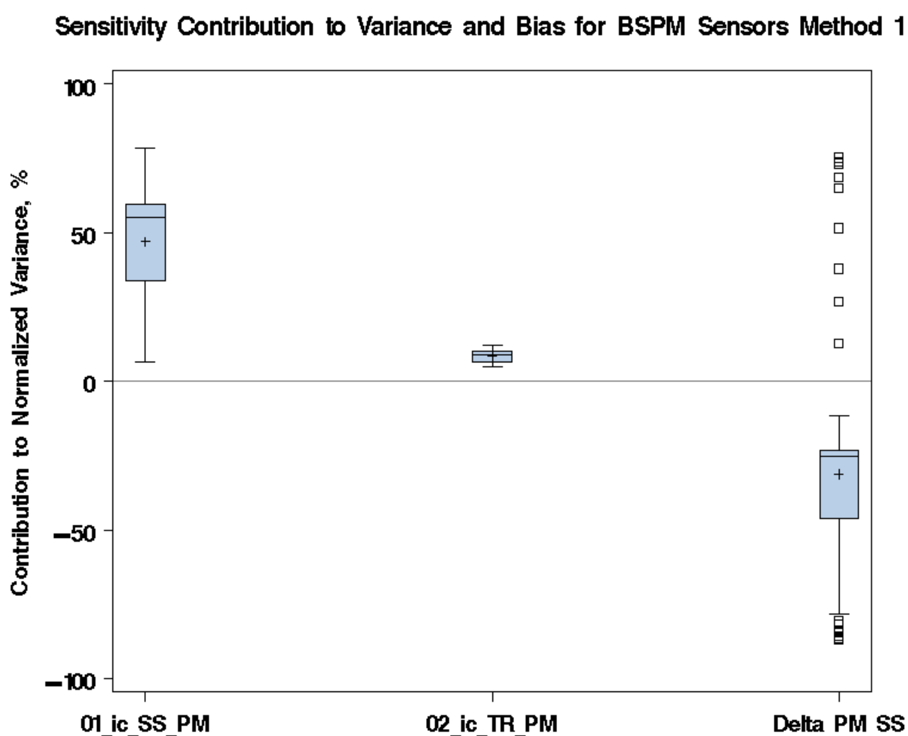


FIGURE 146. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR SENSORS BSPM METHOD 1

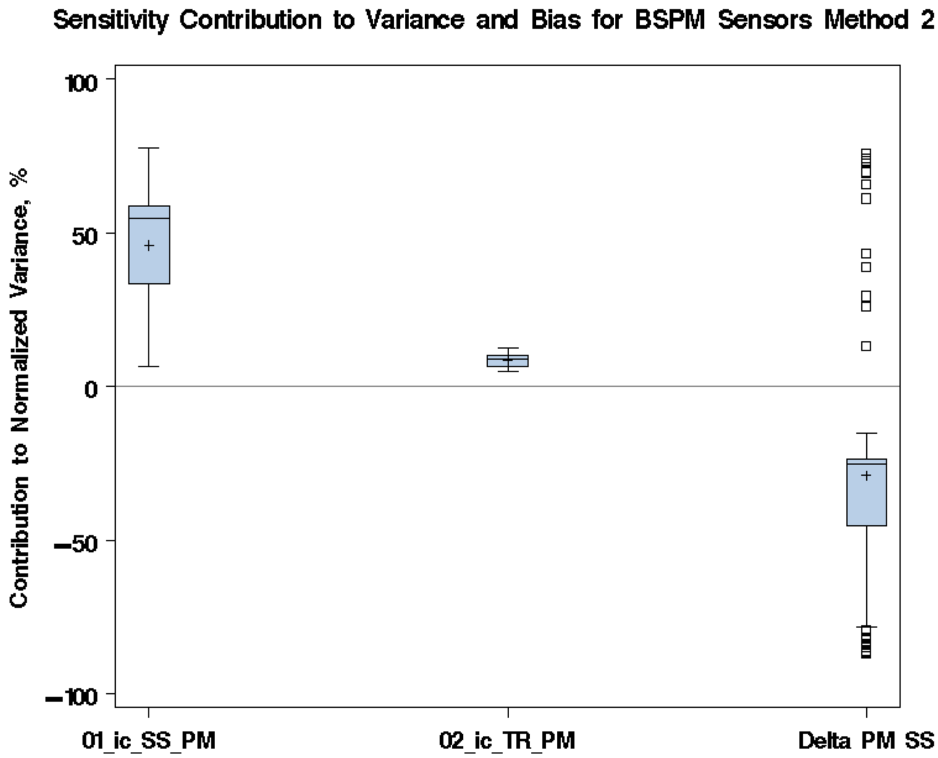


FIGURE147. BOX PLOT OF ERROR SURFACE SENSITIVITY BASED ON BIAS AND VARIANCE FOR SENSORS BSPM METHOD 2

TABLE 30 SUMMARY OF ERROR SURFACE SENSITIVITIES TO BIAS AND VARIANCE FOR BSPM METHOD 1

Method 1							
		AVL		Horiba		Sensors	
Error Surface No.	**Error Surface**	**No. NTE Events**	**Avg Contribution to Normalized Variance, %**	**No. NTE Events**	**Avg Contribution to Normalized Variance, %**	**No. NTE Events**	**Avg Contribution to Normalized Variance, %**
1	SS PM	141	11.34	138	41.86	138	46.92
2	TR PM	4	7.00	10	5.84	100	8.48
20	SS Exhaust Flow	4	5.57	26	8.94	8	6.11
31	Torque Warm-up	10	-6.64	100	-8.34	30	-8.28
35	Torque Engine Manuf	1	-6.27	29	-5.72	10	-5.60
	Delta Exhaust Flow Pulsation	3	5.78	31	6.67	9	7.01
	Delta SS PM	141	-74.37	83	-32.05	120	-31.19

TABLE 31. SUMMARY OF ERROR SURFACE SENSITIVE TO BIAS AND VARIANCE FOR BSPM METHOD 2

Method 2							
		AVL		Horiba		Sensors	
Error Surface No.	Error Surface	No. NTE Events	Avg Contribution to Normalized Variance, %	No. NTE Events	Avg Contribution to Normalized Variance, %	No. NTE Events	Avg Contribution to Normalized Variance, %
1	SS PM	141	21.48	138	39.55	138	45.92
2	TR PM	38	9.20	10	5.89	101	8.48
31	Torque Warm-up	8	-6.82	95	-8.19	24	-7.84
35	Torque Engine Manuf	1	-6.12	24	-5.72	5	-5.61
42	Fuel Rate Engine Manuf			7	5.52	4	6.18
45	SS CO2	4	-6.89	54	-6.60	10	-6.84
	Delta SS PM	141	-63.27	89	-42.60	127	-28.96

TABLE 32. SUMMARY OF ERROR SURFACE SENSITIVE TO BIAS AND VARIANCE FOR BSPM METHOD 3

Method 3			
		AVL	
Error Surface No.	Error Surface	No. NTE Events	Avg Contribution to Normalized Variance, %
1	SS PM	141	20.91
2	TR PM	36	9.27
31	Torque Warm-up	9	-6.62
35	Torque Engine Manuf	1	-6.12
45	SS CO2	4	-6.96
	Delta SS PM	141	-64.04

6.3 Validation Results

This section contains a summary of the model validation results; Section 0 on *Validation* contains a more detailed description of the validation methodology utilized both in the simulation and in the on-road data collection efforts.

During the Monte Carlo simulation of the 141 reference NTE events some of the error surfaces were excluded in the computation of the BS emissions 'with errors' so that the simulation represented conditions used in collecting the on-road data. The error surfaces excluded were torque errors (Nos. 29-32, 34, 35), fuel rate engine manufacturers (#42), dynamic speed (#43) and dynamic fuel rate (#44). For each reference NTE event, the difference in BSPM emissions was computed as

delta BSPM = BSPM with “Validation error” – “Ideal” BSPM.

These delta BSPM emissions were computed for each of the three PEMS units and all applicable calculation methods. The 5th, 50th and 95th percentiles were identified from the distributions of the delta BSPM emissions during the Monte Carlo simulation using the validation error surfaces only. Figure 148 through Figure 150 depict the validation percentiles for the AVL PEMS unit for methods 1, 2 and 3, respectively. Similar validation plots for the Horiba PEMS unit are illustrated in Figure 151 and Figure 152 for methods 1 and 2, respectively. Sensors PEMS validation plots for methods 1 and 2 are shown in Figure 153 through Figure 154.

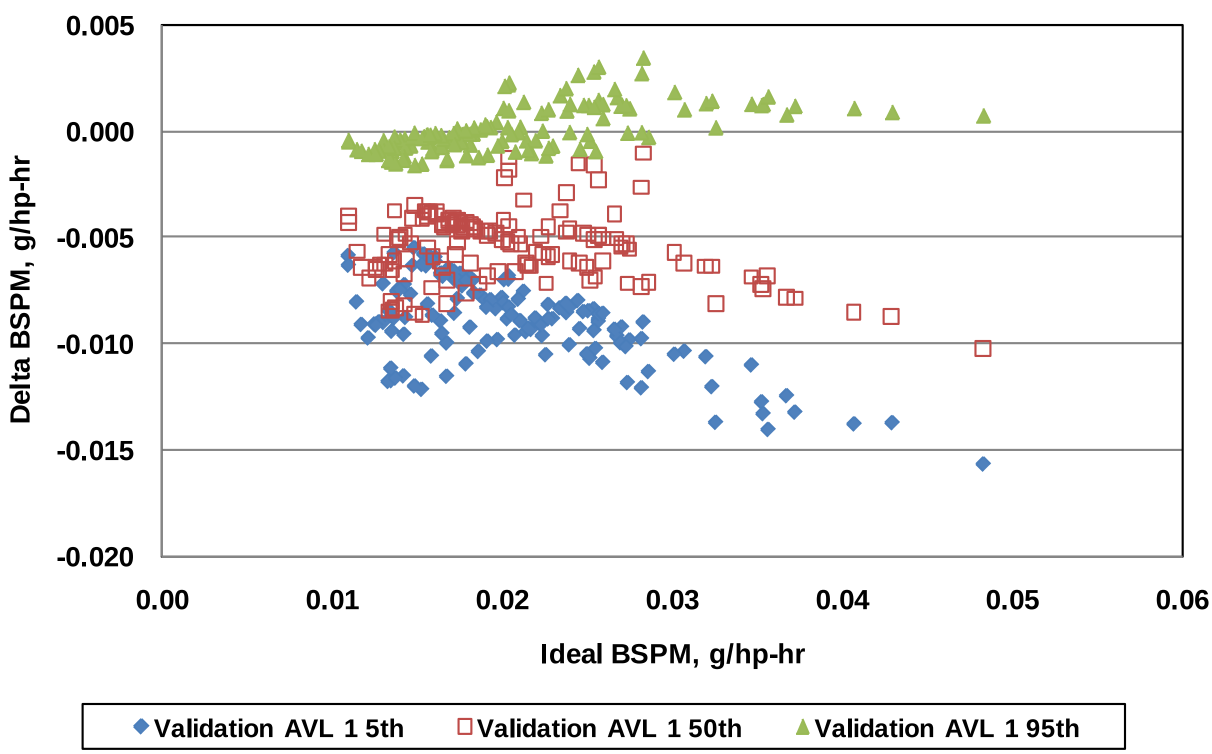


FIGURE 148. VALIDATION PERCENTILES FOR THE 141 REFERENCE NTE EVENTS FOR AVL METHOD 1

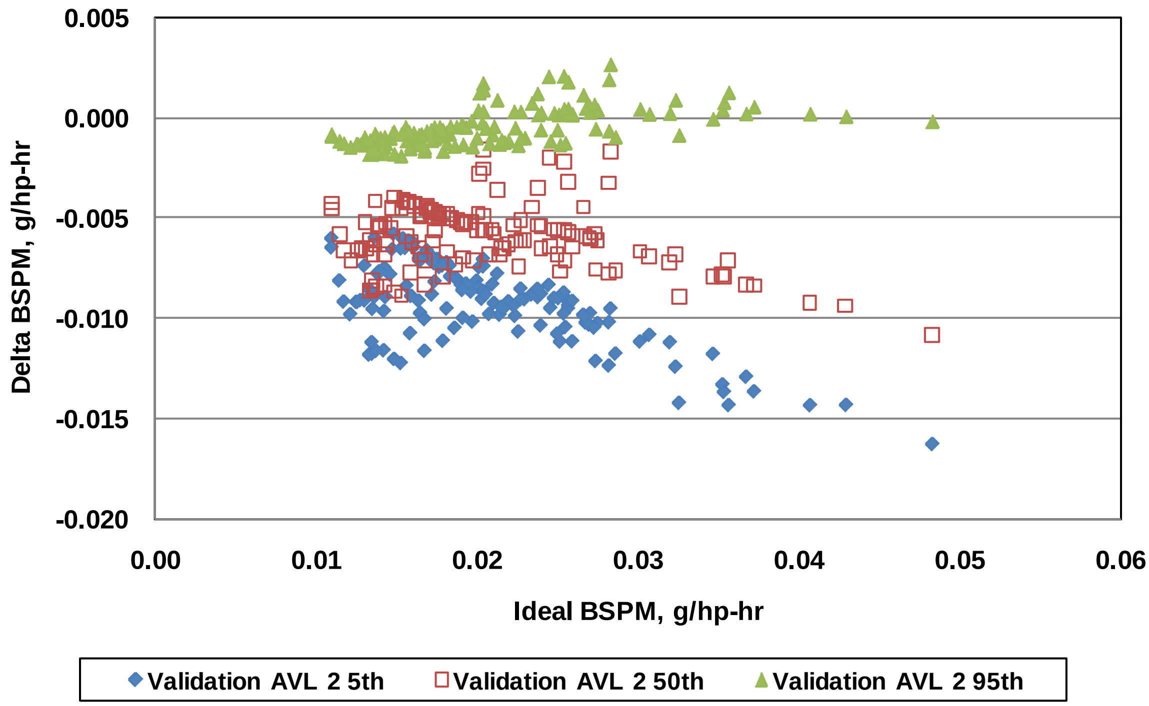


FIGURE 149. VALIDATION PERCENTILES FOR THE 141 REFERENCE NTE EVENTS FOR AVL METHOD 2

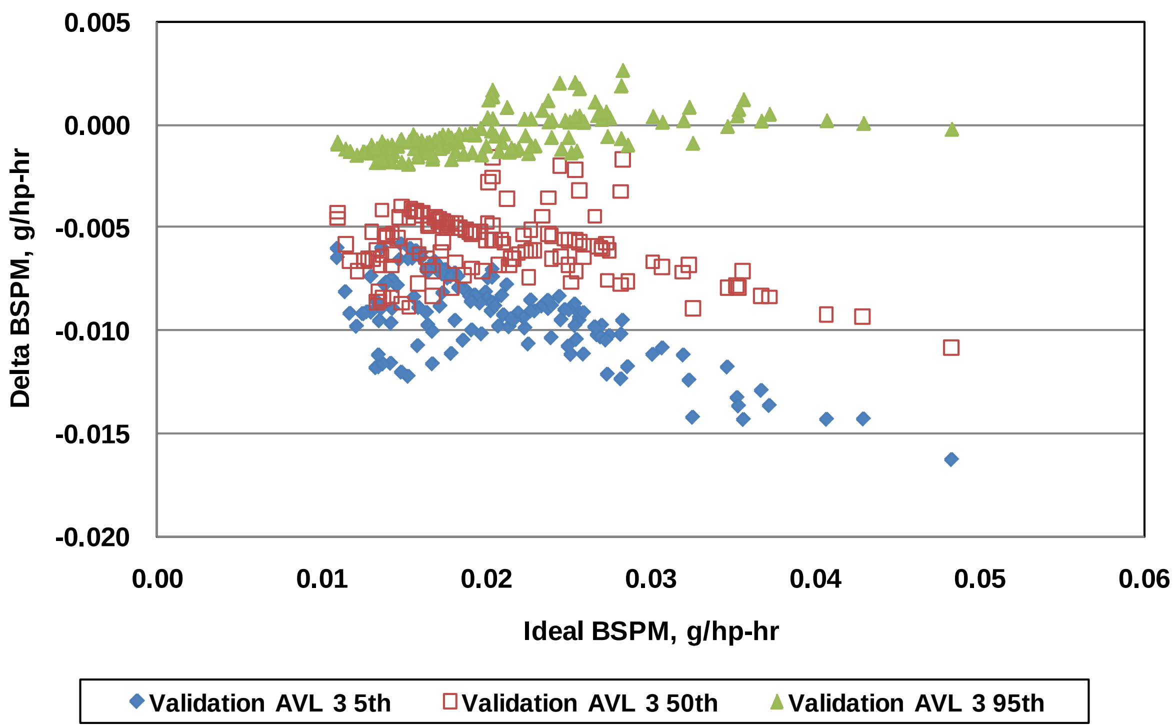


FIGURE 150. VALIDATION PERCENTILES FOR 141 REFERENCE NTE EVENTS FOR AVL METHOD 3

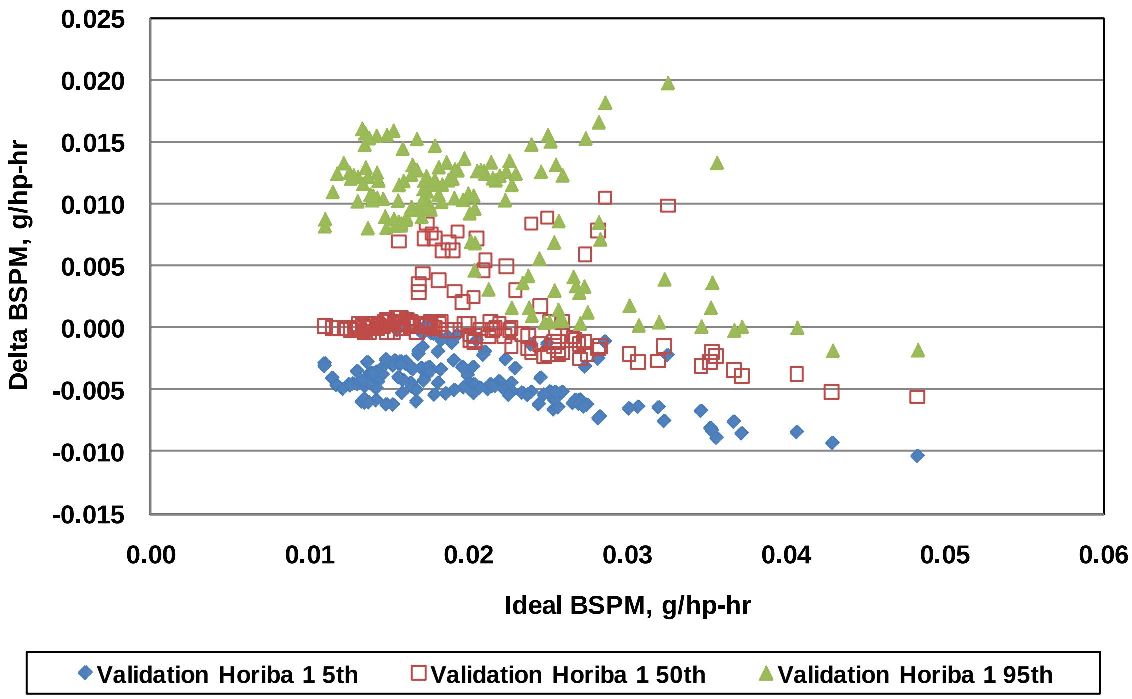


FIGURE 151. VALIDATION PERCENTILES FOR 141 REFERENCE NTE EVENTS FOR HORIBA METHOD 1

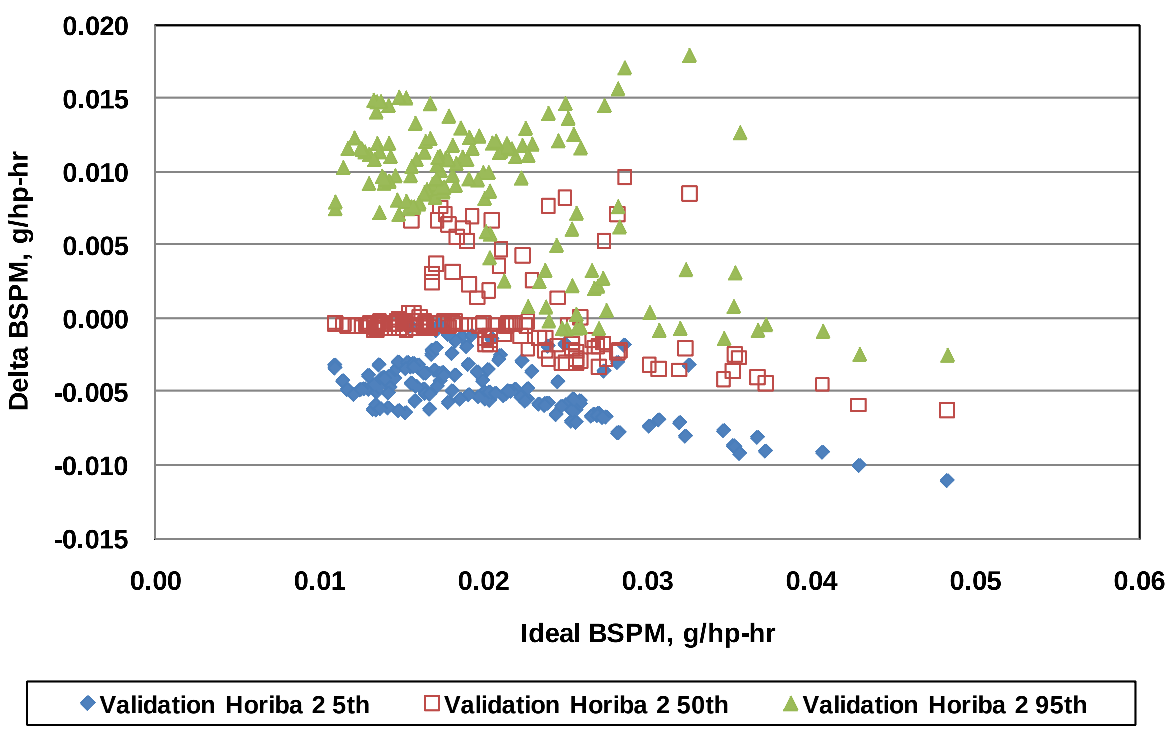


FIGURE 152. VALIDATION PERCENTILES FOR 141 REFERENCE NTE EVENTS FOR HORIBA METHOD 2

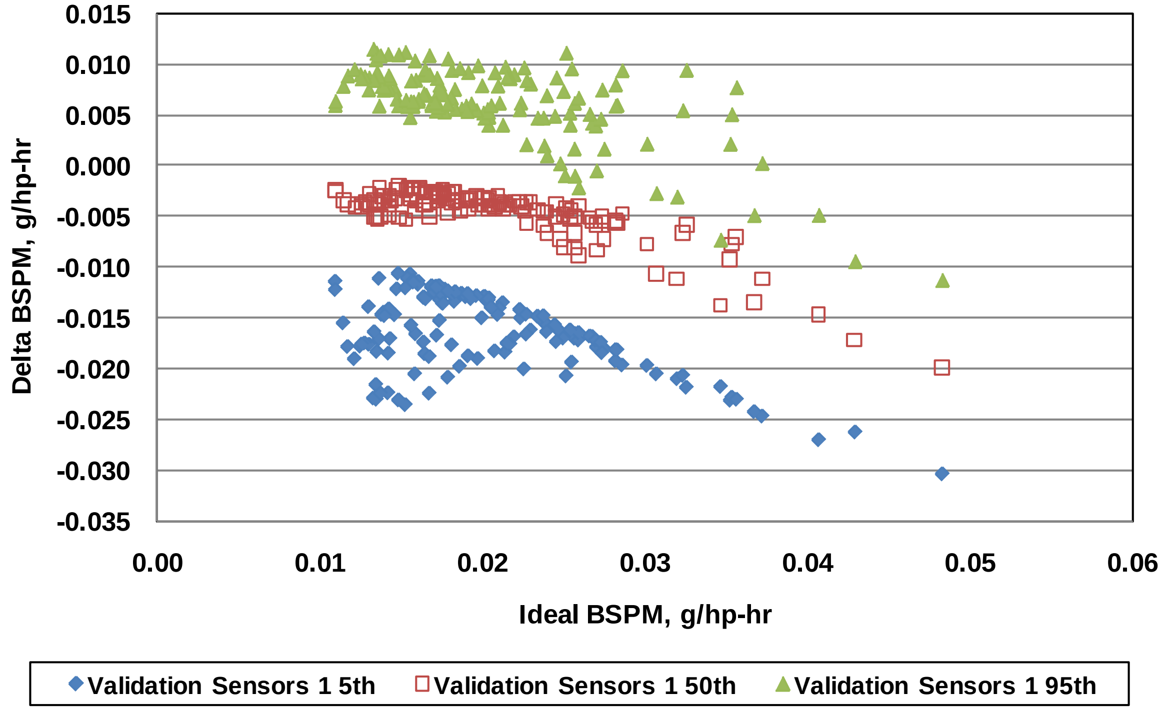


FIGURE 153. VALIDATION PERCENTILES FOR 141 REFERENCE NTE EVENTS FOR SENSORS METHOD 1

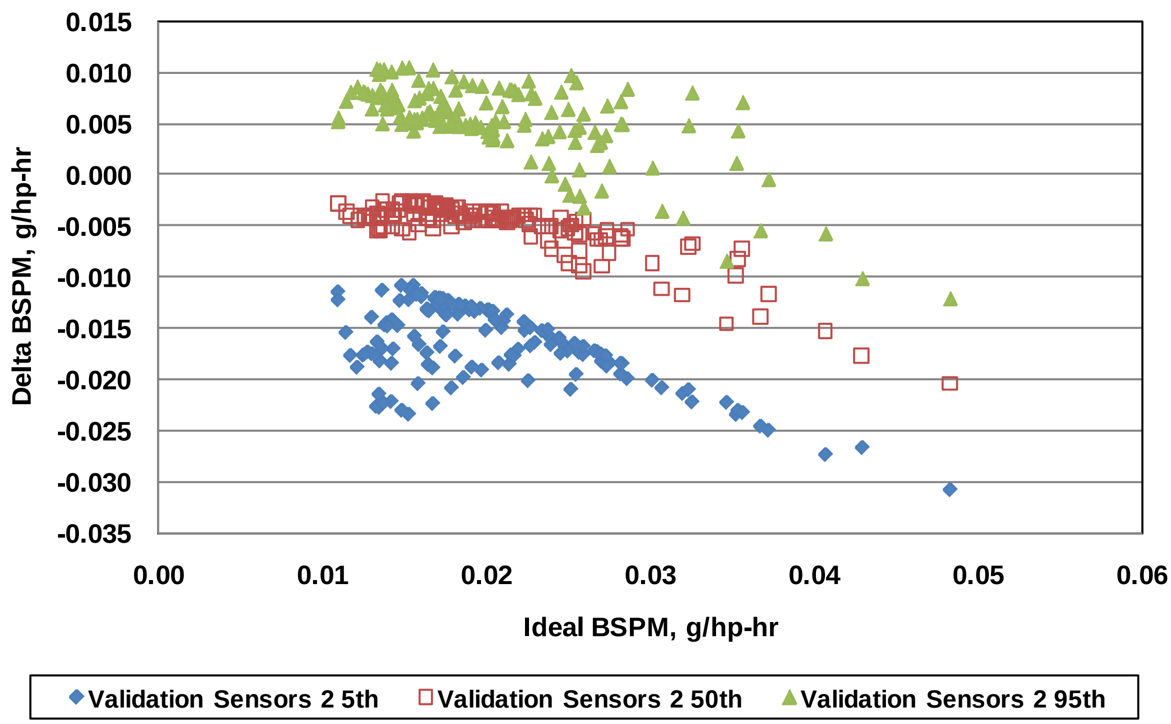


FIGURE 154. VALIDATION PERCENTILES FOR 141 REFERENCE NTE EVENTS FOR SENSORS METHOD 2

The 5th and 95th percentiles of the validation delta BSPM were separately fit for the AVL and Sensors PEMS units using a simple linear regression model. However, the criteria for accepting the linear fits were not met for any of the calculations methods for these two PEMS units. Thus, loess regression fits were used to determine the best functional representation for the 5th and 95th delta BSPM based on the validation simulation modeling. These loess fits for the 95th and 5th percentiles for the Sensors unit methods 1 and 2 can be found in Figure 155 through Figure 158, respectively. The loess fits for the 95th and 5th percentiles for the AVL units methods 1, 2 and 3 can be found in Figure 159 through Figure 164, respectively. The loess smoothing parameters for the regression fits are listed in Table 33.

TABLE 33. LOESS SMOOTHING PARAMETERS FOR VALIDATION PERCENTILES

PEMS	Method	5th Percentile	95th Percentile
Sensors	1	0.290	0.570
	2	0.290	0.570
AVL	1	0.294	0.755
	2	0.294	0.777
	3	0.294	0.777

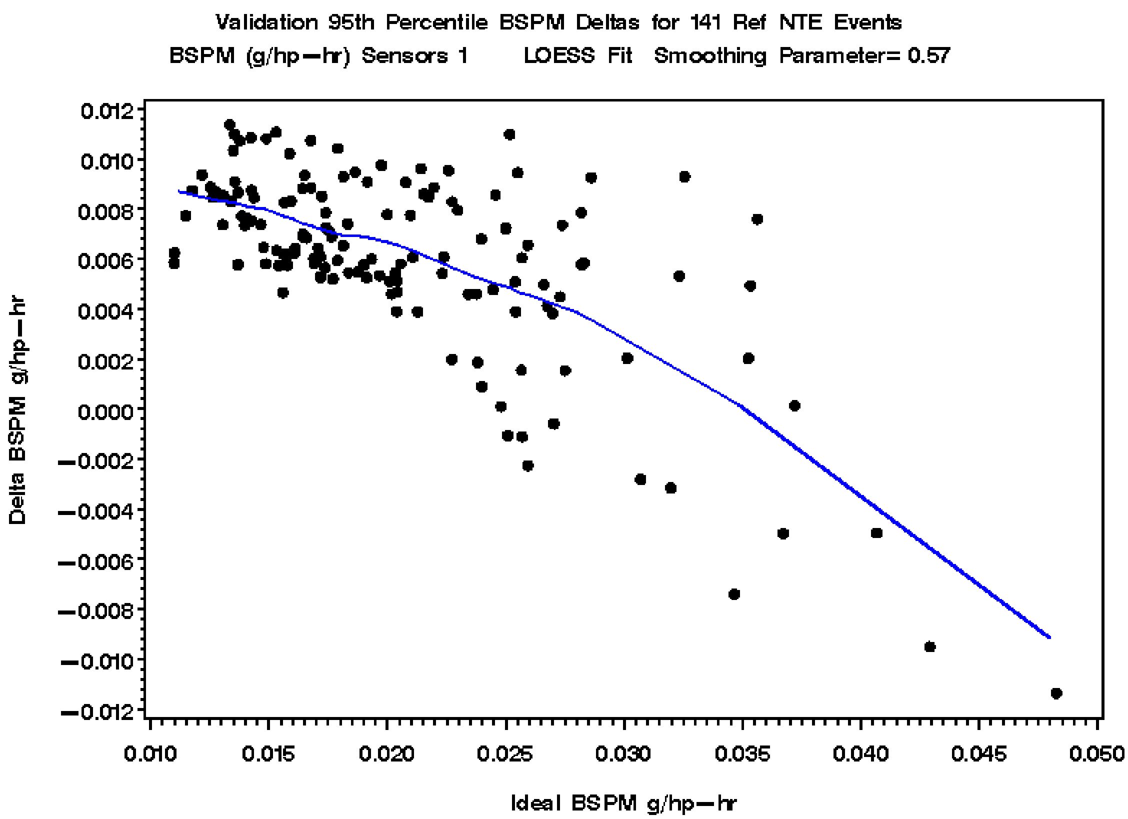


FIGURE 155. VALIDATION 95TH PERCENTILE BSPM DELTAS LOESS FIT FOR SENSORS METHOD 1

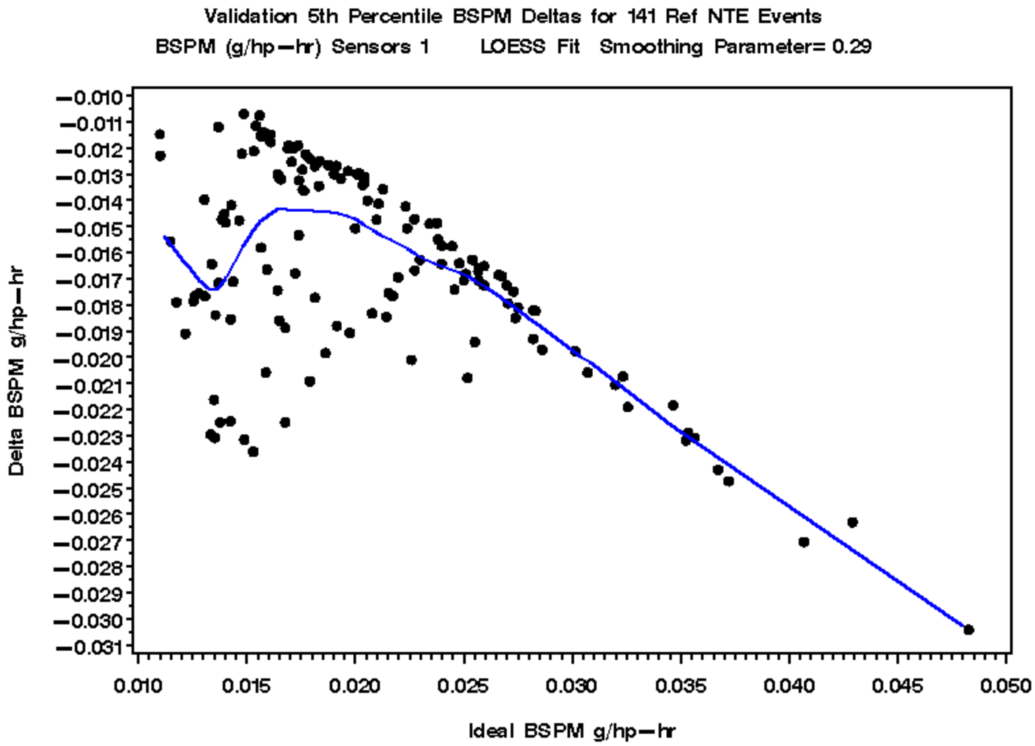


FIGURE 156. VALIDATION 5TH PERCENTILE BSPM DELTAS LOESS FIT FOR SENSORS METHOD 1

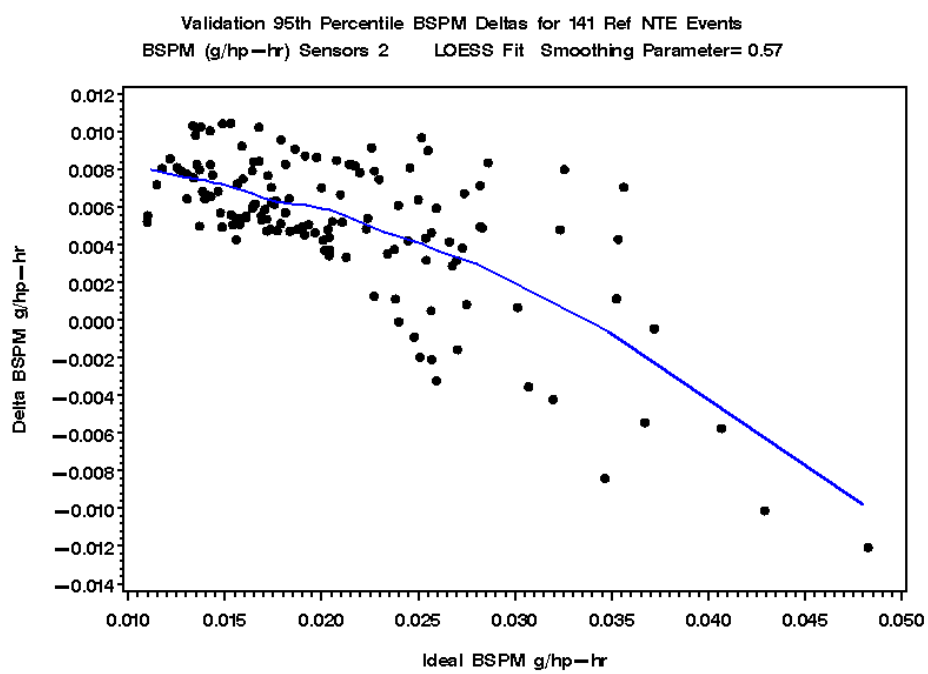


FIGURE 157. VALIDATION 95TH PERCENTILE BSPM DELTAS LOESS FIT FOR SENSORS METHOD 2

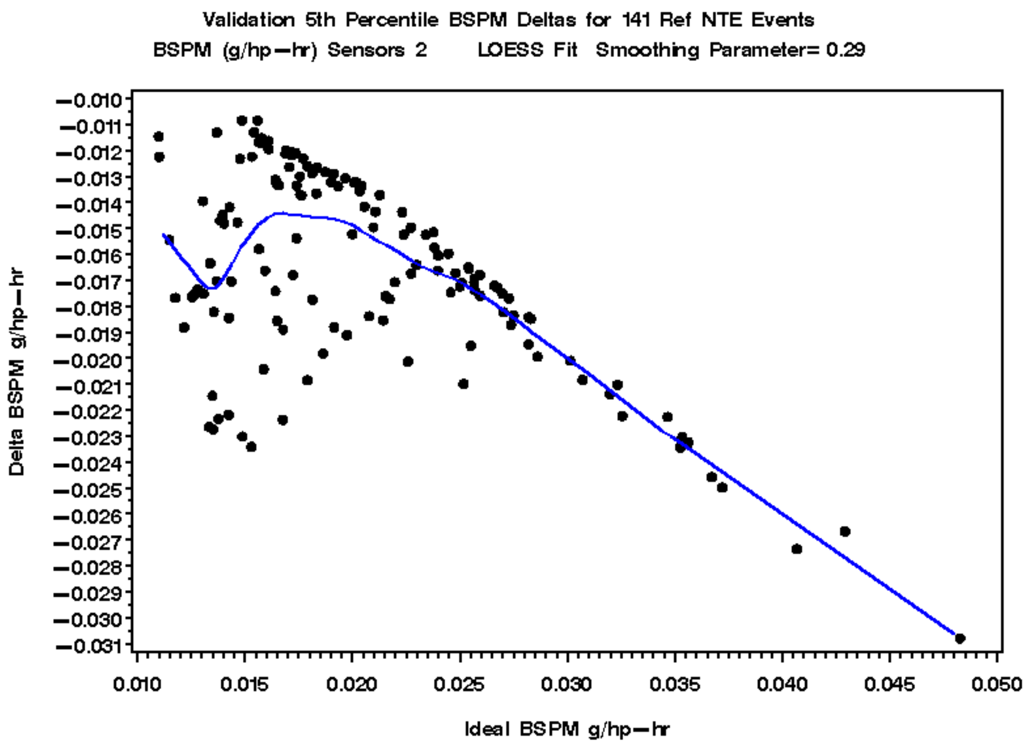


FIGURE 158. VALIDATION 5TH PERCENTILE BSPM DELTAS LOESS FIT FOR SENSORS METHOD 2

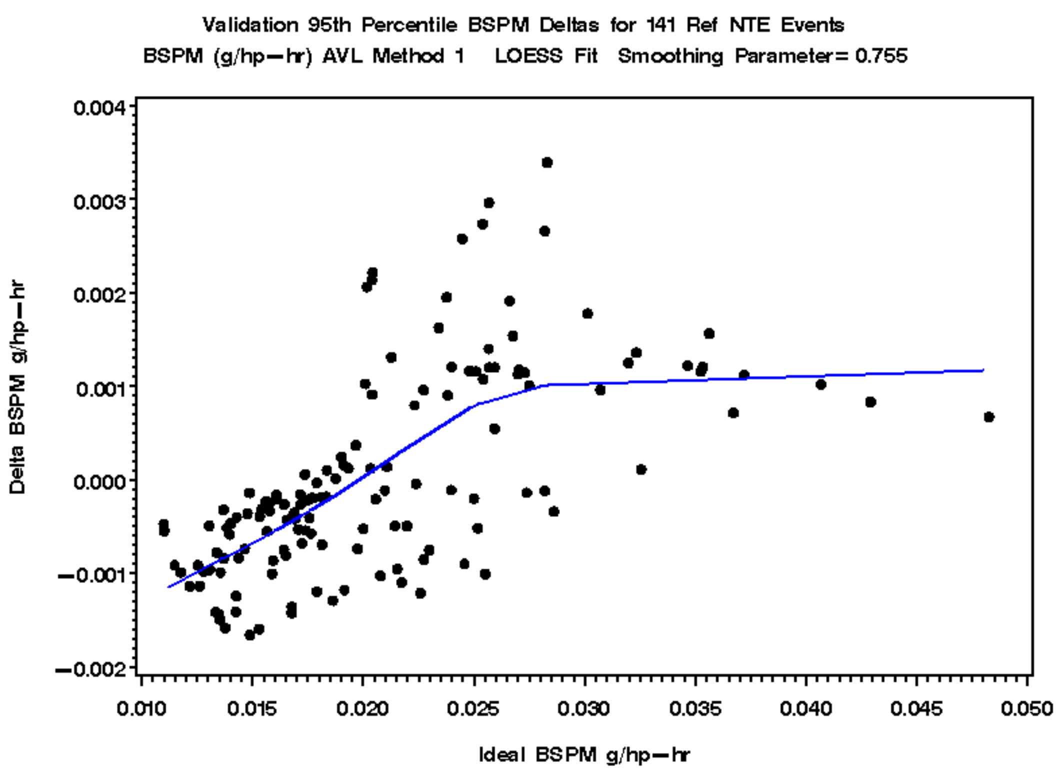


FIGURE 159. VALIDATION 95TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 1

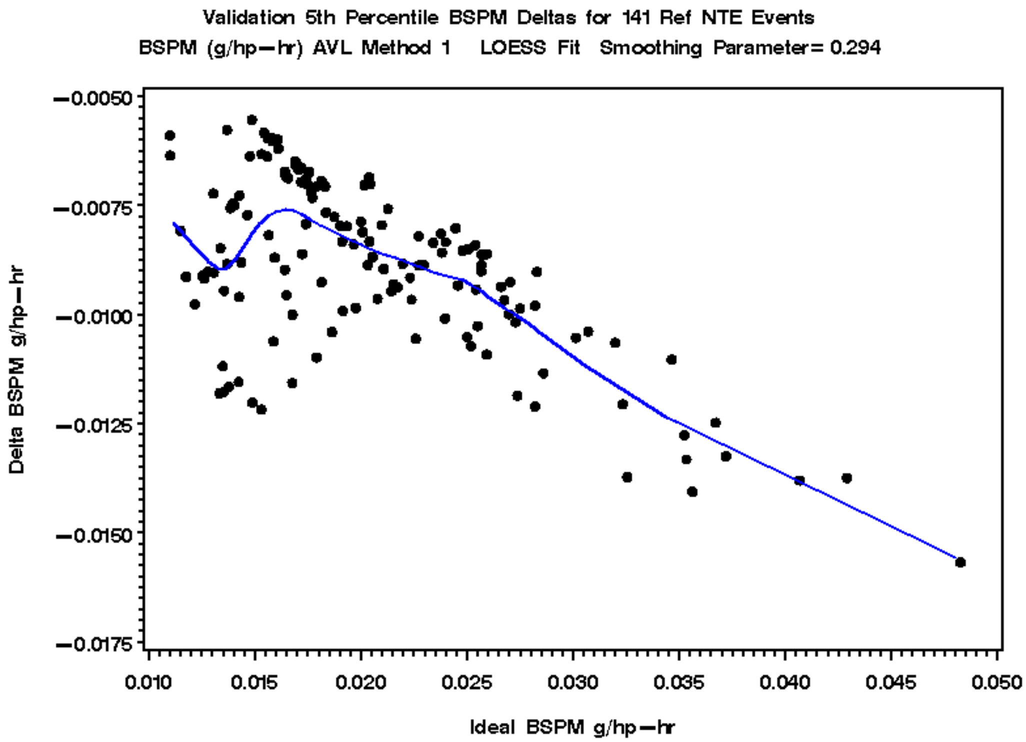


FIGURE 160. VALIDATION 5TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 1

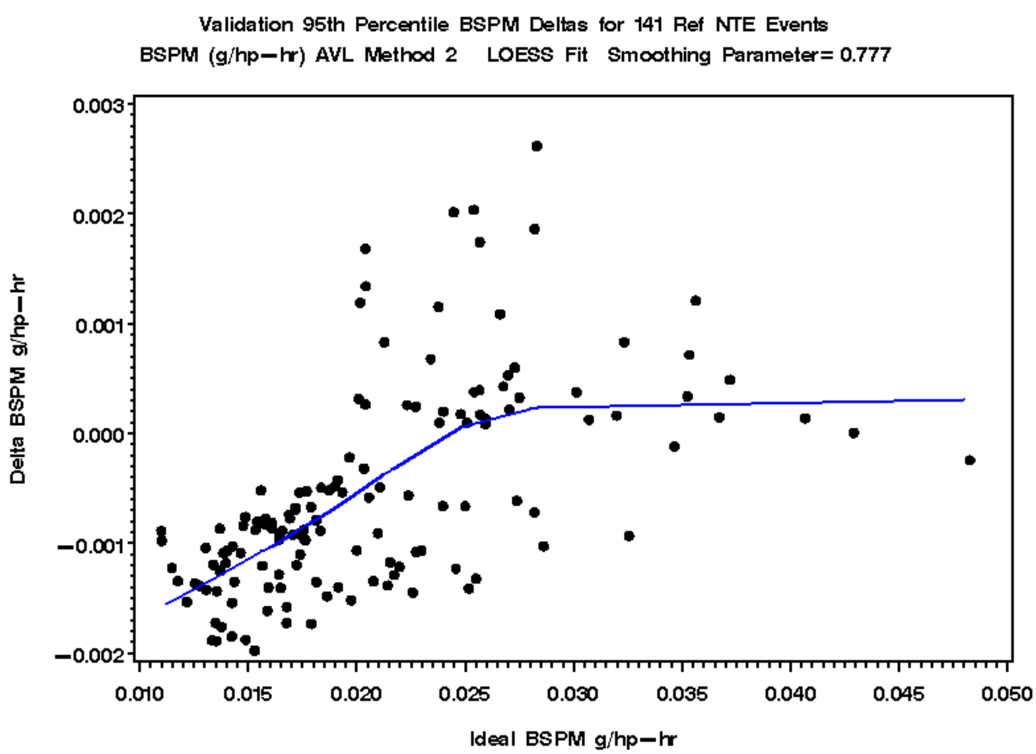


FIGURE 161. VALIDATION 95TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 2

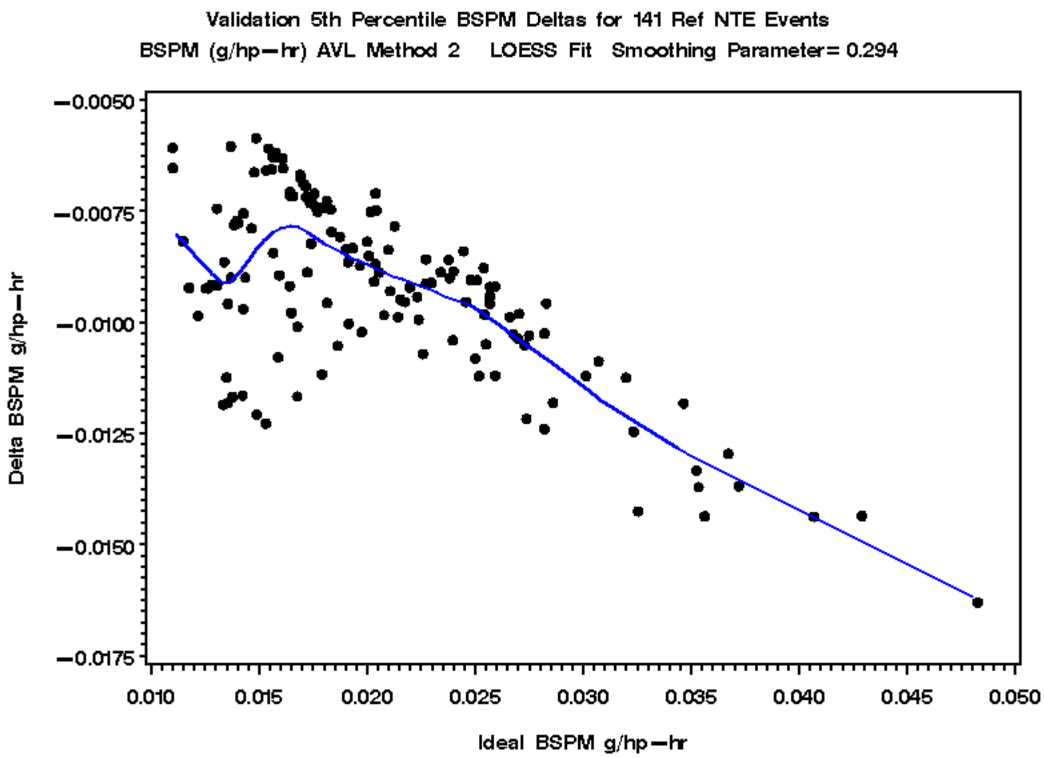


FIGURE 162. VALIDATION 5TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 2

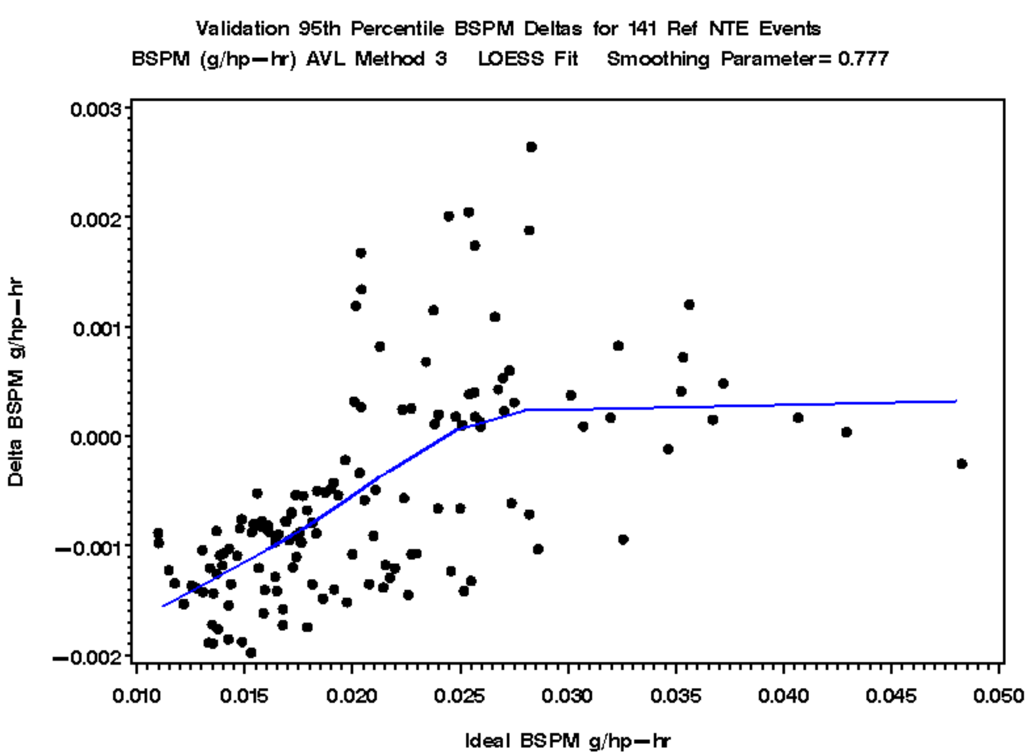


FIGURE 163. VALIDATION 95TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 3

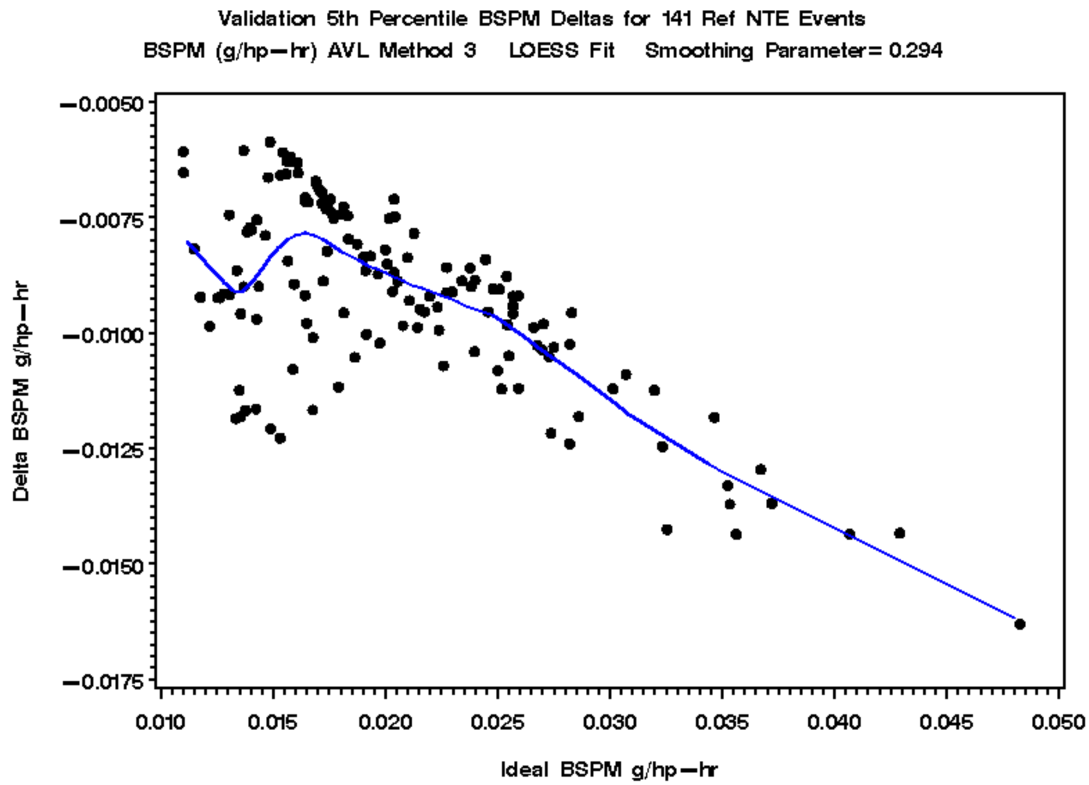


FIGURE 164. VALIDATION 5TH PERCENTILE BSPM DELTAS LOESS FIT FOR AVL METHOD 3

6.4 Measurement Error Allowance Results

This section contains a summary of the measurement error allowance results using both a regression method and a median method to determine the measurement allowance. Section 2.12 on *Measurement Allowance* contains a detailed description of the methodology followed in determining these values. This procedure was applied to the simulation data for all 141 reference NTE events obtained for all three calculation methods for the AVL PEMS and for calculations methods 1 and 2 for the Horiba and Sensors PEMS.

Figure65 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for AVL Method 1. Included in the plot is the equation for the fitted regression line, and the R-square (R^2) value and root mean square error (RMSE) value for the regression fit. The two symbols in the plot represent reference NTE events where there was a dominant bias effect due to the SSPM error surface (diamond symbol) or there was a dominant variance effect due to the SSPM error surface (square symbol). The R-square value indicates that 47.95% of the variation in the 95th percentile BSPM values is explained by the ideal BSPM values for the AVL Method 1 data. The RMSE value of 0.0008 displays the size of the estimated standard deviation of the predicted 95th percentile BSPM values.

Table 34 includes a comparison of the results of the regression method based on Figure 165 and the median method as described in the Section 0 on *Measurement Allowance*. Under the heading of "Regression Method" in the table, it is shown that only the R-square criterion was not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95 th percentile delta BSPM values, is 0.661% when expressed as a percent of the threshold of 0.02 g/hp-hr.

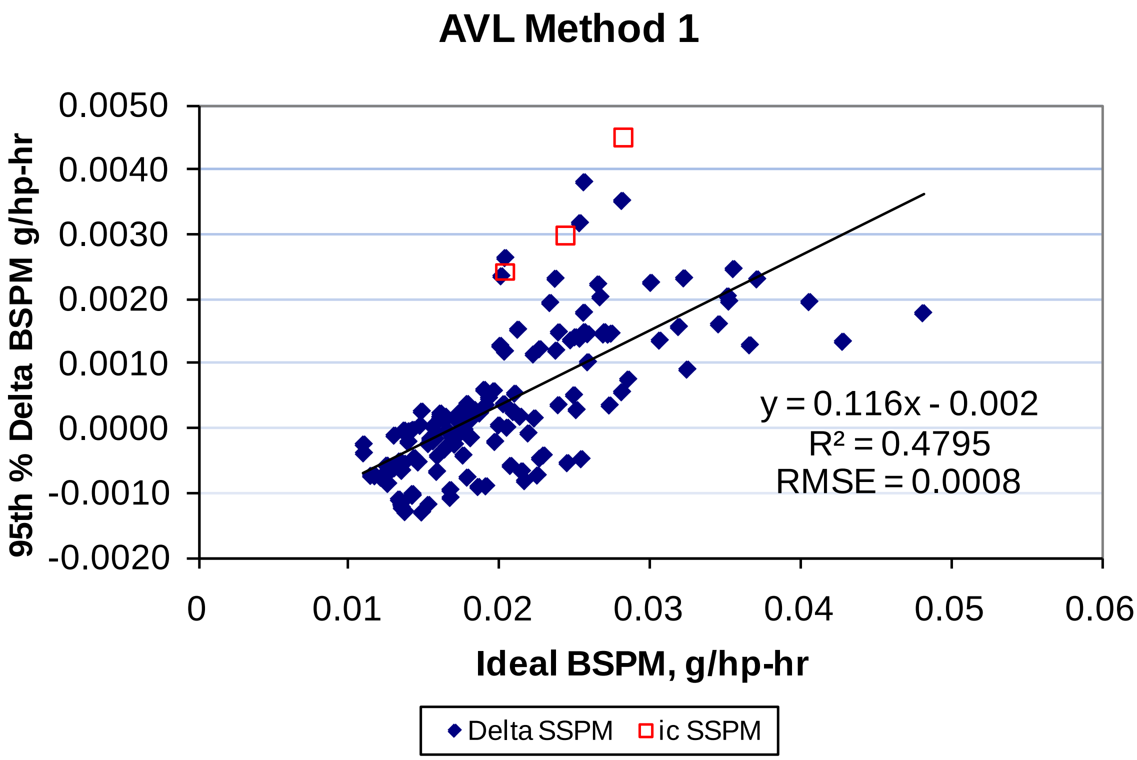


FIGURE165. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR AVL METHOD 1

TABLE 34. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR AVL METHOD 1

Regression Method			Median Method	
R2	0.4795	Did Not Meet Criteria		
RMSE (SEE)	0.0008	Met Criteria		
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	0.0003399		Median 95th % Delta	0.0001322
Measurement Error @ Threshold = 0.02	1.6993%		Measurement Error @ Threshold = 0.02	0.661%

Figure 166 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for AVL Method 2. The R-square value indicates that 46.02% of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the AVL Method 2 data. The RMSE value is 0.0008.

Table 35 includes a comparison of the results of the regression method based on Figure 166 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square criterion for using this method is not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is -2.375% when expressed as a percent of the threshold value of 0.02.

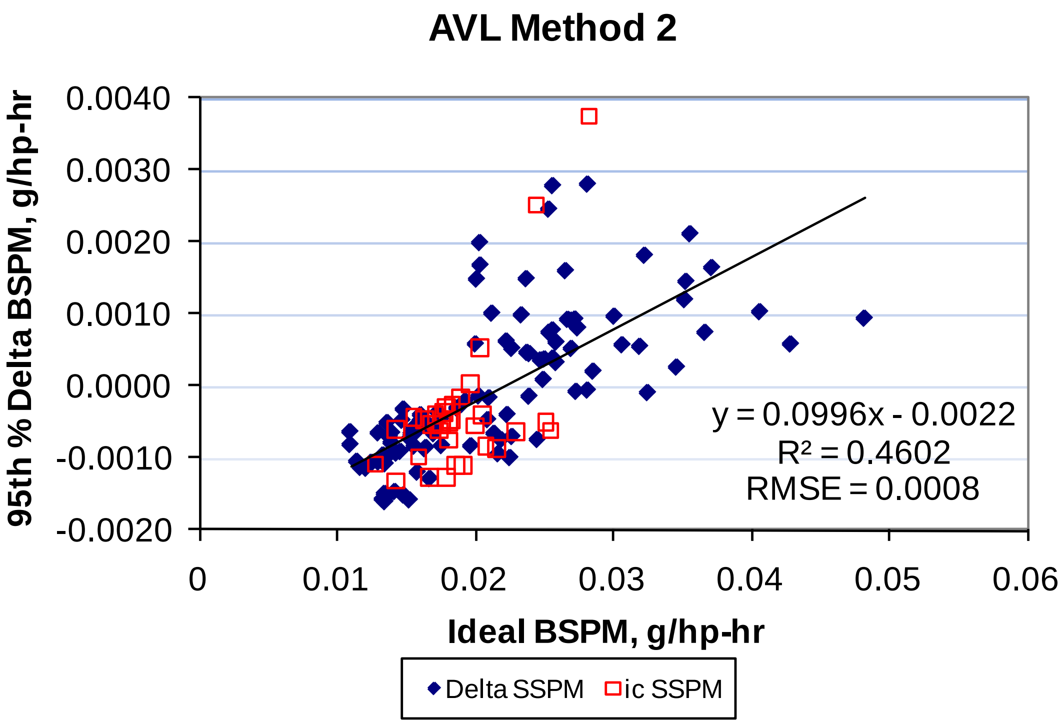


FIGURE 166. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR AVL METHOD 2

TABLE 35. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR AVL METHOD 2

Regression Method			**Median Method**	
R^2	0.4602	Did Not Meet Criteria Met Criteria		
RMSE (SEE)	0.0008			
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	-0.0002124		Median 95th % Delta	-0.0004751
Measurement E rror @ Threshold = 0.02	-1.0618%		Measurement E rror @ Threshold = 0.02	-2.375%

Figure 167 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for AVL Method 3. The R-square value indicates that 46.20% of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the AVL Method 3 data. The RMSE value is 0.0008.

Table 36 includes a comparison of the results of the regression method based on Figure 167 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square criterion for using this method is not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is -2.383% when expressed as a percent of the threshold value of 0.02.

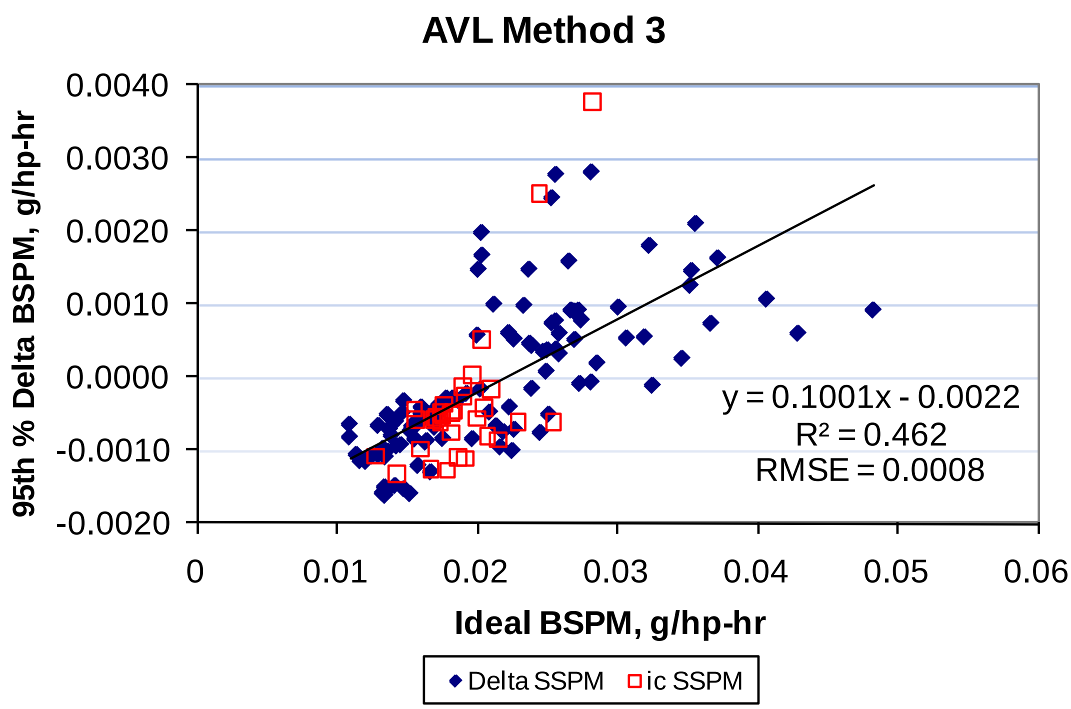


FIGURE167. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR AVL METHOD 3

TABLE 36. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR AVL METHOD 3

Regression Method			Median Method	
R^2	0.4620	Did Not Meet Criteria Met Criteria		
RMSE (SEE)	0.0008			
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	-0.0002118		Median 95th % Delta	-0.0004766
Measurement Error @ Threshold = 0.02	-1.0592%		Measurement Error @ Threshold = 0.02	-2.383%

Figure 168 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for Horiba Method 1. The R-square value indicates that 26.57% of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the Horiba Method 1 data. The RMSE value is 0.0041.

Table 37 includes a comparison of the results of the regression method based on Figure 168 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square and the RMSE criteria for using this method were not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is 54.379 % when expressed as a percent of the threshold value of 0.02.

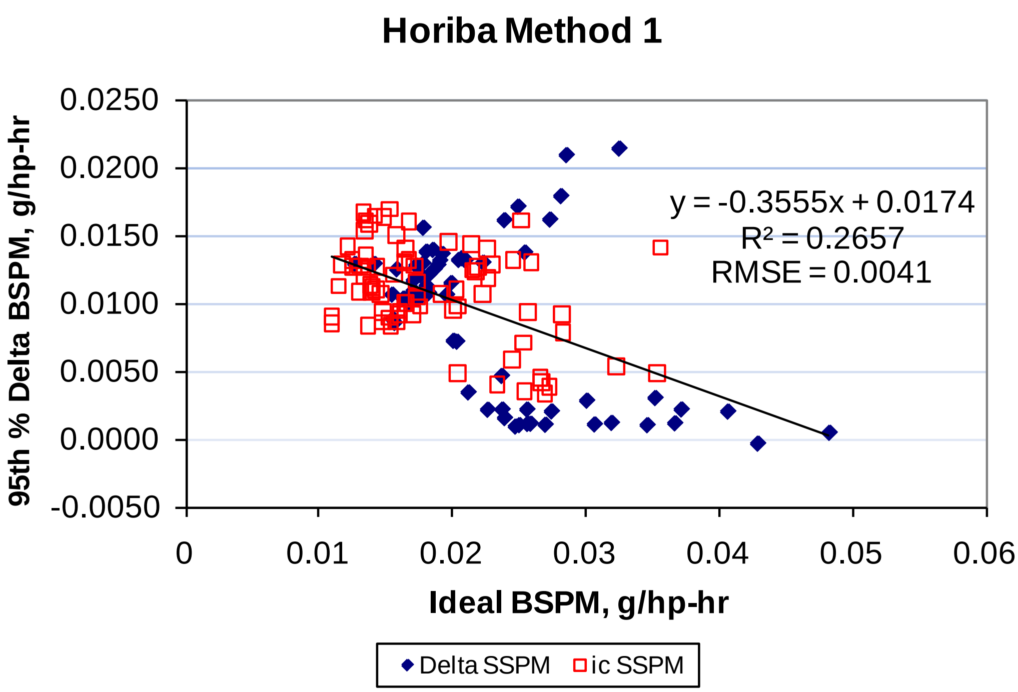


FIGURE168. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR HORIBA METHOD 1

TABLE 37. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR HORIBA METHOD 1

Regression Method			Median Method	
R^2	0.2657	Did Not Meet Criteria		
RMSE (SEE)	0.0041	Did Not Meet Criteria		
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	0.0102566		Median 95th % Delta	0.0108759
Measurement Error @ Threshold = 0.02	51.2831%		Measurement Error @ Threshold = 0.02	54.379%

Figure 169 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for Horiba Method 2. The R-square value indicates that 25.97 % of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the Horiba Method 2 data. The RMSE value is 0.0041.

Table 38 includes a comparison of the results of the regression method based on Figure 169 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square and the RMSE criteria for using this method were not met by the data. Thus, the Median Method must be used. Under the heading " Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is 50.079 % when expressed as a percent of the threshold value of 0.02.

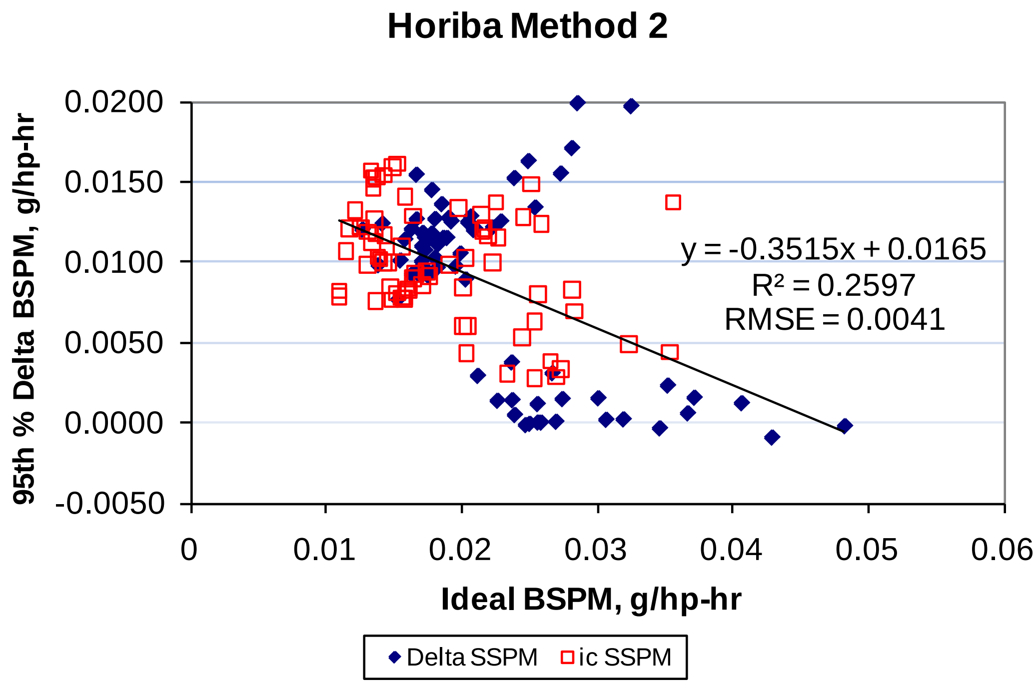


FIGURE169. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR HORIBA METHOD 2

TABLE 38. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR HORIBA METHOD 2

Regression Method			**Median Method**	
R^2	0.2597	Did Not Meet Criteria		
RMSE (SEE)	0.0041	Did Not Meet Criteria		
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	0.0094282		Median 95th % Delta	0.0100158
Measurement Error @ Threshold = 0.02	47.1408%		Measurement Error @ Threshold = 0.02	50.079%

Figure 170 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for Sensors Method 1. The R-square value indicates that 45.49 % of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the Sensors Method 1 data. The RMSE value is 0.0029.

Table 39 includes a comparison of the results of the regression method based on Figure 170 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square and the RMSE criteria for using this method were not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is 34.361 % when expressed as a percent of the threshold value of 0.02.

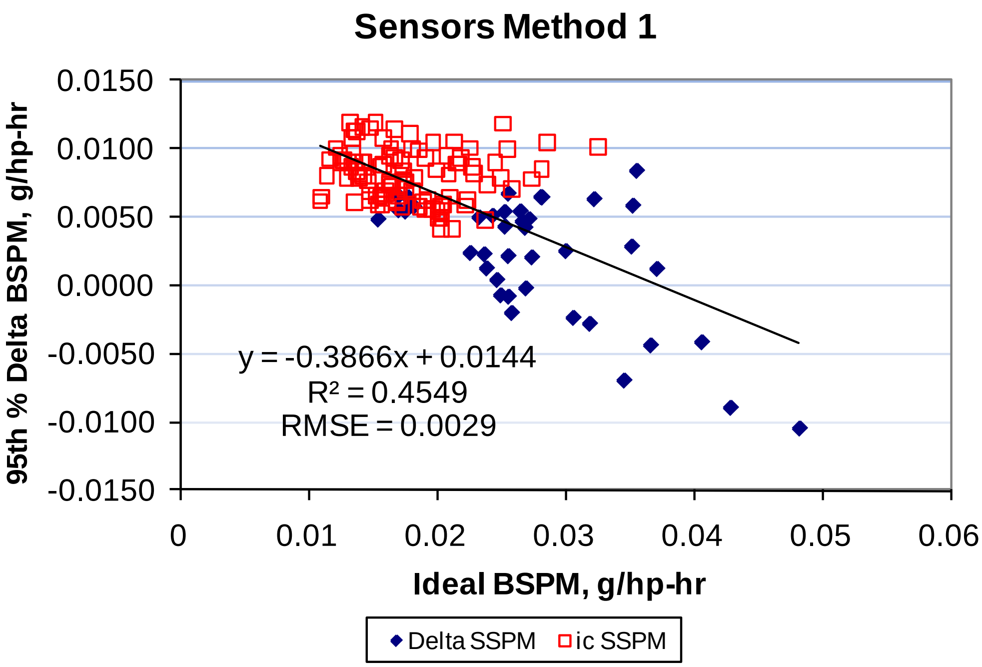


FIGURE 170. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR SENSORS METHOD 1

TABLE 39. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR SENSORS METHOD 1

Regression Method			**Median Method**	
R2	0.4549	Did Not Meet Criteria		
RMSE (SEE)	0.0029	Did Not Meet Criteria		
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	0.0066785		Median 95th % Delta	0.00687227
Measurement Error @ Threshold = 0.02	33.3924%		Measurement Error @ Threshold = 0.02	34.361%

Figure 171 contains a regression plot of the 95th percentile delta BSPM values versus the Ideal BSPM values for the 141 reference NTE events for Sensors Method 2. The R-square value indicates that 45.03 % of the variation in the 95th percentile BSPM values is explained by the Ideal BSPM values for the Sensors Method 1 data. The RMSE value is 0.0030.

Table 40 includes a comparison of the results of the regression method based on Figure 171 and the median method. Under the heading of "Regression Method" in the table, it is shown that the R-square and the RMSE criteria for using this method were not met by the data. Thus, the Median Method must be used. Under the heading "Median Method" in the table, the measurement error at the BSPM threshold, based on using the median of the 141 95th percentile delta BSPM values, is 30.285 % when expressed as a percent of the threshold value of 0.02.

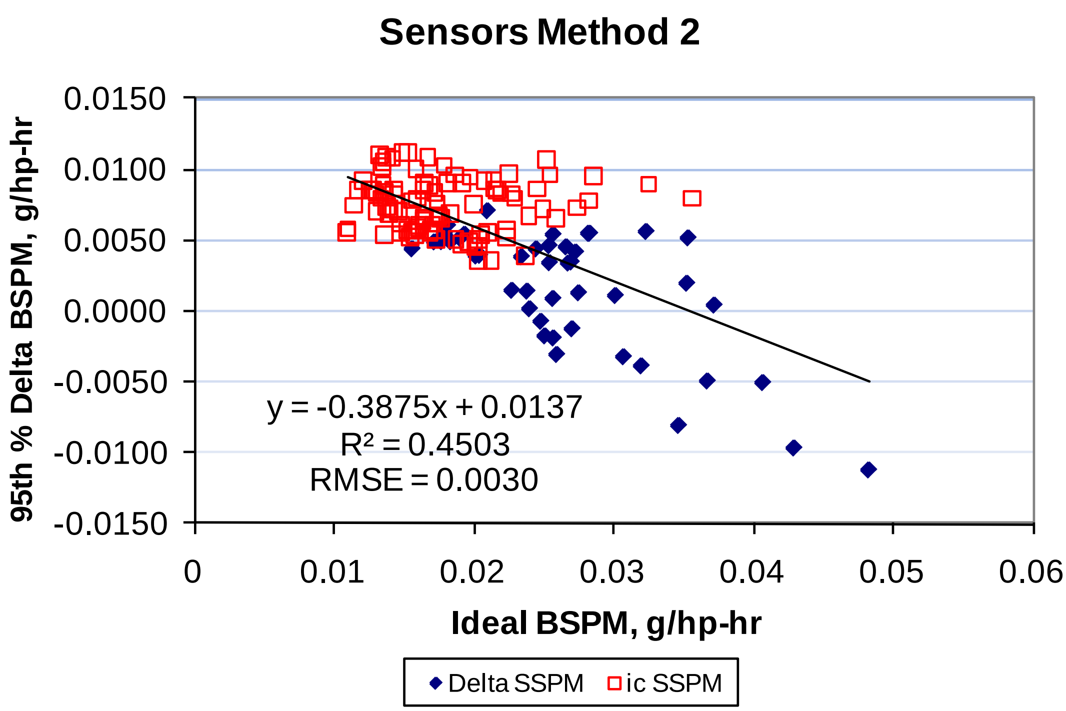


FIGURE 171. REGRESSION PLOT OF 95TH PERCENTILE DELTA BSPM VERSUS IDEAL BSPM FOR SENSORS METHOD 2

TABLE 40. MEASUREMENT ERROR AT THRESHOLD FOR BSPM USING REGRESSION AND MEDIAN METHODS FOR SENSORS METHOD 2

Regression Method			Median Method	
R^2	0.4503	Did Not Meet Criteria		
RMSE (SEE)	0.0030	Did Not Meet Criteria		
5% Median Ideal	0.0191007			
Predicted 95th % Delta at Threshold	0.0059333		Median 95th % Delta	0.0060569
Measurement Error @ Threshold = 0.02	29.6663%		Measurement Error @ Threshold = 0.02	30.285%

Table 41 contains a summary of the measurement error values contained in Table 34 through Table 40. The values are categorized by PEMS unit and by calculation method.

TABLE 41. BSPM MEASUREMENT ERROR IN PERCENT OF NTE THRESHOLD BY PEMS AND CALCULATION METHOD

Measurement Errors (%) at Respective NTE Threshold			
PEMS	Method 1 Exhaust Flow Torque-Speed	Method 2 Exhaust and Fuel Flow Torque-Speed	Method 3 Fuel Flow Torque-Speed
AVL	0.661	-2.375	-2.383
Horiba	54.379	50.079	n/a
Sensors	34.361	30.285	n/a

Table 42 includes in the measurement allowance selected based on the minimum normalized PM. The AVL was not used in the measurement allowance determination because the AVL at the start of the program was not accepted as an official PEMS, and the measurement Steering Committee had decided that the measurement allowance would only be based on the Sensors or the Horiba PEMS.

TABLE 42. MEASUREMENT ALLOWANCE AT NTE THRESHOLD BY EMISSIONS FOR METHOD 2

PEMS	Method 2 Measurement Error %	NTE Threshold g/hp-hr	Measurement Allowance, g/hp-hr
Sensors	30.285	0.02	0.00605

On-road PM emissions were gathered from selected routes driven to collect emissions data with a CE-CERT trailer and a PEMS installed on the tractor pulling the trailing. For each on-road NTE event, a delta BSPM emissions value was computed as follows:

Delta BSPM = PEMS BSPM – CE-CERT BSPM.

These differences were computed for the BSPM emissions for each PEMS unit tested in-use. The in-use BSPM was computed using Method 1 and 2 for the Sensors PPMD and Method 1, 2, and 3 for AVL MSS. The in-use delta BSPM emissions calculated for the AVL PEMS using methods 1, 2, and 3. CE-CERT validation data were produced without any diesel particle filter (DPF) active regeneration (referred to as “no regen”). (referred to as ”)informational purposes active AVL methods 1, 2 and 3 including three individual units (#2, #3 and #4) and 271 NTE events. This data set was computed as “no regen”. The second PEMS unit tested for validation was the Sensors. The on-road delta BSPM emissions were calculated for Sensors methods 1 and 2 also using three individual units in the “no regen” scenario and resulted in 217 NTE events.

The validation plots for the Sensors and the AVL systems are shown in Figures 172 through 176. The y-axis scale on each figure was intended to make the best representation of the data relative to the validation lines shown on each plot. Because Method 1 depends strongly on exhaust flow, and some concerns were raised about the accuracy of exhaust flow measurement during CE-CERT testing, results reported using Method 1 might not be accurate. Details about exhaust flow measurement are expected to be part of CE-CERT Final Report on PM-PEMS In-Use Validation Testing.

The loess regression fits in Figures 176 through 176 and the Sensors CE-CERT BSPM differences collected on-road were plotted in order to determine if the simulation method validated. If the number of CE-CERT delta BSPM values does not exceed 10% of the total number of on-road NTE events collected, then the simulation method would be considered valid. Figure 172 represents the validation plot for the BSPM method 1 analysis for Sensors. Note that 7 of the 217 on-road NTE events were either below or above the range of the ideal BSPM and were excluded from the validation percentage calculation. Therefore, 68 of the 210 CE-CERT NTE events (32.38%) fell below the simulation model 5th percentile based on the loess regression. Thus, the model was not considered valid for the BSPM Sensors Method 1.

Figure 173 represents the validation plot for the BSPM method 2 analysis for Sensors. Note that again 7 of the 217 on-road NTE events were either below or above the range of the ideal BSPM and were excluded from the validation percentage calculation. Therefore, 71 of the 210 CE-CERT NTE events (33.81%) fell above the simulation model 95th percentile or below the simulation model 5th percentile based on the loess regressions. Thus, the model was not considered valid for the BSPM Sensors Method 2.

Figure 174 represents the validation plot for the BSPM method 1 analysis for AVL with 'no regen'. In this case, 8 of the 271 on-road NTE events were either below or above the range of the ideal BSPM and were excluded from the validation percentage calculation. Therefore, 49 of the 263 CE-CERT NTE events (18.63%) fell above the simulation model 95th percentile or below the simulation model 5th percentile based on the loess regressions. Thus, the model was not considered valid for the BSPM AVL Method 1.

Figure 175 represents the validation plot for the BSPM method 2 analysis for AVL with 'no regen'. Again in this case 8 of the 271 on-road NTE events were either below or above the range of the ideal BSPM and were excluded from the validation percentage calculation. Therefore, 30 of the 263 CE-CERT NTE events (11.41%) fell above the simulation model 95th percentile or below the simulation model 5th percentile based on the loess regressions. Thus, the model was not considered valid for the BSPM AVL Method 2.

Figure 176 represents the validation plot for the BSPM method 3 analysis for AVL with 'no regen'. Again in this case 8 of the 271 on-road NTE events were either below or above the range of the ideal BSPM and were excluded from the validation percentage calculation. Therefore, 26 of the 263 CE-CERT NTE events (9.89%) fell above the simulation model 95th percentile or below the simulation model 5th percentile based on the loess regressions. Thus, the model was considered valid for the BSPM AVL Method 3 since the number of CE-CERT NTE events outside the 5th and 95th percentile loess regression was less than 10%.

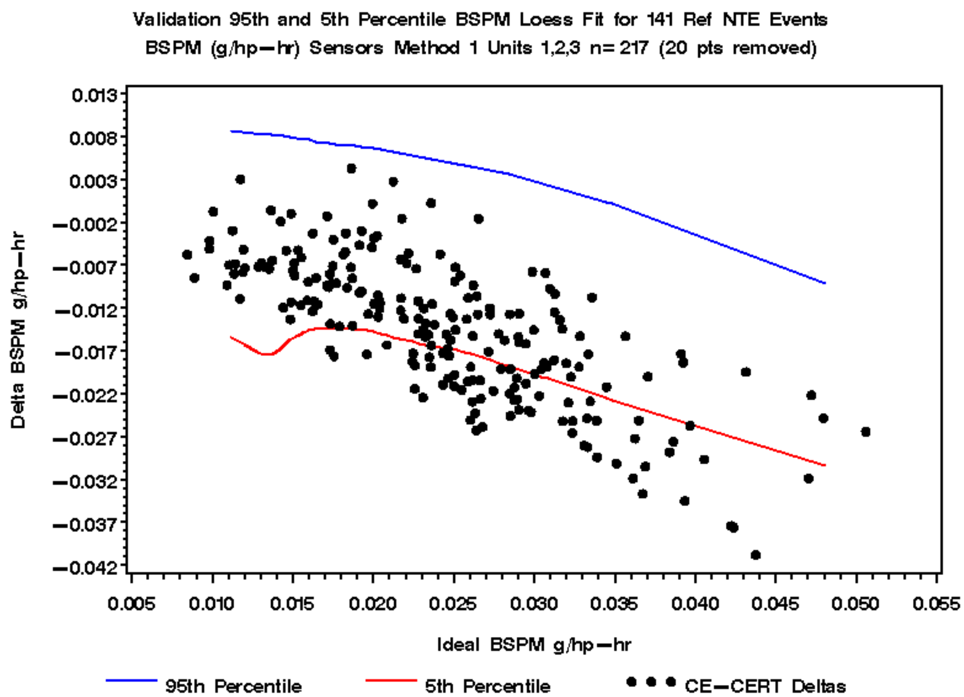


FIGURE 172. VALIDATION ON-ROAD AND REGRESSION FUNCTIONS BASED ON THE SIMULATION MODEL FOR BSPM SENSORS METHOD 1 WITH NO REGEN

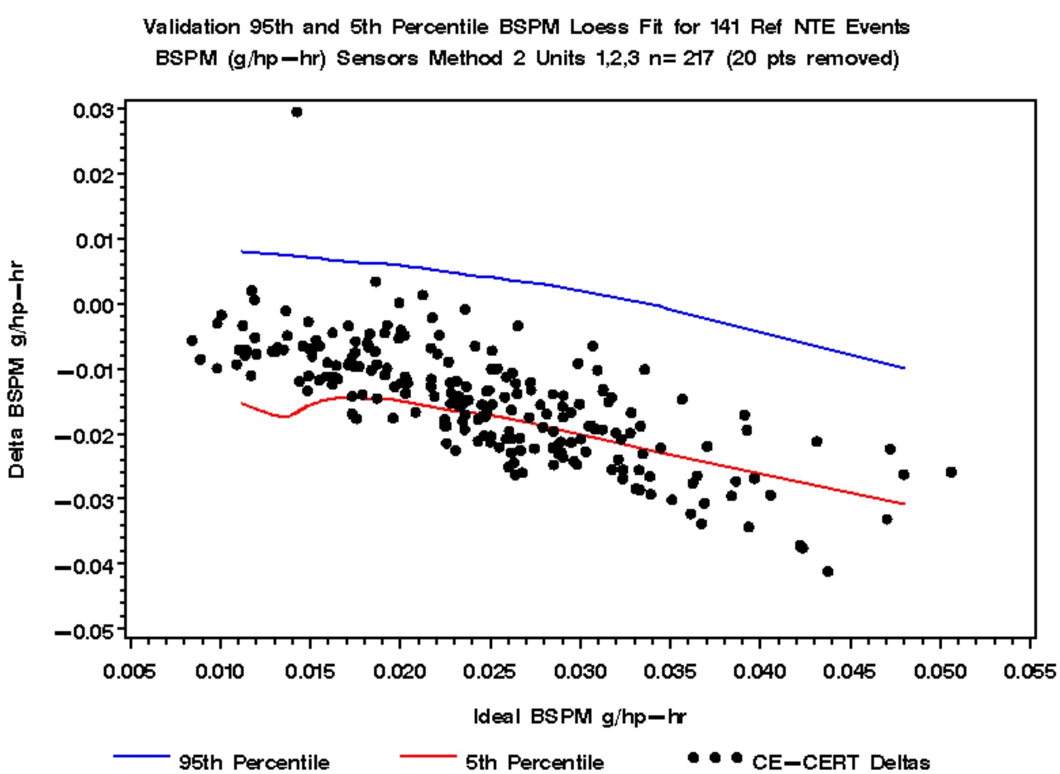


FIGURE 173. VALIDATION ON-ROAD AND REGRESSION FUNCTIONS BASED ON THE SIMULATION MODEL FOR BSPM SENSORS METHOD 2 WITH NO REGEN

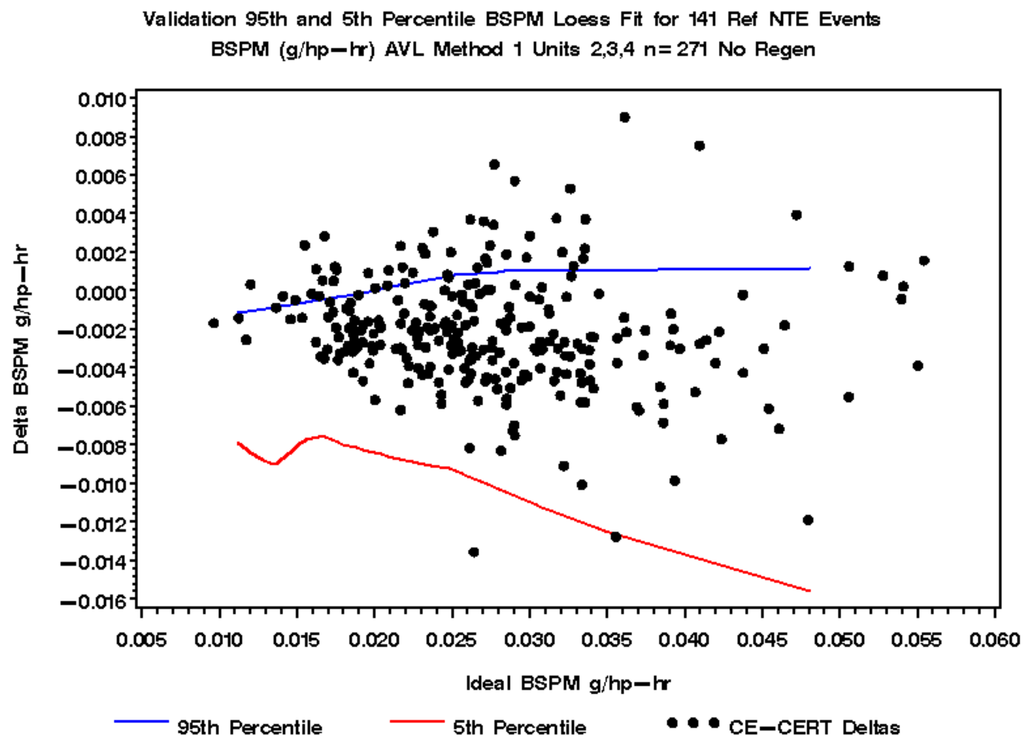


FIGURE 174. VALIDATION ON-ROAD AND REGRESSION FUNCTIONS BASED ON THE SIMULATION MODEL FOR BSPM AVL METHOD 1 WITH NO REGEN

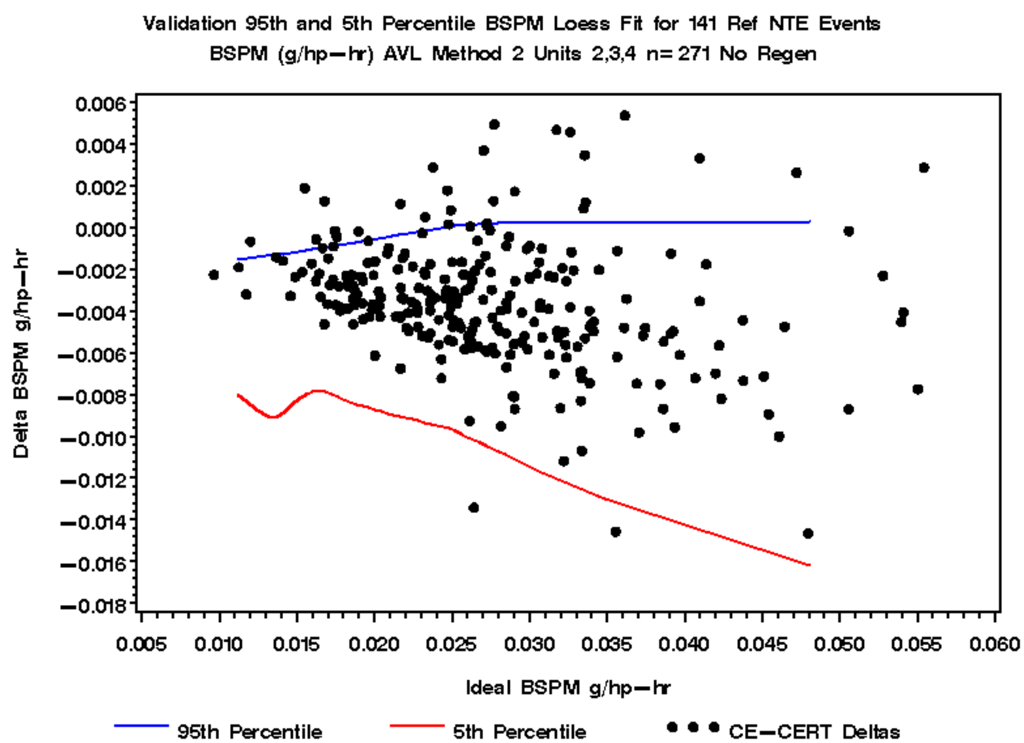


FIGURE 175. VALIDATION ON-ROAD AND REGRESSION FUNCTIONS BASED ON THE SIMULATION MODEL FOR BSPM AVL METHOD 2 WITH NO REGEN

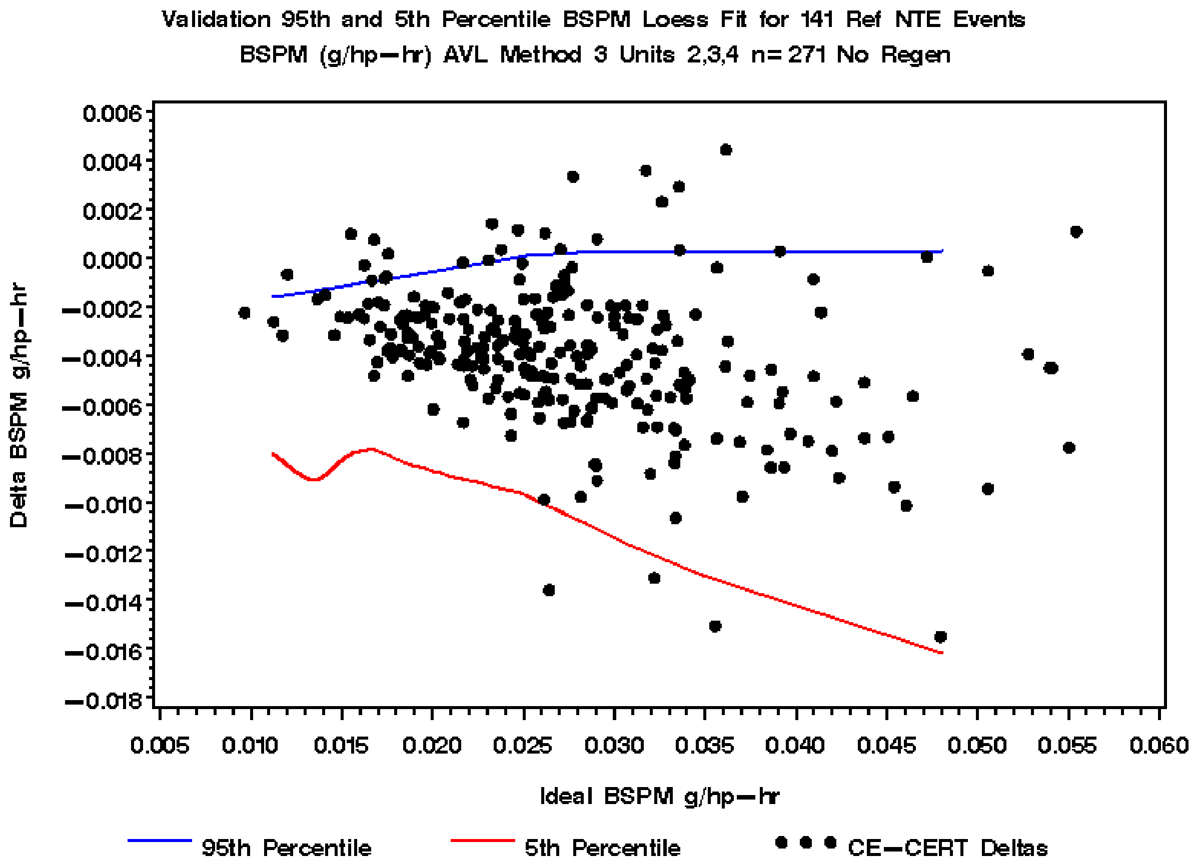


FIGURE 176. VALIDATION ON-ROAD AND REGRESSION FUNCTIONS BASED ON THE SIMULATION MODEL FOR BSPM AVL METHOD 3 WITH NO REGEN

Table 43 summarizes the model validation results. Only the AVL Method 3 passed the model validation.

TABLE 43. SUMMARY OF BSPM MODEL VALIDATION RESULTS

PEMS Unit	Method 1 Exhaust Flow Torque-Speed	Method 2 Exhaust and Fuel Flow Torque-Speed	Method 3 Fuel Flow Torque-Speed
Sensors "no regen"	No	No	No
AVL "no regen"	No	No	Yes

7.0 SUMMARY

A series of engine experiments and environmental tests were performed on three PM-PEMS that included the Sensors PPMD, Horiba TRPM, and AVL MSS. The Sensors PPMD and Horiba TRPM were treated as official PEMS, and only those were used for official results and determination of next steps. The AVL MSS were used in conjunction with the Sensors PPMD based on an agreement reached between Sensors and AVL. Error surfaces were developed based on experimental work to determine PM-PEMS bias and precision errors using Monte Carlo simulation model. The output of the model was to determine the error distribution at a set of reference NTE events, compared to their ideal value. The PM-PEMS with the lowest 95th percentile error that is greater than zero was selected for in-use validation testing of the model.

The PM-PEMS that was selected for in-use validation was the Sensors PPMD. The PPMD produced a 95th percentile measurement allowance error of 0.006 g/hp-hr at a threshold NTE limit of 0.02 g/hp-hr using Method 2, compared to the 0.01 g/hp-hr that was produced by the Horiba TRPM. As for the AVL MSS, the instrument produced zero measurement allowance, but its measurement allowance value was not officially used because the MSS only measures the carbon fraction of PM, compared to the required total (solid plus volatile) PM measured by the other two PM-PEMS. However, because the AVL MSS was used in conjunction with the PPMD, the SC agreed to include it during in-use validation testing. Due to funding limitation, the Horiba TRPM was not included in in-use validation testing.

Based on in-use validation testing, the Sensors PPMD failed validation because 32 percent and 34 percent of the data produced in-use were below the 5th percentile of the validation window, using Method 1 and Method 2, respectively. The SC agreed during the development of the Test Plan that less or equal 10 percent (≤ 10%) of the data are allowed to be outside the validation window to pass validation.

As for the AVL MSS, it passed validation using Method 3 by having 9.89 percent of the data outside the validation window, with the majority of these data being higher than the 95th percentile. Method 2 failed by two percentage points and Method 1 failed by 8 percentage points.

Because the MSS using Method 3 passed validation and funding run out to do any further work with the Sensors PPMD and/or to perform in-use validation testing with the Horiba TRPM, the SC concluded the measurement allowance program. The SC also accepted the measurement allowance based on the Sensors PPMD as the final PM-PEMS measurement allowance for Methods 1, 2, and 3

8.0 REFERENCES

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APPENDIX A

TEST PLAN TO DETERMINE PEMS MEASUREMENT ALLOWANCE FOR THE PM EMISSIONS REGULATED UNDER THE MANUFACTURER-RUN HEAVY-DUTY DIESEL ENGINE IN-USE TESTING PROGRAM

DEVELOPED BY:

**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY,
CALIFORNIA AIR RESOURCES BOARD, AND
ENGINE MANUFACTURERS ASSOCIATION**

NOVEMBER 11, 2008

EXECUTIVE SUMMARY

This test plan sets forth the agreed upon processes and methodologies to be utilized to develop additive, brake-specific, data-driven measurement allowance for PM emissions measured by PEMS as required under the HDIUT regulatory program.

As detailed in this test plan, there is a clear consensus on what components of measurement error are intended to be covered by the measurement allowance. Namely, the allowance is to be calculated in a manner that subtracts lab error from PEMS error. Specifically, utilizing Part 1065 compliant emissions measurement systems and procedures for both the lab and PEMS, the lab error associated with measuring heavy-duty engine emissions at stabilized steady-state test points within the NTE zone, will be subtracted from the PEMS error associated with measuring heavy-duty engine emissions utilizing PEMS over events under a broad range of environmental conditions. This subtraction will yield "PEMS minus laboratory" measurement allowance. The experimental methods and procedures specified in this test plan for determining, modeling, and comparing each of the various components of measurement error are designed to generate statistically robust data-driven measurement allowance for the PM emissions.

Successful completion of this test plan is part of the resolution of a 2001 suit filed against EPA by EMA and a number of individual engine manufacturers. The suit challenged, among other things, certain supplemental emission requirements referred to as "not-to-exceed" (NTE) standards. On June 3, 2003, the parties finalized a settlement of their disputes pertaining to the NTE standards. The parties agreed upon a detailed outline for a future regulation that would require a manufacturer-run heavy-duty in-use NTE testing ("HDIUT") program for diesel-fueled engines and vehicles. One section of the outline stated:

"The NTE Threshold will be the NTE standard, including the margins built into the existing regulations, plus additional margin to account for in-use measurement accuracy. This additional margin shall be determined by the measurement processes and methodologies to be developed and approved by EPA/CARB/EMA. This margin will be structured to encourage instrument manufacturers to develop more and more accurate instruments in the future."

Given the foregoing, the work to be completed under this test plan is a vital component to the fulfillment of the settlement agreement, and it is vital to the successful implementation of a fully-enforceable HDIUT program. Because of this significance, it is critically important that the work detailed in this test plan be carried out in as thorough, careful and timely a manner as possible.

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1 INTRODUCTION

This test plan will establish a PEMS measurement allowances for PM, as regulated by the manufacturer-run on-highway heavy-duty diesel engine in-use test program. The measurement allowance will be established using various laboratory facilities and PEMS. The measurement allowance will be established in units of brake-specific emissions (g/hp-hr), and it will be added to the final NTE PM standard, after all the other additive and multiplicative allowances have been applied. This test plan will establish the PM measurement allowance.

The PEMS used in this test plan must be standard in-production makes and models that are for sale as commercially available PEMS. In addition, PEMS and any support equipment must pass a "red-face" test with respect to being consistent with acceptable practices for in-use testing. For example, the equipment must meet all safety and transportation regulations for use on-board heavy-duty vehicles.

Even though the PEMS cannot be "prototypes" nor their software "beta" versions, the steering committee has already agreed that after delivery of PEMS to the contractor, there may be a few circumstances in which PEMS modifications might be allowed, but these modifications must meet certain deadlines, plus they are subject to approval by the steering committee. Also, any implementation of such approved modifications will not be allowed to delay the test plan, unless the steering committee specifically approves such a delay. Table 1 summarizes these allowable modifications and their respective deadlines:

TABLE 1. ALLOWED MODIFICATIONS

Allowed Modifications	Before start of…
Steering committee approved hardware and software modifications that affect emissions results; including but not limited to fittings, components, calibrations, compensation algorithms, sampling rates, recording rates, etc.	Steady-State Testing
Steering committee approved hardware modifications for DOT approval or any other safety requirement approval	Environmental Chamber Testing
Delivery of any environmental / weather enclosure to contractor	Environmental Chamber Testing
Post-processing software to determine NTE results	Model Validation
DOT approval and documentation	Model Validation
Steering committee approved hardware or software that improves the contractor's efficiency to conduct testing and data reduction	Always Allowed

The steering committee approved three different PEMS that includes the AVL Micro-Soot Sensor (MSS), the Horiba Transient Particulate Matter (TRPM), and the Sensors Proportional Particulate Matter Diluter (PPMD). However, because of the different measurement technologies employed by each of these systems, the three different PEMS hold slightly different status with respect to determining the PM measurement allowance. Because inertial microbalances are already approved for PEMS applications in 40 CFR Part 1065, the Sensors PPMD will be one of the PEMS used to determine the measurement allowance. And because EPA's PM standard is based upon a gravimetric filter analysis, the Horiba TRPM will also be used to determine the measurement allowance. The lowest measurement allowance value between the two will be selected as the final measurement allowance for PM. If that value does not validate, then the lowest validated value will be chosen. If the lowest validated value chosen is within 0.0075 g/hp-hr from the lowest non-validated value, then the lowest validated value will be the measurement allowance. Otherwise, the MASC will spend up to a $100,000 to figure out a resolution to the problem by generating more data or changing the way the validation was performed. If that does not lead to a resolution, then Executive Management of EMA and EPA will have to settle the issue.

Note that at the conclusion of successful testing of the Horiba system in this measurement allowance program, EPA intends to approve the Horiba system as an alternative for use, or EPA may elect to amend 40 CFR Parts 86 and/or 1065 to allow the use of the Horiba TRPM or other PEMS that operate upon similar measurement principles. Because the AVL system measures only the soot component of PM, the measurement allowance will not be determined using the AVL results, unless both the Sensors and Horiba systems fail to complete the measurement allowance program. Note that the steering committee may determine at the conclusion of the program that the AVL MSS is a viable alternative for demonstrating compliance. Under such a circumstance EPA may amend the Heavy-Duty In-Use regulation to allow for its use.

This test plan describes a computer model, a series of experiments that are used to calibrate the model, and another series of experiments that are used to validate the calibrated model.

The test plan first describes the computer model. The computer model statistically combines many sources of PEMS and lab error, which are nearly impossible to capture simultaneously in a single test. The model will use statistics to apply the errors in a way that simulates actual running of a PEMS in-use. The model will also consider only the portion of error that is attributable to PEMS, and it will subtract the error that is already tolerated in an emissions lab today. The model will also calculate and validate results according to 40 CFR Part 1065.

The test plan then describes the series of experiments. These tests will characterize the many sources of PEMS and lab error so that the specific nature of the errors can be programmed into the computer model. The nature of the error has to do with the way PEMS and the lab react to certain conditions. For example, under varying environmental conditions such as temperature or vibration, a PEMS might exhibit signal drift, or it may record noise that is not a part of the true emissions.

Next, the experimental results will be entered into the computer model, and the measurement allowances are calculated by the model. The model uses a “reference" PEMS data set, which will have many “reference NTE events.” The model statistically applies all the errors to the reference data set, calculates results, and saves the results. Then the model will be run with all errors set to zero to calculate the ideal results of the reference data set. Each difference between a reference NTE event’s result with errors and its respective ideal result will be a brake-specific difference that is recorded for later use. Then the process repeats using the same reference data set, to which new, statistically selected errors are applied, and thus another unique set of differences is calculated. As the model continues to iterate and generate more and more results, patterns are expected to appear in the output data. These patterns should be the distributions of differences, based upon the error that was statistically and repeatedly applied to the reference data set. Many difference distributions will be determined: for each reference NTE event, for each of the two brake-specific calculation methods (three in case of the AVL system only), and for each PEMS. It has been agreed that the 95th percentile values of these distributions will be taken as reasonable "worst case" results for each reference NTE event. Details on how all these distributions will be reduced to determine the PM measurement allowance is given in the "Error Model" section of this test plan.

Because the calculation based on Method 2 and Method 3 require gas-based fuel flow calculation based on the measurement of CO_2, CO, and NMHC, a decision was made to use the gaseous PEMS data for this purpose, without the need to perform gaseous measurement during the PM-PEMS program.

Finally, the test plan describes how the computer model will be validated against real-world over-the-road in-use PEMS operation as well as additional lab testing. For the over-the-road testing, PEMS emissions measurements will be conducted, while at the same time a reference laboratory will be towed along to measure the same emissions. For the lab testing, an attempt will be made to simulate real-world engine operation to "replay" an over-the-road test in the lab. Data from these final experiments will be used to validate the model, which must be done in order to gain sufficient confidence that the model did not establish unreasonable measurement allowances.

The following sections of this test plan are written as instructions to the contractor or contractors who will complete the test plan.

2 MONTE CARLO ERROR MODEL AND MEASUREMENT ALLOWANCE

2.1 OBJECTIVE

Use Monte Carlo (e.g. random sampling) techniques in an error model to simulate the combined effects of all the agreed-upon sources of PEMS error incremental to lab error. Create error "surfaces" for the Monte Carlo simulation to sample, based upon results from the experiments described in Sections 3 and 4. Exercise the model over a wide range of NTE events, based on a single, reference data set of at least 150 but no more than 200 unique NTE events. Determine the pollutant-specific brake-specific additive measurement allowance for PM.

2.2 BACKGROUND

The error model uses Monte Carlo techniques to sample error values from "error surfaces" that are generated from the results of each of the experiments described in Section 3 on engine dynamometer laboratory tests and Section 4 on environmental chamber tests. The lab test error surfaces cover the domain of error versus the magnitude of the signal to which the error is to be applied (i.e. 1st to 99th percentile error vs. concentration, flow, torque, etc.). This is illustrated later in this section. The environmental test error surfaces for shock & vibration and electromagnetic & radio frequency interference (EMI/RFI) cover the same domain as the lab tests. The environmental test error surfaces for pressure and temperature are characteristically different because they cover the domain of environmental test cycle time versus the magnitude of the signal to which the error is to be applied (i.e. error at a selected time vs. concentration). Details on how each surface is generated are given in each of the respective sections. These surfaces will already be adjusted to represent PEMS error incremental to lab error; therefore, these surfaces are sampled directly by the model.

The error model will use two different probability density functions (PDFs) as shown in Figure 1 to sample the error surfaces, depending upon which experiment the surface represents. To sample error surfaces that are generated from all the laboratory test results (Section 3), and the environmental test results for shock & vibration (Section 4), the model will use a truncated normal PDF because these tests are designed to evenly cover the full, but finite, range of engine operation and ambient conditions. To sample error surfaces that are generated from the pressure and temperature environmental test results (Section 4), the model will use a uniform PDF because these tests are already designed to cover the typical range and frequency of the respective conditions.

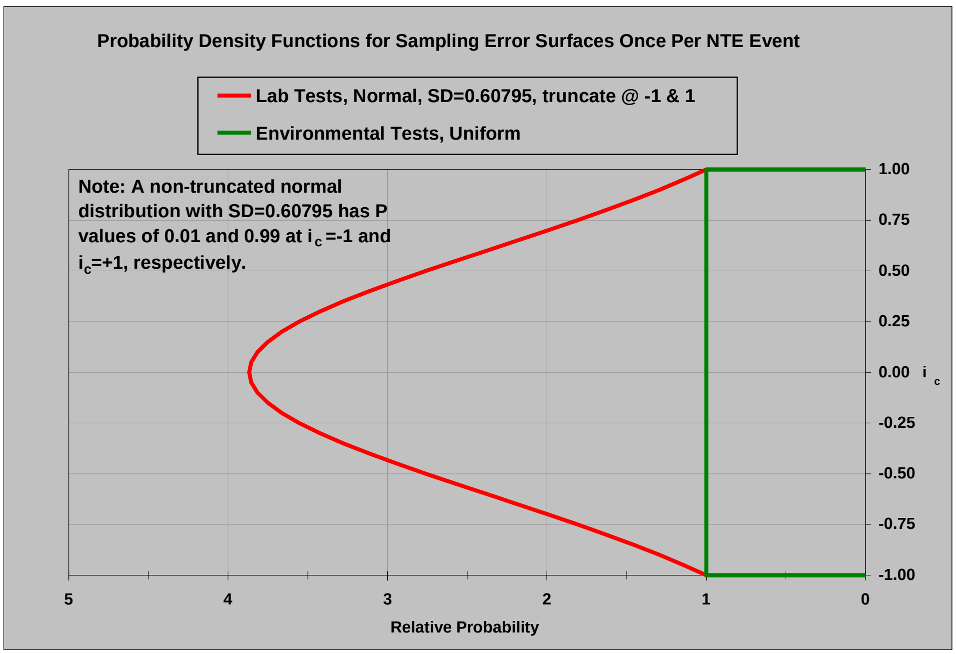


FIGURE 1. PROBABILITY DENSITY FUNCTIONS FOR SAMPLING ERROR SURFACES

The random values that are obtained from both distributions are labeled i_c in Figure 1 and range from -1 to 1. Note that for the pressure and temperature environmental tests, a uniform PDF will be used to sample test time, from which the nearest (in time) calculated errors are used. The errors from the other tests will be aligned with the truncated normal PDF such that each of the 50th percentile values at each of the tested signal magnitudes is centered at the median of the PDF ($i_c = 0$), and the 1st and 99th percentile error values at each of the tested signal magnitudes will be aligned with the extreme negative ($i_c = -1$) and positive ($i_c = +1$) edges of the PDF, respectively.

Each error surface will be sampled along its i_c axis (y-axis) once per reference NTE event trial, and it will be sampled along its parameter value axis (x-axis, e.g., concentration (only for AVL MSS), flow, torque, etc…) once per second, within a given reference NTE event trial. An error will be determined for a given second and parameter along the error axis (z-axis) at the intersection of an i_c value and a parameter value.

To ensure that the magnitudes of the error surfaces are appropriate, each data point used to generate the surfaces will be a mean or a weighted mean of 30 seconds of sampling.

Interpolation will be performed by first linearly interpolating error values at each tested magnitude along the selected line perpendicular to the i_c axis. Then from that line of errors, individual error values will be linearly interpolated at each second-by-second signal magnitude of the given NTE event in the reference data set.

The reference data set to which all errors will be applied will be a large data set of engine operation over a wide range of NTE events. This reference data set will be initially generated from collections of real-world PEMS data sets. The reference data set should contain at least 150 but no more than 200 unique NTE events. Parameters in the reference data set may be scaled in order to exercise the model through a more appropriate range of parameters (i.e. concentrations, flows, ambient conditions, etc.). If the parameters are scaled, care should be taken to maintain the dynamic characteristics of the reference data set.

After the errors are applied, NTE brake-specific PM emissions results are calculated, using each of the three agreed-upon NTE calculation methods. The three different brake-specific emission calculation methods for PM referred to in this test plan are i) Torque-Speed method, ii) BSFC method, and iii) ECM-Fuel Specific method, and these are illustrated in Figure 2, 3, and 4, respectively.

For all PM PEMS:

$\overline{m_{PM}}$ is a flow weighted particulate matter exhaust concentration in g/mol

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i(rpm)*T_i(N\cdot m)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

Where for AVL:

$\overline{m_{PM}}$ is computed numerically as follows,

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\sum_{i=1}^{N}\left[mPM_i\left(\frac{g}{mol}\right)*\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}$$

FIGURE 2. BRAKE-SPECIFIC PM EMISSIONS CALCULATION FOR METHOD 1

For all PM PEMS:

$\overline{m_{PM}}$ is a flow weighted particulate matter exhaust concentration in g/mol

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\frac{M_C}{w_{fuel}}*\sum_{i=1}^{N}\left[\frac{\dot{n}_i\left(\frac{mol}{s}\right)*\left[xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}\right]*\Delta t}{\left[\frac{\dot{m}_{fueli}\left(\frac{g}{s}\right)}{\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159}{60*1000*3600}}\right]}\right]}$$

Where for AVL:

$\overline{m_{PM}}$ is computed numerically as follows,

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\sum_{i=1}^{N}\left[mPM_i\left(\frac{g}{mol}\right)*\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}$$

FIGURE 3. BRAKE-SPECIFIC PM EMISSIONS CALCULATION FOR METHOD 2

For AVL Only:

$$e_{PM}\left(g/kW\cdot hr\right)=$$

$$\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i\left(rpm\right)*T_i\left(N\cdot m\right)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

Where:

$$\overline{m_{PM}}\left(\frac{g}{mol}\right)=\frac{\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\left(mPM_i\left(g/mol\right)\right)*\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}{\frac{w_{fuel}}{M_C}*\sum_{i=1}^{N}\left[\frac{\dot{m}_{fuel}\left(\frac{g}{s}\right)}{xTHC_i\left(ppm\right)*10^{-6}+\left(xCO_i\left(\%\right)+xCO_{2_i}\left(\%\right)\right)*10^{-2}}*\Delta t\right]}$$

FIGURE 4. BRAKE-SPECIFIC PM EMISSIONS CALCULATION FOR METHOD 3

Next, the NTE events are calculated by each of the three calculation methods, but with no error sampled or applied to the reference data set. These results are considered the "ideal" results of the reference NTE events. These ideal results are subtracted from each respective NTE event result 'with errors', and the difference is recorded. Then a new set of errors are sampled and applied to the reference NTE event, and the NTE results 'with errors' are calculated again. The ideal results are again subtracted, and the difference is recorded. This is repeated thousands of times so that the model converges upon distributions of brake-specific differences for each of the original NTE events in the reference data set.

Then the 95th percentile difference value is determined for each NTE event distribution of brake-specific differences for PM for each calculation method. At this point there is one distribution of 95th percentile differences for PM, where all the NTE events are pooled by the PM emissions for each of the three different calculation methods. Each of the 95th percentile distributions represents a range of possible measurement allowance values.

From each of these three distributions of possible measurement allowance values, one measurement allowance per distribution must be determined. First the correlation between 95th percentile differences versus the ideal PM emission is tested. For each calculation method, if a least squares linear regression of 95th percentile differences versus ideal PM emissions has an r^2 (squared correlation coefficient) > 0.85 and an SEE (standard error of the estimate or root-mean-squared-error) < 5 % of the median ideal PM emission, then that linear regression equation will be used to determine the measurement allowance for that calculation method at the following NTE threshold:

PM = 0.02 g/hp-hr and 0.03 g/hp-hr

In cases where extrapolation is required to determine the measurement allowance at the NTE threshold, the measurement allowance will be determined using the linear regression, but evaluated at the ideal PM emission that is closest to the NTE threshold, not extrapolated to the NTE threshold itself. If the linear regression does not pass the aforementioned r^2 and SEE criteria, then the median value of the 95th percentile differences is used as the single measurement allowance for that calculation method.

Next, the calculation method is selected. The above procedure will provide three measurement allowances, where applicable, one for each of the three different calculation methods. To make them comparable, the three measurement allowance values will be normalized by the PM threshold and expressed as a percent. Also, if any measurement allowance is determined to have a value less than zero, then that measurement allowance will be set equal to zero. The calculation method with the minimum normalized PM value will be chosen and the corresponding normalized PM value will be selected as the best measurement allowance for PM, assuming it validates. If it does not validate, then the minimum value that validates will be chosen as long as it is within 0.0075 g/hp-hr from the minimum value that did not validate. If the difference between the minimum value that validates and the minimum value that did not validate is greater than 0.0075 g/hp-hr, additional investigation with up to a $100,000 will be spent in order to understand why the minimum value chosen did not validate. If the problem is not resolved after spending the $100,000, then the matter will be referred to executive management of EPA and EMA to decide on the PM measurement allowance.

Table 2 below illustrates the selection of the calculation method. The example is based on a hypothetical set of normalized PM measurements for the three calculation methods. The minimum of these normalized allowances is used to select the best method (highlighted in blue). In this hypothetical case, the BSFC method would be selected.

TABLE 2. EXAMPLE OF SELECTION OF MEASUREMENT ALLOWANCE AT 0.02 G/HP-HR NTE THRESHOLD

	Allowance at Respective NTE Threshold (%)		
Calc. Method ==>	Torque-Speed	BSFC	ECM fuel specific
BSPM	38 %	18 %	N/A
Selected Method==>	BSFC Method		

Therefore, 18% would be selected as the best measurement allowance for PM, assuming it validates. Otherwise, the 38 % will be chosen if it validates. Thus, the additive brake-specific measurement allowance would be:

PM = 18 % * 0.02 g/hp-hr = 0.0036 g/hp-hr, if it validates, and if not, then:

PM = 38 % *0.02 g/hp-hr = 0.0076 g/hp-hr, if it validates, and if not, then:

spend up to a $100,000 to figure out why it did not validate in the first place, and then apply the above strategy again, assuming the value now validates. If not, then EPA and EMA executive management will decide on the PM measurement allowance value.

This PM value would be the value added to the actual brake-specific NTE threshold for a given engine, based on actual family emissions limit, mileage, model year, etc.

2.3 METHODS AND MATERIALS

Exercise the model using three different calculation methods: a) Torque-Speed method, b) BSFC method, and c) ECM-Fuel Specific method (only for AVL MSS). Determine which calculation method is the most accurate, and use it to estimate the measurement allowance. Each calculation method is described in Figured 2, 3, and 4.

Prepare an Excel spreadsheet model for use with the Crystal Ball Monte Carlo software for error analysis of brake specific emissions, BSE, as outlined in section 2.4. Changes to the model specifications may be requested as agreed up on by the Steering Committee. Prepare the spreadsheet in a modular structure following the specified model outline, and make provisions for the identified calculation modules. Additionally, clearly identify and easily locate input cells to the model to facilitate any revisions that may become necessary for users who want to exercise the model with other Monte Carlo add-ins such as @Risk or the newest versions of Crystal Ball. Test the spreadsheet with controlled test cases of simplified input distributions with the Crystal Ball add-in to confirm correct model implementation in accordance with this test plan. Run at least one typical analysis as an additional confirmation.

Deliver the electronic spreadsheet and a brief report describing the model, presenting the test cases, and describing pertinent information including the Crystal Ball version number, the Excel version number, the operating system and the computer. Use standard spreadsheet calculations so that no serious difficulties will be anticipated regarding application in other spreadsheet versions. Use Crystal Ball Version 7 or higher, and confirm test cases using Excel 2003.

Control revisions of the spreadsheet model using descriptive file names. Extensive revisions or testing with other software versions beyond that initially proposed may be re-proposed by the Steering Committee if and when a need for such additional work is identified.

2.4 SIMULATION PROCEDURE

For each of the measurement errors in Section 3, create an error surface and sample it according to the aforementioned PDFs. Each error surface represents an additive error—or a subtractive error if the sign is negative—relative to the reference value to which it is applied. Figure 5, Figure 6, and Figure 7 serve as a hypothetical PM example of how these error surfaces should be created for every error. The plots shown correspond to PM emissions concentration data representing 1 PEMS, two engines, and three exhaust configurations each, with all 6 sets of PEMS data pooled together. Note that separate error surfaces will be constructed for each of the three PEMS units (AVL, Horiba and Sensors). The example applies to the error module for steady-state (SS) bias and precision PM concentration errors (Section 3.2). These figures will be referenced by each "Data Analysis" section for the various errors discussed in this test plan.

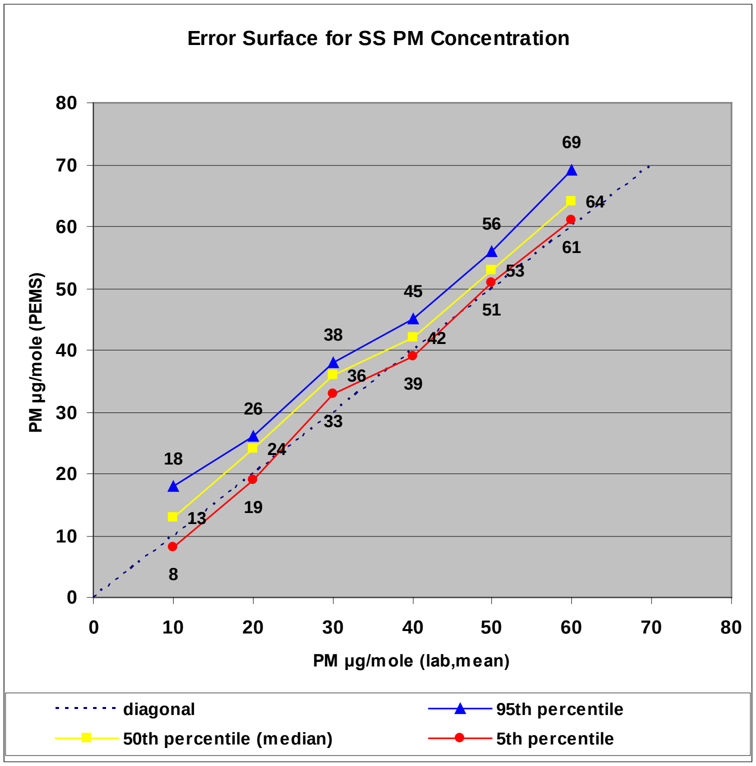


FIGURE 5. ERROR SURFACE: PEMS VS. LAB

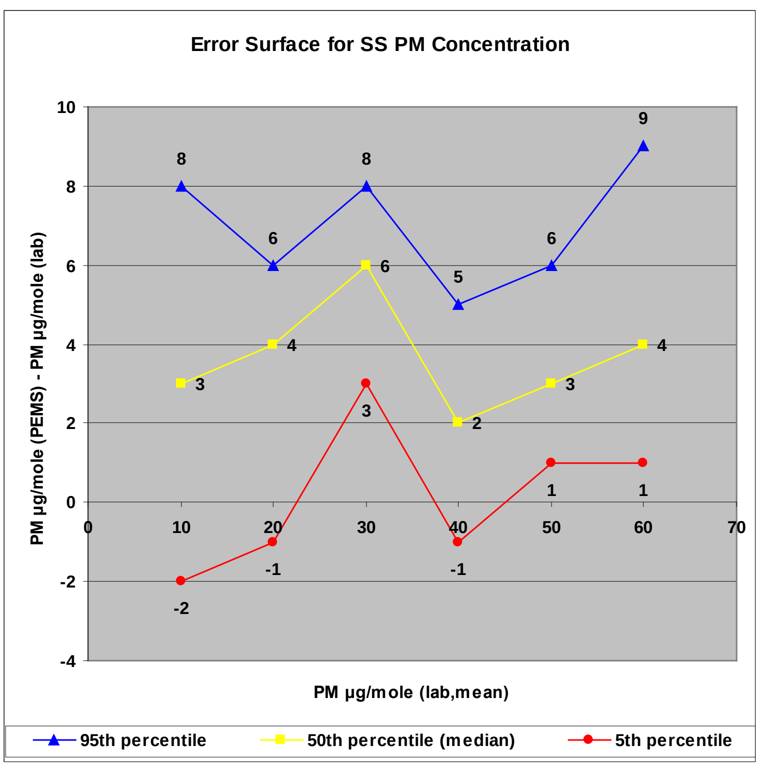


FIGURE 6. ERROR SURFACE: (PEMS-LAB) VS. LAB

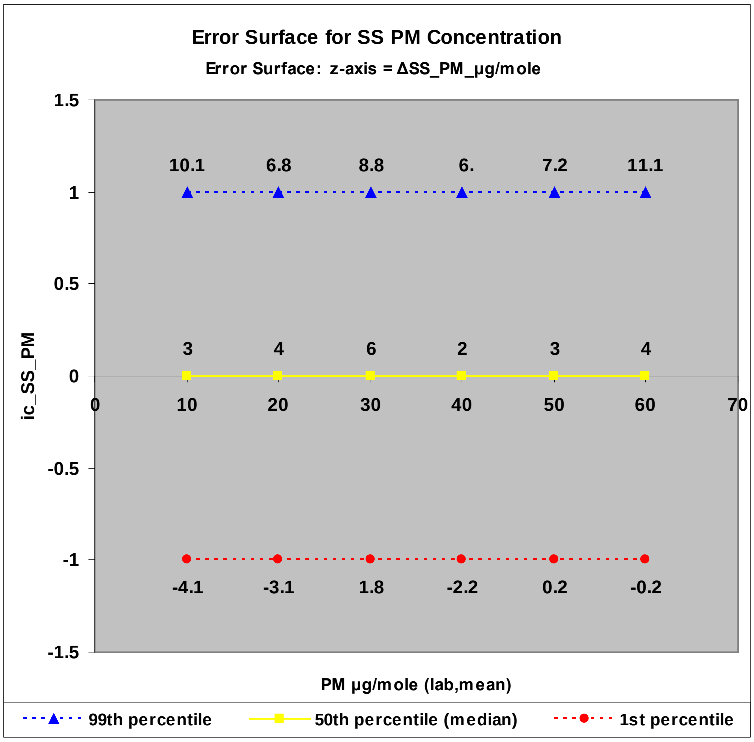


FIGURE 7. ERROR SURFACE: FINAL VERSION

Errors from Section 3 (Engine Dynamometer Laboratory tests) and Section 4 (Environmental Chamber Tests) are combined by adding all of the sampled errors once per NTE event trial. For example, in order to assess the errors in PM concentration for each NTE event, several modules will be created such that:

$$PM\_with\ errors = PM\ \_ideal + \Delta(\mu g/mole)_1 + \Delta(\mu g/mole)_2 + \Delta(\mu g/mole)_3 + \ldots$$

where,

$\Delta(\mu g/mole)_1$ = PM concentration errors due to steady state bias and precision errors,
$\Delta(\mu g/mole)_2$ = PM concentration errors due to ambient temperature,
$\Delta(\mu g/mole)_3$ = PM concentration errors due to ambient pressure,
etc….

2.4.1 Construction of the Error Surface

2.4.1.1 PEMS vs. Lab

Acquire raw data with the PEMS at various average concentration levels as per Section 3.2. Plot the "PEMS" signals versus the corresponding "lab" signals that were measured using lab equipment. This plot pools all bias and precision errors for one PEMS and for all data from all engines for all steady-state modes. Shown in Figure 5 are the 5th, 50th and 95th percentiles at the mean PM concentration level from the lab (note that the distribution of data at each level is not necessarily Gaussian). If the 50th percentile is different than the line of perfect agreement (diagonal), the data suggests that there is a bias error between PEMS and Lab. In essence this graph shows the statistical distribution measured by the PEMS at each average concentration level sampled. The example shows only 6 discrete PM concentration levels (ranging from 10-60 μg/mole). However, the actual number of discrete levels will be determined by the total number of operating conditions actually run for all the tests of all the engines. For example, the SS PM testing will select 6 modes representing typical operating conditions. Thus, the actual plot for SS PM will likely have 36 discrete concentration levels (6 modes x 1 PEMS x 2 engines x 3 exhaust configurations).

2.4.1.2 (PEMS – Lab) vs. Lab

The plot in Figure 6 basically shows the "additive error band" measured during testing. The plot is created by first subtracting the "lab" PM value from the corresponding individual PEMS PM measurement for each test run. This difference is defined as the 'delta' error. Next, the "PEMS – Laboratory" delta errors are pooled at each average lab PM value to obtain the 95^{th}, 50^{th}, and 5^{th} percentile values, respectively, displayed in Figure 5. Notice that if lab error exceeds PEMS error at a given percentile, crossover of values can occur. This is acceptable because the crossover effectively reduces PEMS error whenever lab error exceeds PEMS error.

In order to obtain estimates of the 1^{st} and 99^{th} percentiles for the delta errors for a given "lab" PM value, each side of the corresponding error distribution will be assumed to independently fit a normal distribution. Because of the asymmetry of the data, this methodology will yield two halves of a normal distribution. The median of each normal distribution will be the median based on the delta errors given in Figure 6. The 95^{th} percentile delta error will form the upper boundary of one half of the normal distribution, and the 5^{th} percentile delta error will form the lower boundary of the other half of the normal distribution. When each side of the data distribution is fitted to a normal distribution using the above boundary conditions, one can then expand each half of the distribution from the error surface to obtain the 1^{st} and 99^{th} percentiles of the data for the given "lab" PM value.

2.4.1.3 Error Surface

This step normalizes the data in Figure 7 using what is called a "variability index (i_c)", which represents the random sampling by the Monte Carlo technique, in order to select a given error level. This variability index is allowed to vary from –1 to +1. The likelihood of i_c being any value between –1 through +1 is specified by the PDF assigned to i_c. In the given example, i_c is assumed to vary according to a normal distribution during Monte Carlo calculations. This is because it is believed that the distribution of errors due to steady-state bias and precision will be centered about the 50^{th} percentile of the full range of conditions measured according to Section 3.2. The pressure and temperature environmental error modules use uniform probability density functions for their respective variability index. Each set of data for each lab set-point mean (i.e., lab reference value) in Figure 6 is normalized by aligning the 1^{st} percentile error from the fitted normal distributions with i_c = -1, the 50^{th} percentile error with i_c = 0, and the 99^{th} percentile error from the fitted normal distribution with i_c = +1.

Error surfaces such as the one presented in Figure 7 are the input modules that the Monte Carlo simulation program will use during calculations of brake-specific PM emissions. For example, for a given NTE calculation a random i_c value is chosen once per NTE event trial. Let us assume that the first random sample produced an i_c = 0.5. Let us also assume that during this NTE event trial, the reference PM concentration is 10 μg/mole. In this case,

$$\Delta(\mu g/mole)_1 = (3 + 10.1) / 2 = 6.55\ \mu g/mole.$$

Also, from Figure 7, for $i_c = 0.5$, the reference PM = 10 µg/mole.

For that step in the calculation, the Monte Carlo approach will add this "delta" to the reference concentration value of 10 µg/mole (10 µg/mole + 6.55 µg/mole = 16.55 µg/mole) to represent errors in steady-state bias and precision for $i_c = 0.5$, and reference NTE PM = 10 µg/mole. If during the same NTE event in the reference data set, a reference concentration of 35 µg/mole is read, then,

$$\Delta(\mu g/mole)_1 = ((6 + 8.8) / 2 + (2 + 6.2) / 2) / 2 = 5.75\ \mu g/mole \text{ (from Figure 7)}$$

Note that first the error along the i_c line perpendicular to the i_c axis (in this case the line along 0.5) is linearly interpolated at each discrete concentration level. Then those interpolated values are themselves linearly interpolated to determine the error corresponding to each reference concentration in the NTE event. Note that the random selection is once per reference NTE event trial, but the error along that i_c line is applied to every second-by-second value within the given reference NTE event, except for PM concentration in the case of Horiba and Sensors, where no second-by-second information are available, but different PM concentration levels may be available for a specific NTE event.

Now let us assume that the error in PM concentration is composed of only 3 deltas: $\Delta(\mu g/mole)_1$, $\Delta(\mu g/mole)_2$, and $\Delta(\mu g/mole)_3$. And let us assume that for a given reference NTE event trial we have the following values:

- Reference PM at one second= 30 µg/mole
- $\Delta(\mu g/mole)_1 = 6$ µg/mole
- $\Delta(\mu g/mole)_2 = -2$ µg/mole
- $\Delta(\mu g/mole)_3 = -3$ µg/mole.

When the model calculates brake-specific emissions by each of the three calculation methods, it will use the following PM value, which has all of its error applied:

$$PM = 30 + 6 - 2 - 3 = 31\ \mu g/mole.$$

The application of error at the first selected i_c continues during the entire NTE event without having to randomly sample again. In other words, i_c will not change during that random trial. For all of the variables except for $\bar{m}_{PM}$, the errors may continue to change during an NTE event on a second-by-second basis if their error surface happens to be a function of level. For the second randomly selected i_c this entire process of determining the Δµg/mole errors is repeated. The simulation will continue to randomly selected i_c values for thousands of trials until convergence is met.

For the Horiba and Sensors generated reference NTE events, there is only one flow-weighted PM value for the entire NTE event. During the simulation for these types of reference NTEs, the single PM value will be used in the interpolation of the corresponding PM error surfaces (i.e., steady-state PM, transient PM) at all seconds of the reference NTE event. Since the PM value will not vary from second-to-second, the only interpolation will occur according to the i_c value at each of the simulation trials.

The same second-by-second sampling and interpolation approach would be used for other deltas such as ambient temp, ambient pressure, shock and vibration, BSFC interpolation, torque, exhaust flow rate, etc. An overview of the Monte Carlo simulation for PM is detailed in Figure 8.

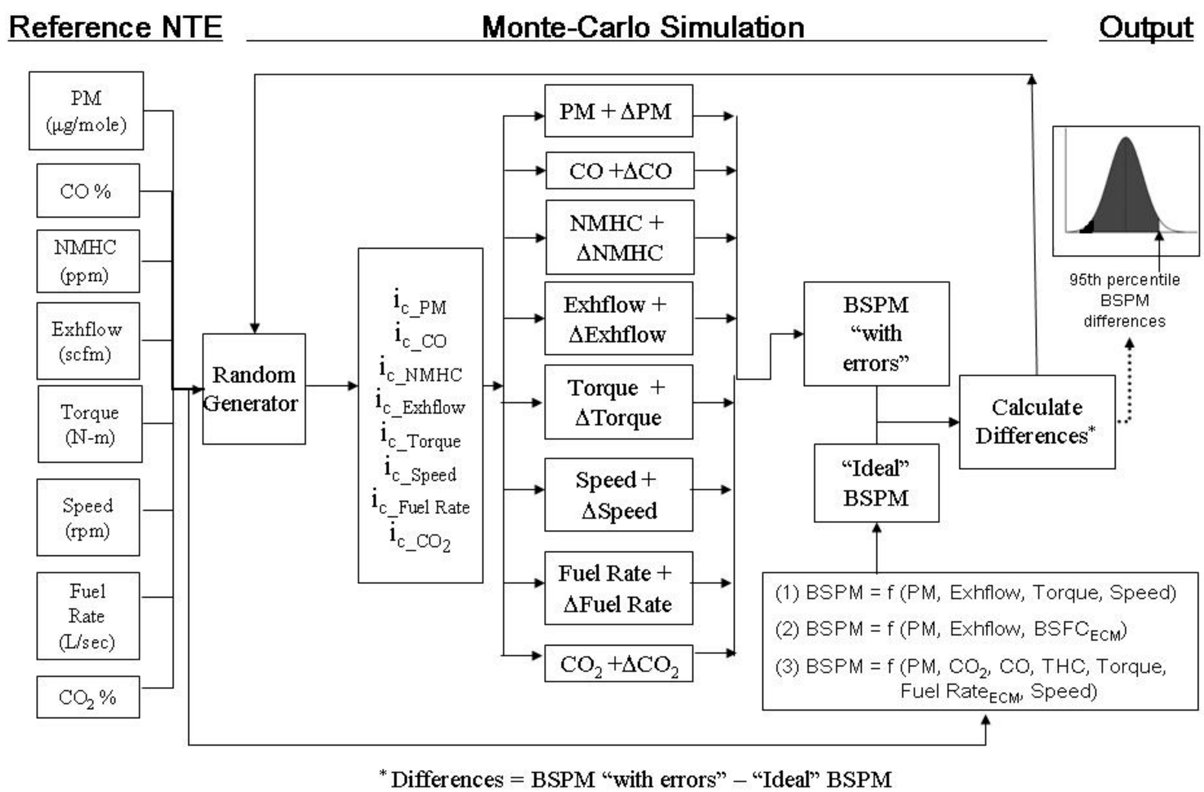


FIGURE 8. OVERVIEW OF MONTE CARLO SIMULATION

Table 3 lists the error surfaces that will be created for use in simulating the BSPM error differences.

TABLE 3. ERROR SURFACES FOR THE BSPM SIMULATION

Calculation Component	Test Source	Error Surface
Delta PM	Engine Dyno	Delta PM SS
Delta PM	Engine Dyno	Delta PM Transient
Delta PM	Environ	Delta PM Ambient Temperature
Delta PM	Environ	Delta PM EMI/RFI
Delta PM	Environ	Delta PM Atmospheric Pressure
Delta PM	Environ	Delta PM Vibration
Delta CO	Engine Dyno	Delta CO SS
Delta CO	Environ	Delta CO Atmospheric Pressure
Delta CO	Environ	Delta CO Ambient Temperature
Delta CO	Engine Dyno	Delta CO Time Alignment
Delta CO2	Engine Dyno	Delta CO2 SS
Delta CO2	Engine Dyno	Delta CO2 Transient
Delta CO2	Environ	Delta CO2 Ambient Temperature
Delta NMHC	Engine Dyno	Delta NMHC SS
Delta NMHC	Engine Dyno	Delta NMHC Transient
Delta NMHC	Environ	Delta NMHC Atmospheric Pressure
Delta NMHC	Environ	Delta NMHC Ambient Temperature
Delta NMHC	Environ	Delta Ambient NMHC
Delta Exhaust Flow	Engine Dyno	Delta Exhaust Flow SS
Delta Exhaust Flow	Engine Dyno	Delta Exhaust Flow Transient
Delta Exhaust Flow	Engine Dyno	Delta Exhaust Flow Pulsation
Delta Exhaust Flow	Engine Dyno	Delta Exhaust Flow Swirl
Delta Exhaust Flow	Environ	Delta Exhaust EMI/RFI
Delta Exhaust Flow	Environ	Delta Exhaust Temperature
Delta Exhaust Flow	Environ	Delta Exhaust Pressure
Delta Torque	Engine Dyno	Delta Dynamic Torque
Delta Torque	Engine Dyno	Delta Torque DOE Testing
Delta Torque	Engine Dyno	Delta Torque Warm-up
Delta Torque	Engine Dyno	Delta Torque Humidity/Fuel
Delta Torque	Engine Dyno	Delta Torque Interpolation
Delta Torque	Engine Manuf	Delta Torque Engine Manuf
Delta Speed	Engine Dyno	Delta Dynamic Speed
Delta Fuel Rate	Engine Dyno	Delta Dynamic Fuel Rate

2.5 MODEL CONSIDERATIONS

2.5.1 Convergence

The main goal of the convergence criteria is to define how many simulation trials at a given reference NTE event are required to estimate the 95th percentile BSPM emission differences with a given precision. The convergence method to be used is based on a nonparametric statistical technique[3] which defines a 90% confidence interval for the 95th percentile of the BSPM emissions differences for an individual reference NTE simulation. If the width of the 90% confidence interval is less than 1% of the BSPM emissions threshold, then convergence is met. The following steps define the convergence method:

1. Run the Monte Carlo simulation for *N* trials for a single reference NTE event.
2. Order the BSPM emissions differences from smallest to largest.
3. Identify the trial number at the lower end of the 90% confidence interval
$$n_{lower} = 0.95 * N - 1.645\sqrt{0.95 * 0.05 * N}$$
4. Identify the trial number at the upper end of the 90% confidence interval
$$n_{upper} = 0.95 * N + 1.645\sqrt{0.95 * 0.05 * N}$$
5. Compute (BSPM difference value at n_{upper}) – (BSPM difference value at n_{lower}).
6. If the result in (5) < 1% of the BSPM emissions NTE threshold (0.02 g/hp-hr) then convergence is met.

2.6 SIMULATION OUTPUT

It is important to understand and identify what error surfaces have the most influence (i.e., sensitivity) on the BSPM emissions 'with errors' and, thus, the resulting BS emissions differences. Contributions to sensitivity can be attributable to changes in variance and/or bias.

2.6.1 Sensitivity Variation Effect

During the Monte Carlo simulation for each reference NTE event, sensitivity charts produced by Crystal Ball will be generated and stored in output REPORT files. Crystal Ball calculates sensitivity by computing the rank correlation coefficient between every assumption (error surface) and forecast value (delta BS emissions) while the simulation is running. Positive rank correlations indicate that an increase in the assumption is associated with an increase in the forecast. The larger the absolute value of the rank correlation the stronger the relationship.

Sensitivity charts in Crystal Ball provide a means to determine how the variances of the error surfaces affect the variance in the forecast values. Hence, the sensitivity charts developed during a simulation are displayed as "Contribution to Variance" charts which are calculated by squaring the rank correlation coefficients for all assumptions used in a particular forecast and then normalizing them to 100%. The assumption (error surface) with the highest contribution to variance (in absolute value of the percent) is listed first in the sensitivity chart.

Simulation results from all reference NTE events will produce sensitivity values for the 95th percentile delta PM emissions by all three calculation methods.

2.6.2 Sensitivity Bias Effect

Another type of sensitivity to be examined in this study is concerned with the effects of potential "bias" in error surfaces and their effects on the forecast values. In order to study these effects a new error surface assumption will be added to the simulation model for each of the original error surfaces.

This assumption will be sampled as a discrete binary distribution (i.e., on or off) during the simulation. For each trial of the simulation, the original error surfaces and 'on/off' error surfaces will be sampled according to their defined sample distribution. If the 'on/off' error surface produces an 'off' condition, the delta emissions from that particular error surface will not be added to the BSPM emissions computations for the BSPM emissions 'with errors'. Similarly, if the 'on/off' error surface produces an 'on' condition, the delta emissions from that particular error surface will be added to the BSPM emissions calculations.

During every trial of the simulation, the exclusions due to the 'off' conditions will result in various combinations of the error surface delta emissions being added to the BSPM emissions 'with errors' computations. Over the course of a simulation with thousands of trials, the sensitivity of a particular error either 'on' or 'off' will be assessed by examining the change in the forecast delta emission. Therefore, in a single Monte Carlo simulation of a reference NTE event sensitivities due to variance and/or bias will be explored.

3 ENGINE DYNAMOMETER LABORATORY TESTS

Utilize engine dynamometer laboratory testing to establish the difference between PM PEMS and PM based on laboratory measurement in accordance with Part 1065. Also establish how well ECM parameters can be used to estimate torque and BSFC.

First, however, audit all the PEMS and lab equipment to ensure that they are operating properly, according to 40 CFR Part 1065, Subpart D. Next, conduct steady-state engine dynamometer tests to establish PEMS steady-state bias and precision relative to the lab. Then, conduct transient engine dynamometer testing to determine PEMS transient precision by repeating transient NTE events. Finally, compare ECM derived torque and BSFC to laboratory measured torque and BSFC.

3.1 PRELIMINARY AUDITS

3.1.1 Objective

Conduct 40 CFR Part 1065, Subpart D audits of all engine dynamometer laboratory systems and all PEMS.

3.1.2 Background

Because the overall purpose of this entire test plan is to establish measurement allowance that account for the incremental difference in the performance of PEMS versus engine dynamometer laboratory systems, the first task is to audit all of the measurement systems to ensure that the specific systems used for testing meet EPA's minimum performance requirements. The audits also help to minimize bias errors between PEMS and lab systems measurements. However, in case a specific PM-PEMS does not meet the specifics of Part 1065 requirement, the MASC will decide on how to move forward by perhaps allowing some flexibility in passing Part 1065 audit, in situations where it might be needed, especially if the performance of a system is within the expectation of the manufacturer.

3.1.3 On-site meeting to establish 1065 compliance requirements

In order to clarify what are all the requirements expected from the lab-grade instrumentation and PEMS equipment, with respect to 1065 compliance, a meeting will be held between the test plan steering committee and the contractor at the contractor site to provide the contractor with guidance regarding which specific sections of Part 1065 Subpart D are required and which are optional. In case Part 1065 requirement is demonstrated to be too stringent or impractical, the contractor may seek approval from the MASC to lessen the stringency of Part 1065 in relation to the PEMS.

3.1.4 Methods and Materials

Use the methods and materials described in 40 CFR Part 1065, Subpart D to conduct audits of all lab and PEMS measurement systems. Even if lab systems and PEMS pass initial Subpart D audits, allow lab operators and PEMS manufacturers to make on-site adjustments to improve the performance of their systems prior to engine testing. Allow adjustments to be based on recalibrations with reference signals that are allowed in 40 CFR Part 1065. The steering committee may direct the contractor to calibrate or adjust the laboratory sampling system based on audit results. The steering committee may also suggest that a PEMS manufacturer calibrate or adjust one or more PEMS based on lab audits.

3.1.5 Data Analysis

Use the data analyses described in CFR Part 1065 Subparts D, J and G. For all subsequent testing, use only those measurement systems that pass the minimum performance criteria in Subpart D, unless a deficiency is deemed acceptable in writing by all parties including PEMS manufacturers. Provide a list and brief description of all the audits conducted for each PEMS manufacturer type. EPA would likely use this list as a template for the data requirements in the PM portion of the HDIU testing program.

3.1.6 PEMS Manufacturer PM PEMS Commissioning

Notify PEMS manufacturers when the 1065 audits are complete and the first set of PM PEMS are completely installed in the engine dynamometer test cell—in preparation for emissions testing. Schedule dates and times that are prior to the start of emissions testing for each PEMS manufacturer to conduct a final commissioning of all their PEMS that are on site, including those PEMS that are not installed in the test cell. PEMS manufacturers may inspect their PEMS and make any final adjustments to their respective PEMS in order for the PEMS to meet their specifications. Allow PEMS manufacturers to inspect the installation of their PEMS in the test cell. If PEMS manufacturers take exception to any portion of the installation or on-site configuration, attempt to resolve any such installation issues. If such issues are not easily resolvable, notify the steering committee, who will determine a course of action. Once PEMS manufacturers have completed their commissioning, notify the steering committee. From this point any further modifications to the PEMS may only be made according to Table 1 of this test plan.

3.2 BIAS AND PRECISION ERRORS UNDER STEADY STATE ENGINE OPERATION

3.2.1 Objective

Evaluate the bias and precision using one engine and one exhaust configuration, shown in Table 4, and 10 repeats of steady-state modes, and three sets of PEMS units, each set including the MSS, TRPM, and PPMD. Thus, the total number of NTE steady-state points required to conduct the steady-state experiments is 30. This constitutes six steady-state modes of engine operation (6), 10 repeats (10), one exhaust configuration, one engine (1), and three different PEMS units (3), 6x10x1x1x3= 180.

TABLE 4. ENGINE, EXHAUST CONFIGURATION, AND STEADY-STATE MODES

	No. of Steady-State Modes for Bypass Setting 1 (BSPM and PM Concentration, representative of PM threshold of 0.025 g/hp-hr under NTE Transient Operation)	PM-PEMS Units	Number of Repeats
07 Engine 1	SS1, SS2, SS3, SS4, SS5, SS6	Three Sets of (MSS, TRPM, and PPMD)	10 per Mode per PM-PEMS Set

Determine the $\Delta_{SS}\overline{m}_{PM}\left(\frac{g}{mol}\right)$ surface plots for the error model based upon all data pooled. Note that each brand of PEMS will have its own $\Delta_{SS}\overline{m}_{PM}$ error surface generated for use in both calculation methods 1 and 2. For calculation method 3, the AVL brand PM PEMS will have a unique $\Delta_{SS}\overline{m}_{PM}$ calculated according to Figure 4 of this test plan.

Recommend six steady-state points based on the PM measurement, using the AVL MSS, of 80 SS points of the Cummins cycle that is typically used to generate ECM torque and BSFC errors versus laboratory. The MASC will accept the six steady-state points or choose alternative points for each exhaust configuration. The objective for the MASC will be to select steady-state points within a given exhaust configuration that provides a nominal spread of concentrations within that configuration's target brake-specific levels. Note that to achieve the brake-specific targets under steady-state conditions, the bypass might have to be opened further, relative to the transient NTE bypass settings.

3.2.2 Background

Testing will be conducted to capture bias and precision errors in PEMS' emissions instruments versus the laboratory filter-based method. The tests will be steady-state only.

Note: Section 3.3 (next section) will evaluate precision errors (not bias) due to the dynamic response of the PEMS instrumentation. The precision error captured during steady state testing (section 3.2) will have to be subtracted from the overall precision error captured in section 3.3 in order not to double-count the steady state precision errors of PEMS instrumentation. This process is detailed in Section 3.3.

3.2.3 Methods and Materials

Use the following systems:

a) One model year 2007 heavy duty diesel engines, equipped with a DPF in the exhaust (Mack MP9)
b) Nine PM PEMS (3 Sensors PPMD, 3 AVL MSS, 3 Horiba TRPM)
c) One PEMS exhaust flow-meter from Sensors, Inc., and one and from Horiba, applicable to the engine to be tested
d) DPF with Bypass Setting 1 for SS testing, representing a threshold level of about 0.025 g/hp-hr under NTE transient testing

Use the following overall guidelines:

e) Measure PM via the CVS, Part 1065 Lab Method (most recent publication)
f) Measure engine inlet airflow through use of LFE or equivalent
g) Use a series of six steady-state modes, and set each mode time to collect a CVS filter mass of at least 75 microgram per mode, simultaneously with other PM-PEMS
h) Regenerate DPF system prior to each series of steady-state tests
i) Capture ECM broadcast channels and other common diagnostic channels, as recommended by engine manufacturer(s), to ensure proper engine operation
j) Do not measure gaseous species by the PEMS
k) Stabilization time = 180 seconds, with a different running time per mode to achieve a 75 microgram or higher of PM on the CVS filter
l) Always power off PEMS equipment at end of each day, according to PEMS manufacturer instructions. Re-start start-up process every day according to PEMS manufacturer instructions and Part 1065, Subpart J.
m) Whenever PEMS are exchanged, swap the order of the Horiba and Sensors flowmeters, if the steup allows for it.

6 point steady-state repeat-testing, evaluate bias and precision errors:

a) The MASC will select 6 SS operating conditions for repeat testing from a matrix of 80 SS points containing information on PM emissions using the AVL MSS
b) Randomize the order of the six modes
c) Repeat each six steady-state cycle two or three times, prior to DPF regeneration
d) Each test will use three PEMS (Sensors, AVL, and Horiba) at a time, to measure PM emissions concentration and exhaust flow rate.
e) Expected test duration is 5 days per PEMS set, with a total of 15 days for all three sets.

Bypass Setting:

a) Run NTE transient cycle using the CVS filter-based method
b) Set bypass to produce CVS filter-based average brake-specific of about 0.025 g/hp-hr
c) Determine the average PM mass concentration
d) Run the 80 S S Cummins cycle to capture PM concentration at each mode using the AVL MSS
e) Check the PM concentration levels and select the six-steady state modes from the 80 point matrix. As a first order, check the concentration at the pre-selected steady-state modes to see if they spread within reason around the concentration produced for the NTE transient cycle. If not, adjust the bypass as needed to establish the right spread in brake-specific emissions and concentration for the six steady-state modes
f) Make sure that the points selected spread around a brake specific level and concentration level of a threshold of 0.025 g/hp-hr, and concentration range of 4 to 15 milligram per cubic meter.

3.2.4 Data Analysis

Use the acquired data to create the "error surfaces" to be used by the Monte Carlo simulation. An example of the steady-state error surface determination is shown in Table 5 for PM.

TABLE 5. EXAMPLE OF SS ERROR SURFACE

Error Surface for SS PM Concentration Figure 5	
x-axis	PM µg/mole (lab mean at setpoint)
y-axis	PM µg/mole (PEMS)
Figure 6	
x-axis	PM µg/mole (lab mean at setpoint)
y-axis 5th percentile	5th [PM µg/mole (PEMS) - PM µg/mole (lab)]
y-axis 50th percentile	50th [PM µg/mole (PEMS) - PM µg/mole (lab)]
y-axis 95th percentile	95th [PM µg/mole (PEMS) - PM µg/mole (lab)]
The 5th, 50th and 95th percentiles from the (PEMS - lab) delta data will be used to estimate the 1st and 99th percentiles from assumed Gaussian distributions.	
Figure 7	
x-axis	PM µg/mole (lab mean at setpoint)
y-axis	ic_SS_PM
z-axis = ΔSS_PM_µg/mole	1st Percentile from Gaussian distribution based on 5th and 50th [PM µg/mole (PEMS) - PM µg/mole (lab)] deltas. 99th Percentile from Gaussian distribution based on 50th and 95th [PM µg/mole (PEMS) - PM µg/mole (lab)] deltas. 50th Percentile based on [PM µg/mole (PEMS) - PM µg/mole (lab)] deltas.
ic sample frequency	once per NTE event trial
ic sample distribution	Gaussian (normal distribution)

3.3 PRECISION ERRORS UNDER TRANSIENT ENGINE OPERATION (DYNAMIC RESPONSE)

3.3.1 Objective

The objective of this portion of the work is to determine the precision error, $\Delta_{TR}\bar{m}_{PM}$, with each PM-PEMS under NTE transient engine operation. This will be achieved by creating a 20 to 25-minute transient NTE cycle where the PEMS measure in each NTE.

3.3.2 Background

PEMS are expected to operate in a repeatable manner over NTE events as short as 30 seconds. Two sources of PEMS precision error are hypothesized: 1) dynamic response to rapidly changing signals, and 2) susceptibility to "history" effects. Dynamic response error includes error due to measurement signal time alignment, and the dissimilarity of the dynamic response and aliasing of signals; including those signals used to determine entry into and exit from the NTE zone. History effects include the effects of previously measured quantities on currently measured quantities. For example, this may be caused by ineffective sample exchange in the PM emissions sampling volumes, or it may be caused by one or more sensors' characteristic rise time or fall time. To account for any dynamic response precision error, the increase in precision error incremental to the steady-state emissions measurement precision will be incorporated into the overall error model.

Selection of short NTE cycles (each 32 seconds) maximizes the sensitivity of this test to effects of dynamic response. Thirty-two seconds was chosen as the minimum instead of thirty seconds, which is the shortest NTE event time, to ensure that 1 Hz ECM updating of torque and speed values would be unlikely to interfere with capturing NTE events. For each repeat of the test cycle, the order of the 30 different NTE events will be the same. In addition the 29 different intervals separating each NTE event from the next will have a range of durations and these will be randomly arranged in each test cycle as well. Fixed arrangement of the NTE events and the inter-NTE events will maximize the sensitivity of this test to dynamic response and history effects, and make the DPF and bypass operation very consistent.

The total length of the NTE transient cycle will assume that only 5 quartz crystal of the Sensors PPMD are working, and it takes five minutes of stabilization time for reusing a crystal after PM collection. Thus, the same NTE transient cycle used in the gaseous PEMS program will be used here, except for changes in the inter-NTE times to accommodate the Sensors PPMD.

3.3.3 Methods and Materials

a. Use a transient engine dynamometer emissions laboratory.
b. Use a laboratory that can accommodate at least three PEMS, their power supplies, the PEMS flow meters, cables and lines.
c. Use same overall guidelines described in section 3.2, but applied to transient engine testing.
d. Record the EEPS' total mass signal during transient testing.

Challenge PEMS to 30 different 32-second NTE events, shown in Table 5, over about 23 minute test cycle, or whatever needed to accommodate the need for five crystals of the PPMD to be operational. Randomize the NTE events shown in Table 6 once, scale up every fifth inter-NTE time, shown in Table 7, to accommodate the PPMD, and use the same order for repeat testing. Repeat the test cycle 10 times for each set of three PEMS. Note that for any torque command that is less than zero, command closed throttle (i.e. zero or minimum fuel command), and motor the engine at the commanded speed for that data point. An example of an NTE transient cycle is shown in Figure 9.

Based on 10 repeats with each set of PEMS, the total number of repeats will be 30 cycles, assuming 1 NTE cycle x 10 repeats x one exhaust configuration x 3 sets of PEMS x one engine (1x10x1x3x1 = 30). Assuming a 25 minutes of NTE with 30 minutes of forced regeneration and preparation for the second repeat, the total number of days for NTE transient testing is 10 days (8 hours per day). This time includes PEMS and engine setup, PEMS warm up, and daily checks.

Prior to executing the first repeat, setup each PEMS and stabilize engine operation at the first inter-NTE operating point. Setup the PEMS according to 40 CFR Part 1065 and PEMS manufacturer instructions, including any warm-up time, zero-spans of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc. Then, when the test cycle starts, switch the PEMS' to sample emissions from the engine. When the text cycle ends, switch the PEMS back to ambient sampling. Complete all post-test lab and PEMS validations according to 40 CFR Part 1065 and according to PEMS manufacturer instructions.

3.3.4 Data Analysis

Discard from further data analysis any NTE events invalidated by any criteria in 40 CFR Part 1065 Subpart J. For each NTE_i event (i=1 to 30), which was repeated 30 times per engine with a specific exhaust configuration (j = 1 to 30), calculate the transient median absolute deviation, MAD_{TRi}, for $\bar{m}_{PM}$, where for each NTE_i event, MAD_{TRi} = median[| NTE_{ij} – median (NTE_{ij}) |]. Next calculate the difference of MAD by subtracting a corresponding steady-state MAD, MAD_{SSi} for $\bar{m}_{PM}$. $MAD_{TRi-SSi} = MAD_{TRi} - MAD_{SSi}$. To determine a corresponding MAD_{SSi}, calculate the PEMS MAD_{SS} at each steady-state median lab value, and then use the median PEMS NTE_i value along the median lab value's axis to find MAD_{SSi} for the corresponding MAD_{TRi} . Do not extrapolate any MAD_{SSi} beyond the minimum or maximum median lab values. Note that some MAD_{SSi} values might be zero because the lab data for that median failed the F-test in the previous section.

For any $MAD_{TRi-SSi}$ less than zero, set that $MAD_{TRi-SSi}$ equal to zero.

Create a transient error surfaces using all of the $MAD_{TRi-SSi}$. Be sure to include any $MAD_{TRi-SSi}$ data points that are equal to zero because they will affect the 1st and 99th percentile values.

TABLE 6. NTE TRANSIENT CYCLE

NTE Event	[1]Speed % Range	[2]Torque % Range	Description
NTE1	17%	[3]32%	Steady speed and torque; lower left of NTE
NTE2	59%	[3]32%	Steady speed and torque; lower center of NTE
NTE3	Governor line	[3]32%	Steady speed and torque; lower right of NTE
NTE4	17%	66%	Steady speed and torque; middle left of NTE
NTE5	59%	66%	Steady speed and torque; middle center of NTE
NTE6	Governor line	66%	Steady speed and torque; middle right of NTE
NTE7	17%	100%	Steady speed and torque; upper left of NTE
NTE8	59%	100%	Steady speed and torque; upper center of NTE
NTE9	100%	100%	Steady speed and torque; upper right of NTE
NTE10	Lower third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE11	Upper third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE12	Middle third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE13	17% - governed	Lower third	Highly transient speed; moderate transient torque
NTE14	17% - governed	Upper third	Highly transient speed; moderate transient torque
NTE15	17% - governed	Middle third	Highly transient speed; moderate transient torque
NTE16	Lower right diagonal		Transient; speed increases as torque increases
NTE17	Upper left diagonal		Transient; speed increases as torque increases
NTE18	Full diagonal; lower left to upper right		Transient; speed increases as torque increases
NTE19	Lower left diagonal		Transient; speed decreases as torque increases
NTE20	Upper right diagonal		Transient; speed decreases as torque increases
NTE21	Full diagonal; lower right to upper left		Transient; speed decreases as torque increases
NTE22	Third light—heavy-duty NTE event from International, Inc. data set		Sample from LHDE
NTE23	Cruise; ~ 50 mph		Sample from HDDE
NTE24	Cruise; ~ 75 mph		Sample from HDDE
NTE25	Small bulldozer		Sample from NRDE
NTE26	Large bulldozer		Sample from NRDE
NTE27	Second of three NTE events in FTP		Seconds used from FTP: 714-725, 729-743, 751-755
NTE28	Third light—heavy-duty NTE event from International, Inc. data set		Sample from LHDE
NTE29	First of two NTE events in NRTC		Seconds used from NRTC: 423-430, 444, 448-450, 462-481, increased 464 speed from 40% to 42%
NTE30	First of two NTE events in NRTC		Seconds used from NRTC: 627-629, 657-664, 685-696, 714-722

1 Speed (rpm) = Curb Idle + (Speed % * (MTS - Curb Idle)
2 Torque (lbf-ft) = Torque % * Maximum Torque At Speed (i.e. lug curve torque at speed)
3 Torque (lbf-ft) = Maximum of (32 % * peak torque) and the torque at speed that produces (32 % * peak power)

TABLE 7. DYNAMIC RESPONSE INTER-NTE EVENTS

INT Event[1]	Duration (s)	Frequency	Description
INT1	10	1	Initiation of cycle; INT1 is always first
INT2-6	2	5	Shortest and most frequent inter-NTE events
INT7-10	3	4	Short and frequent inter-NTE events
INT11-14	4	4	Short and frequent inter-NTE events
INT15-18	5	4	Short and frequent inter-NTE events
INT19-21	6	3	Short and frequent inter-NTE events
INT22	7	1	Medium inter-NTE event
INT23	8	1	Medium inter-NTE event
INT24	9	1	Medium inter-NTE event
INT25	11	1	Medium inter-NTE event
INT26	13	1	Long inter-NTE event
INT27	17	1	Long inter-NTE event
INT28	22	1	Long inter-NTE event
INT29	27	1	Long inter-NTE event
INT30	35	1	Longest inter-NTE event
INT31	5	1	Termination of cycle; INT31* is always last
Interval speeds and torques are not identical, but they are clustered around zero torque and the speed at which 15% of peak power and 15% of peak torque are output.			

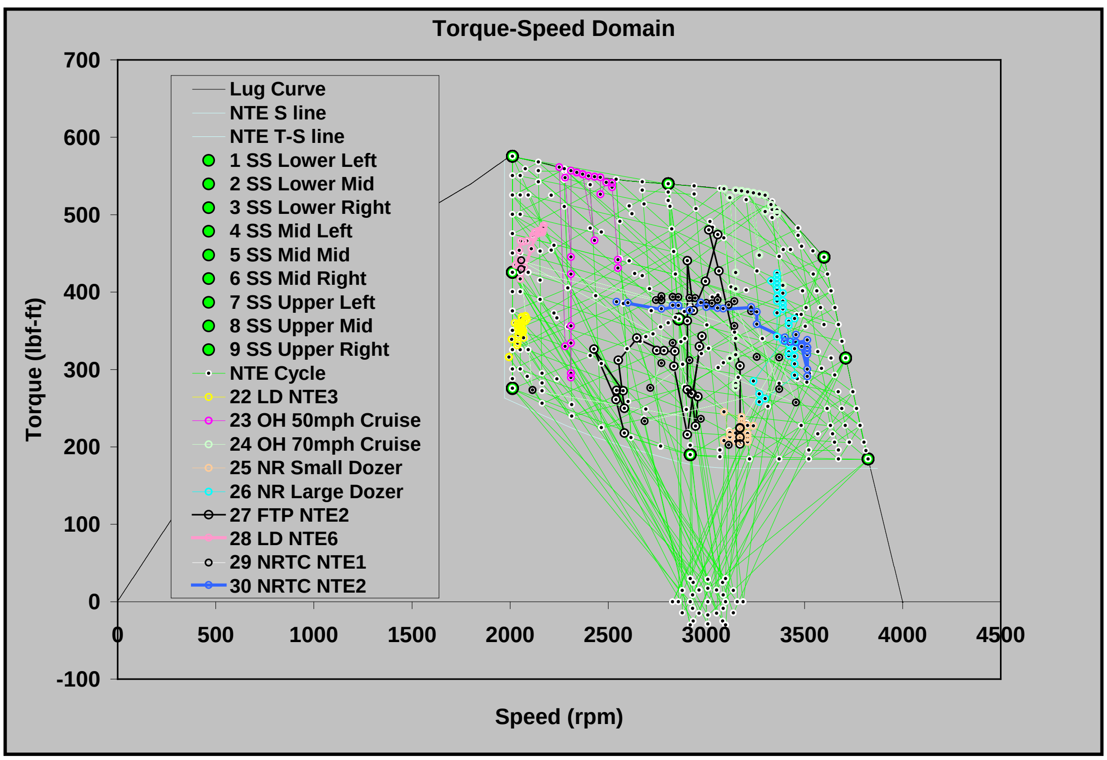


FIGURE 9. EXAMPLE OF A NTE CYCLE

3.4 ECM TORQUE AND BSFC

3.4.1 Objective

Compare the ECM-based torque and fuel rate with that of the laboratory-based measurement using the Cummins 80 SS mode cycles. For the laboratory purposes, use the gas-based fuel flow values instead of the measured fuel flow. Repeat the Cummins 80 SS cycle three times, and use the average values produced.

Use at least six engines for these experiments that include the one engine to be used in the PM PEMS program and Engine B, C, and D of the ACES program.

3.4.2 Data Analysis

Use the acquired data pooled and normalized to % of max torque and % of maximum fuel rate to replace the manufacturer submitted error surfaces that were previously used in the gaseous portion of the Monte Carlo simulation. Refer to section 2.4 for description and example of an error surface. Include any bias error, unless there is an assignable cause that would not occur in-use and the steering committee approves to eliminate such bias error.

4 ENVIRONMENTAL CHAMBER

The environmental chamber tests challenge PEMS to a variety of environmental disturbances, namely electromagnetic interference, atmospheric pressure, ambient temperature and humidity, and shock and vibration.

During each of the tests, plus a baseline test, the PEMS will cycle through sampling four different dilution preparations of aerosol particles that contain volatile hydrocarbon and elemental carbon using a particle generator that mimics the formation of diesel particles. The OC/EC will be used to determine the concentration levels needed for the PM generator. Essentially, after determining the steady-state points to run on the engine, the OC/EC semi-continuous instrument will be used along with the filter-based method. Then, for the concentration levels to be used with the PM generator, the OC/EC instrument will be used to set the PM generator to produce the desired composition and concentration levels, similar to those encountered under steady-state. Three particle concentration levels of 5, 10, and 15 mg/m^3, as shown in Table 8, will be generated by the particle generator. Each concentration will be fed to the PEMS after applying dilution ratios of 6, 12, 20, and 30. For each concentration and dilution ratio combination, the PM generator will be stabilized for 4.5 minutes, and data will be collected by the PEMS for 30 seconds. The test will continue for a period of 8 hours. The first six cycles of every test will serve to be the baseline before any environmental change is made.

The temperature/humidity and pressure tests are designed to mimic real-world environmental disturbances with the magnitude and frequency of the disturbances adjusted to real-world conditions. Randomly sample a uniform distribution of probability for their $i_{c.}$, from any minute of the test. By randomly sampling from the minutes of these tests the magnitude and frequency of the real-world error will be built into the error model, which is described in Section 2. The other environmental tests represent the full range of possible conditions. For these tests, randomly sample the normal distribution in Figure 1 for their i_c.

TABLE 8. CONCENTRATION AND DILUTION RATIO SCHEDULE WITH PM GENERATOR

Raw PM Concentration, µg/m3	Dilution Ratio			
	DR1	DR2	DR3	DR4
	6	12	20	30
	Concentration at Above Dilution Ratio			
5000	833.3	416.7	250.0	166.7
10000	1666.7	833.3	500.0	333.3
15000	2500.0	1250.0	750.0	500.0

For EMI/RFI and vibration, the instruments will be subjected to screening tests with HEPA filtered air to detect if there any changes in the response of the instruments. Based on these results, the MASC will decide if the particle generator will need to be used with these tests.

For the vibration screening test, in order to avoid damage to the instruments, a frequency sweep will be used at low amplitude. The idea here is to detect the frequency that may trigger a response by the instrument, without doing any damage due to high amplitude.

4.1 DATA ANALYSIS FOR ENVIRONMENTAL TESTS

Reduce data by first calculating means for each 30-second period of stabilized measurements. Subtract from each mean the respective baseline concentration. The results are errors or "deltas". Correct each of these error distributions by removing their respective baseline variances, which were determined by quantifying PM Generator output with no environmental perturbations. Calculate the variance of each of the distributions. Subtract the respective baseline variance from each calculated variance. Use the resulting difference in variance as the target variance for adjusting the error distributions. If the target variance is zero or negative, leave all error values of the distribution as is and do not proceed to the next step. If the target variance is positive, iteratively solve to find a single numerical value that can be used to divide each error in a given distribution such that the resulting distribution has a variance equal to the target variance. Now each of the errors is corrected for baseline variance.

Then, calculate the NTE result with all errors, including torque and flow errors set to zero. This is the true value. Then subtract the true NTE value from the result with all errors and record this difference in one of the 7 measurement allowance distributions: $\bar{m}_{PM}$ times three calculation methods (torque-speed, fuel-specific * BSFC, ECM fuel flow) times three PEMS manufacturers, except Sensors and Horiba can not use the ECM fuel flow calculation method. Then proceed to the next NTE event in the nominal data set. Repeat the entire nominal data set over and over until all 7 measurement allowance distributions converge. Follow the data reduction steps set out in Section 2 to select the final measurement allowance.

4.2 PM GENERATOR COMMISSIONING

The PM generator is developed by EPA. The PM generator can create various hydrocarbon mixtures along with solid particle generation using carbon rods arcing. The PM generator is also equipped with a micro-proportional diluter, and is intended to simulate diesel exhaust particle phase compounds.

EPA will ship the PM generator to SwRI. EPA (Matt Spears) will train SwRI staff on using it. In addition, SwRI together with EPA may incorporate to it a soot particle generation mechanism that is different than the carbon rod arcing, using instead a propane flame mini-CAST technology.

The PM generator will be used during atmospheric chamber testing, temperature and humidity testing, and may be used during EMI/RFI and vibration experiments.

4.3 BASELINE

4.3.1 Objective

The baseline *variance* will be established using an 8 hour baseline test in which the PM generator cycles through the same compositions and concentrations of PM used during the actual environmental tests. Mean values will be determined from the first five cycles through the PM concentrations. Deviations (deltas) from these mean values during subsequent cycles through the concentrations will be used to determine the baseline variance. This variance will be subtracted from the environmental test results.

4.3.2 Background

All of the other environmental tests inherently incorporate the baseline bias variance of the PEMS. Because the Monte Carlo simulation model adds all the errors determined from the various environmental tests, it would add the baseline variance of PEMS to the model too many times. In order to compensate for this in the model, the baseline variance of PEMS is determined and subtracted from each of the environmental tests' results.

Note that the baseline variance of PEMS is measured and modeled (i.e. added) once as part of the steady-state engine dynamometer laboratory experiment.

4.3.3 Methods and Materials

For this experiment use a well ventilated EMI/RFI shielded room capable of maintaining reasonably constant temperature and pressure. Use a room that can house one of each PEMS, their power supplies, the PEMS flow meters, cables and lines.

Prior to executing the baseline test, setup each PEMS and stabilize the PEMS in the room. Perform PEMS setup according to 40 CFR Part 1065 Subpart J and PEMS manufacturer instructions, including any warm-up time, and audit. Then supply the PEMS' sample ports with the sequence of PM from the PM generator as described at the beginning of Section 4.

At each PM concentration, flow PM long enough so that stable readings of the PEMS can be recorded. When the OC/EC analyzer is used to spot-check the output of the PM generator, ensure that enough time has elapsed to achieve an accurate OC/EC analysis.

Position PEMS and configure PM transport tubing to minimize transport delays and PM losses.

Test at least one PEMS from each PEMS manufacturer.

4.3.4 Data Analysis

Reduce the baseline data for each PM PEMS, using artificial NTE sampling event times. Subtract from each $\overline{m}_{PM}$ the mean $\overline{m}_{PM}$ from the initial (short) baseline test of six cycles through the PM concentrations, which were conducted at the beginning of the test. The results are errors or "deltas". Calculate the variance of these values, and use them for baseline variance correction in the data reduction of the remaining environmental tests.

4.4 ELECTROMAGNETIC RADIATION

4.4.1 Objective

Evaluate the effect of Electromagnetic Interference (EMI) and Radio frequency Interference (RFI) on the performance of the PEMS and determine error factors for the PEMS due to these effects. First, a screening test on each instrument will be performed with HEPA filtered air to determine if the EMI/RFI affects the instrument response. If it does, the MASC will decide on the test matrix required for this evaluation.

4.4.2 Methods and Materials

Use an EMI test facility capable of running the SAE tests listed above. This would include: Signal generators, Power amplifiers, Transmit antennas, Electric Field Sensors, Measurement Receiver, Data recording device, LISNs (Line Impedance Stabilization Networks) and shielded enclosure.

4.5 ATMOSPHERIC PRESSURE

4.5.1 Objective

Evaluate the effects of ambient pressure on PEMS PM concentration outputs.

4.5.2 Background

PEMS are expected to operate over ranges of ambient pressures. It is hypothesized that some of the errors of the PEMS concentration outputs may be a function of ambient pressure. Therefore, this experiment will change the ambient pressure surrounding PEMS to evaluate its effects on PEMS measured concentrations and flow meter transducer outputs. As with all of the environmental tests, the test cycle for this test is based on the best-known distribution of real world conditions. For this test, the test cycle pressure distribution was matched to the county-by-county annual average atmospheric pressure distribution in EPA's 2002 National Emissions

Inventory (NEI) model. Figure 10 depicts the NEI data distribution (based on 3149 data points) and the test cycle pressure distribution.

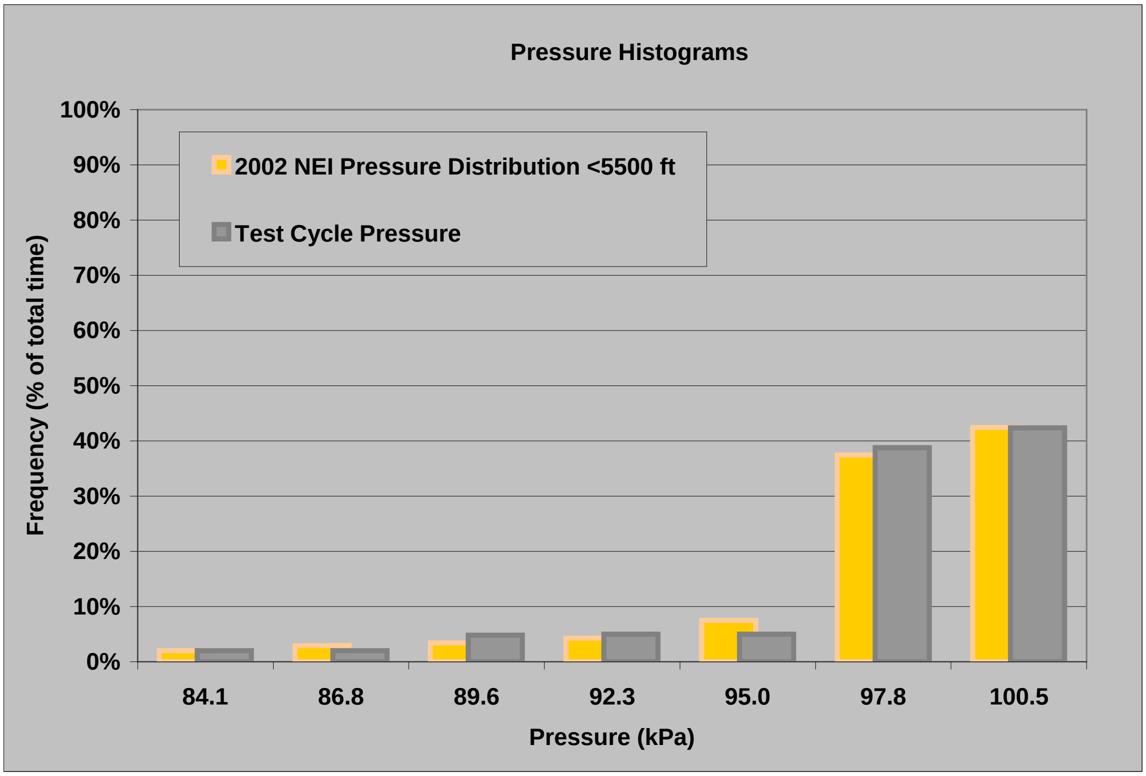


FIGURE 10. PRESSURE HISTOGRAM

4.5.3 Methods and Materials

Use a barometric chamber that can be well ventilated and capable of controlling a wide range of pressure changes (82.74 to 101.87 kPa). Use a chamber that can house at least three PEMS at a time, one of each PEMS manufacturer, their power supplies, the PEMS flow meters, cables and lines, plus the PM generator.

Follow a pattern of first soaking the PEMS at a constant pressure, then ramp the pressure to a new pressure, soak the PEMS at that new pressure, and then ramp to another pressure. Use the sequence of pressures and times, as shown in Table 9 along with Figure 11, to simulate a typical distribution of real-world pressures and changes in pressure, which are believed to be dominated by changes in altitude during driving in the United States.

TABLE 9. ATMOSPHERIC PRESSURE TEST SEQUENCE

Atmospheric Pressure Test Sequence					
	Pressure		Time	Rate	
Phase	kPa	Alt. ft.	min	ft/min	Comments
1 Soak	101	89	10	0	Flat near sea-level
2 Ramp	101-97	89-1203	20	56	Moderate hill climb from sea level
3 Soak	97	1203	20	0	Flat at moderate elevation
4 Ramp	97-101.87	1203- -148	60	-23	Moderate descent to below sea level
5 Soak	101.87	-148	20	0	Flat at extreme low elevation
6 Ramp	101.87-101	-148-89	20	12	Moderate hill climb to near sea level
7 Soak	101	89	20	0	Flat near sea level
8 Ramp	101-97	89-1203	20	56	Moderate hill climb from sea level
9 Soak	97	1203	25	0	Flat at moderate elevation
10 Ramp	97-96.6	1203-1316	20	6	Slow climb from moderate elevation
11 Soak	96.6	1316	20	0	Flat at moderate elevation
12 Ramp	96.6-82.74	1316-5501	20	209	Rapid climb to NTE limit
13 Soak	82.74	5501	20	0	Flat at NTE limit
14 Ramp	82.74-96.8	5501-1259	30	-141	Rapid descent from NTE limit
15 Soak	96.8	1259	20	0	Flat at moderate elevation
16 Ramp	96.8-90	1259-3244	15	132	Rapid hill climb to mid elevation
17 Soak	90	3244	10	0	Flat at mid elevation
18 Ramp	90-96.8	3244-1259	20	-99	Rapid descent within middle of NTE
19 Soak	96.8	1259	20	0	Flat at moderate elevation
20 Ramp	96.8-99.2	1259-586	20	-34	Moderate descent to lower elevation
21 Soak	99.2	586	20	0	Flat at lower elevation
22 Ramp	99.2-101	586-89	10	-50	Moderate decent to near sea-level
23 Soak	101	89	20	0	Flat near sea-level

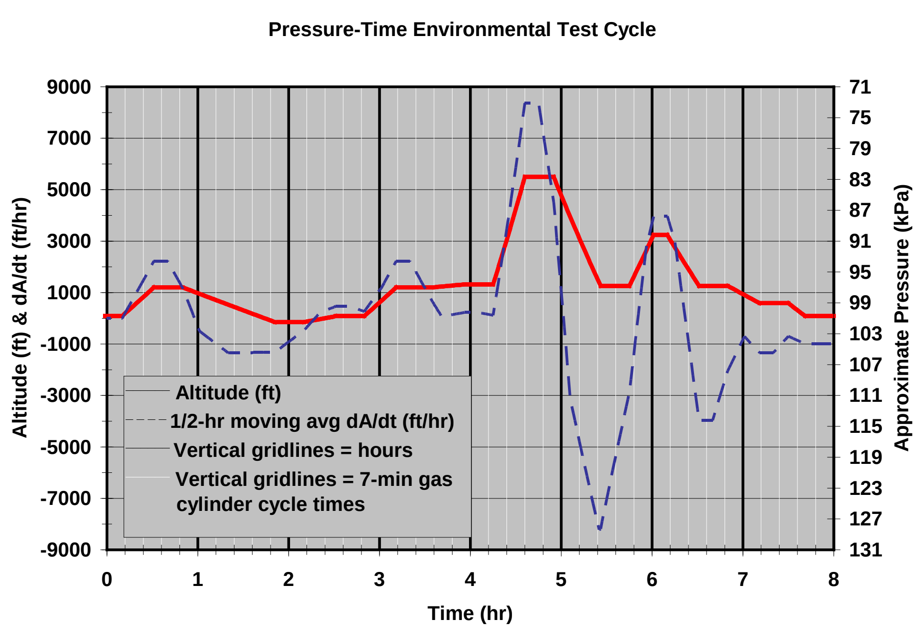


FIGURE 11. PRESSURE-TIME ENVIRONMENTAL TEST CYCLE

Prior to executing this pressure sequence, setup each PEMS and stabilize the PEMS in the chamber's first pressure. Perform PEMS setup according to 40 CFR Part 1065 Subpart J and PEMS manufacturer instructions, including any warm-up time, zero-span-audits of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc. Then supply the PM PEMS' sample port with the sequence of PM from the PM generator as described at the beginning of Section 4.

Flow each generated PM sample long enough so that at least 30 seconds of stable readings are recorded for the slowest responding gas concentration output of all the PEMS. Position PEMS and configure gas transport tubing to minimize transport delays. Target to sample about 30 seconds. Repeat this cycle over the 8-hr test cycle, by cycling through the concentration shown in Table 8, which represents one hour of testing, using a 4.5 minutes of stabilization and 30 seconds of sampling at each condition.

Perform this test once for one set of PEMS with as many PEMS tested at once.

4.5.4 Data Analysis

Perform data analysis according to Section 4.1.

4.6 AMBIENT TEMPERATURE AND HUMIDITY

4.6.1 Objective

Evaluate the effects of ambient temperature and humidity on PEMS PM concentration outputs. The histogram in Figure 12, along with Table 10 and Figure 13, will be updated by a new temperature profile that takes into consideration the data generated by CE-CERT.

4.6.2 Background

PEMS are expected to operate over a wide range of changing ambient temperatures. It is hypothesized that some of the errors of the PEMS outputs may be a function of changes in ambient temperature. Therefore, this experiment will change the ambient temperature surrounding PEMS to evaluate its effects on PEMS measured concentrations and flow meter transducer outputs. As with all of the environmental tests, the test cycle for this test is based on the best-known distribution of real world conditions. For this test, the test cycle temperature distribution was matched to the hour-by hour county-by-county average atmospheric temperature distribution, weighted by vehicle miles traveled according to EPA's 2002 National Emissions Inventory (NEI) model. Figure 12 depicts the NEI data distribution (based on over 900,000 temperatures and over 270 trillion vehicle miles) and the test cycle temperature distribution.

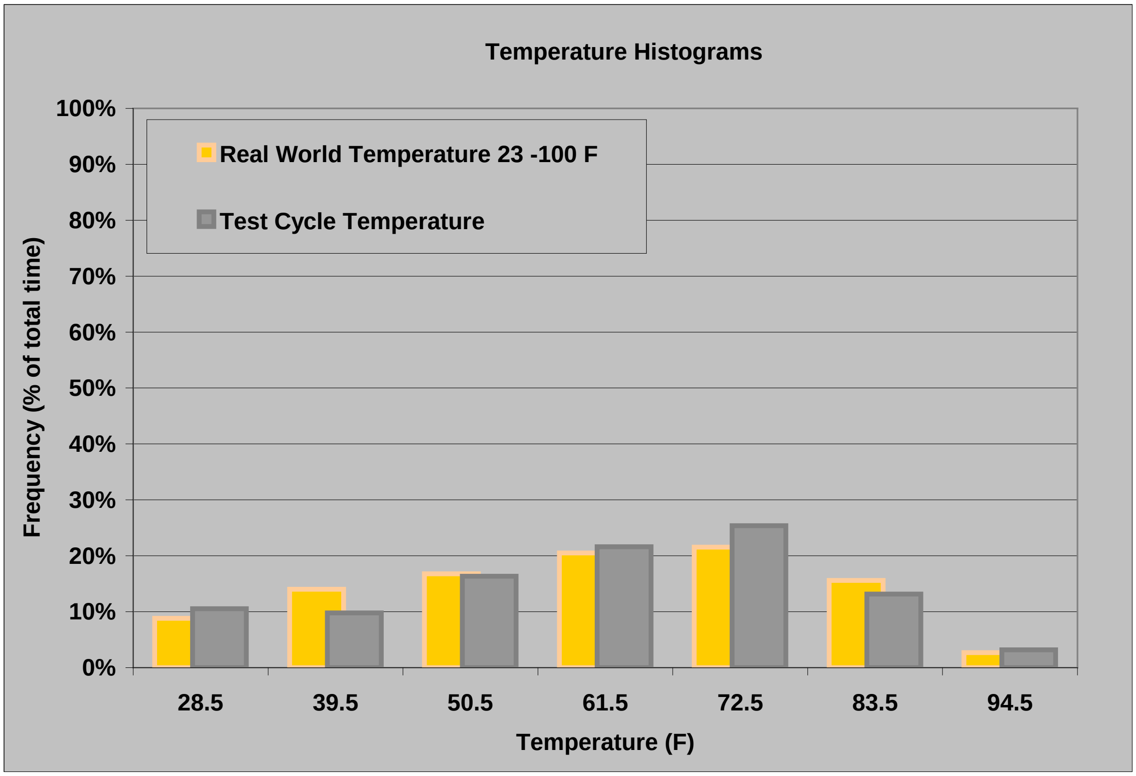


FIGURE 12. TEMPERATURE HISTOGRAM

4.6.3 Methods and Materials

Use a well ventilated room capable of controlling a wide range of temperature changes (-23 to 100°F). Use a room that can house at least six PEMS, their power supplies, the PEMS flow meters, cables and lines, plus seven different zero, audit, and span gas cylinders, and a gas switching system.

Follow a pattern of first soaking the PEMS at a constant room temperature, then ramping the room temperature to a new temperature, soaking the PEMS at that new temperature, and then ramping to another temperature. Use the following sequence of temperatures, shown in Table 10 and Figure 13, and times to simulate the range of real-world temperatures and changes in temperature:

TABLE 10. AMBIENT TEMPERATURE TEST SEQUENCE

Ambient Temperature Test Sequence					
	Temperature		Time	Rate	
Phase	°C	°F	min	°C/min	Comments
1 Soak	13.89	57	10	0.00	Cool in-garage pre-test PEMS operations
2 Ramp	13.89-5.00	57-23	5	-3.78	Leaving cool garage into cold ambient
3 Soak	-5.00	23	5	0.00	Operating at cold temperature outside of vehicle
4 Ramp	-5.00-12.78	23-55	145	0.12	Diurnal warming during cool day
5 Soak	12.78	55	40	0.00	Steady cool temperature during testing
6 Ramp	12.78-28.33	55-83	5	3.11	Return to hot garage on a cool day
7 Soak	28.33	83	52	0.00	Hot in-garage pre- post- test PEMS operations
8 Ramp	28.33-37.78	83-100	5	1.89	Leaving ho garage into hot ambient
9 Soak	37.78	100	8	0.00	Operating at hot temperature outside of vehicle
10 Ramp	37.78-22.22	100-72	100	-0.16	Diurnal cooling during hot day
11 Soak	22.22	72	60	0.00	Steady moderate temperature during testing
12 Ramp	22.22-13.89	72-57	5	-1.67	Return to cool garage on a moderate day
13 Soak	13.89	57	40	0.00	Cool in-garage post-test PEMS operations

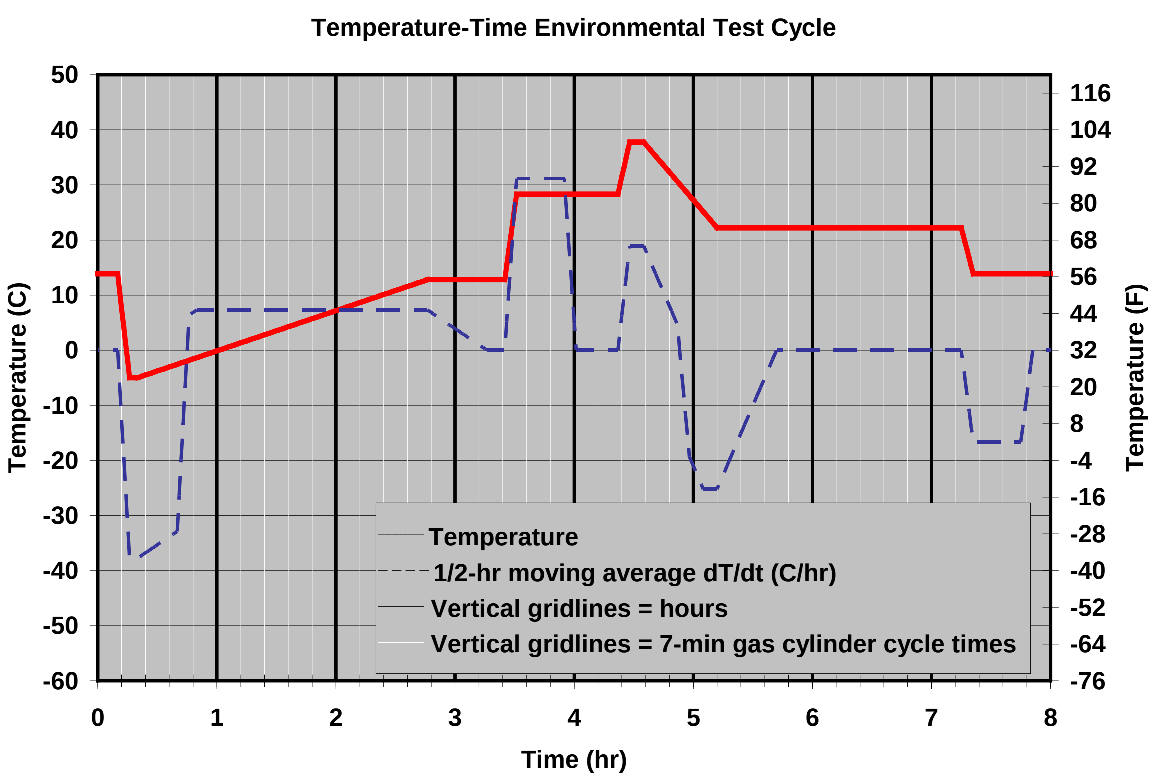


FIGURE 13. TIME SERIES CHART OF AMBIENT TEMPERATURE TEST

Prior to executing this temperature sequence, setup each PEMS and stabilize the PEMS in the chamber's first temperature. Perform PEMS setup according to 40 CFR Part 1065 Subpart J and PEMS manufacturer instructions, including any warm-up time, zero-span-audits of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc.

Run the 8-hour cycle test by stepping through the concentration and dilution ratio shown in Table 8.

4.6.4 Data Analysis

Perform data analysis according to Section 4.1.

4.7 ORIENTATION AND VIBRATION

4.7.1 Objective

Evaluate the effect of vehicle vibration on the performance of the PEMS and determine error factors for the PEMS due to these effects. Prior to doing extensive vibration work, perform a screening using HEPA filtered air sampling at a sweep of different frequencies with low amplitude. If any of the PEMS shows a response to a particular frequency, propose a frequency test and submit it for the MASC for approval.

5 SWRI CVS AND CE-CERT TRAILER CORRELATION

Prior to performing the in-use work with the PM-PEMS, it is important to establish the degree of correlation between SwRI CVS-based PM measurement and CE-CERT CVS-based PM measurement. For this purpose, the CE-CERT trailer will move to SwRI facilities and PM measurement will be conducted on the engine used for the PM-PEMS program.

Prior to the correlation with SwRI, the CE-CERT MEL will conduct a 1065 audit of the PM measurement system and associated weighing chambers and stations and associated electronic sensors and monitors. This audit will include verification of the secondary dilution flow and temperature controllers. The sampling system will be checked to make sure it holds the appropriate temperatures and within the appropriate limits. The filter holders will be checked for compliance and the log books will be examined to ensure they appropriately monitor all the parameters needed for 1065 compliance. CE-CERT will identify areas where the current CE-CERT procedures or equipment does not meet the 1065 regulations and will upgrade these systems or procedures so that they are compliant with the 1065 regulations.

The CE-CERT's MEL will be cross-correlated with an engine cell at SwRI using an engine selected by the SC. Testing will be conducted under the NTE transient cycle with the 0.025 g/hp-hr bypass setting as determined by the SC.

5.1 METHOD AND MATERIALS

Below is a list of a step by step approach for the correlation between SwRI and CE-CERT

1. Perform a propane check on SwRI CVS and 47 mm filter and CE-CERT CVS and 47 mm filter. Both systems should pass Part 1065 on propane. However, even if they pass, note any difference between the two.
2. Set the CVS flow rate to be the same on both systems
3. Set the filter face temperature and velocity to be the same on both systems
4. Set the secondary dilution ratio to be the same on both systems.
5. Use Whatman PTFE membrane filters (7592-104), and filter screens that meet the latest Part 1065.
6. Modify the exhaust path to SwRI CVS to be comparable with that for the CE-CERT Trailer
7. Since SwRI is using a test cell that may have had various PM levels, both SwRI and CE-CERT should precondition on the same engine. Thus, it is recommended that CE-CERT clean their tunnel prior to traveling to SwRI so that both can be conditioned on a similar emissions level.
8. Pre-condition the SwRI CVS tunnel and the CE-CERT trailer CVS tunnel for a period of 10 hours at engine rated power using exhaust configuration with DPF without bypass. The conditioning time may include active DPF regenerations.
9. Run a total of 12 repeats of the NTE transient cycle using DPF with Bypass Level at 0.025 g/hp-hr emission level, over a period of three days. Four repeats per day with the CE-CERT followed by four repeats with SwRI CVS and then alternate. Prior to each set of four repeats manually regenerate the DPF.
10. Use SwRI DMM-230 and CE-CERT DMM-230 to make sure that the engine PM source is not shifting and being consistent.
11. SwRI should handle and weigh all the filters for both SwRI and CE-CERT in accordance with their protocol.
12. The CE-CERT trailer is needed at SwRI for at least two weeks per engine. One week for setup and two weeks of testing assuming the above schedule.
13. In a separate task, EPA will equilibrate and pre-weigh 20 filters using EPA's weighing protocol. EPA will then ship them to SwRI for repeat preweighing using their protocol. SwRI will then ship the same filters to EPA for reweighing. After reweighing at EPA, EPA will ship the filters to CE-CERT for weighing using CE-CERT's weighing protocol. Finally, CE-CERT will ship the filters to EPA for reweighing. Results will be reported by EPA for MASC discussion. No threshold for acceptance has been established at the time of this testplan writing.
14. The target for correlation at the 0.025 g/hp-hr level is CE-CERT's mean of 12 repeats being within +/-10% of the mean value reported by SwRI.

6 MODEL VALIDATION AND MEASUREMENT ALLOWANCE DETERMINATION

The pre-validated measurement allowance value for both or at least one PEMS will be determined prior to the in-use model validation at CE-CERT. If both PEMS systems have determined reasonable measurment allowances, then the validation testing will be performed on the PEMS that shows the lowest measurement allowance.

The MASC decided to validate only one of the complete PM PEMS systems Horiba or Sensors where AVL will "piggy back" on either PEMS as part of the model validation. Thus the testing is a full set of tests where three model PEMS from one manufactures over three routes with one bypass setting and one vehicle will be tested. If the selected model PEMS does not validate the

MA SC has the option to try validating the second manufactures PEMS. This additional validation is not covered in the CE-CERT scope of work and would require a budget modification.

6.1 MODEL VALIDATION

6.1.1 Objective

The objective of the validation testing is to validate the Monte Carlo model by

1. Testing the PEMS in parallel with the CE-CERT trailer
2. Checking the data to see if it fits the model predicted based on the SwRI laboratory efforts

For the model validation testing effort, CE-CERT will conduct preliminary planning for the PEMS installation and commissioning. For each PEMS model tested, a total of 5 test days are allocated for commissioning. Subsequent PEMS commissioning of like models should take less time and thus only 3 test days are allocated. The PEMS commissioning will be performed with the assistance of the PEMS manufacturer on site. CE-CERT will procure Whatman filters for both CE-CERT & Horiba filter weighing process.

CE-CERT will design, construction, and install a bypass. CE-CERT will purchase the parts for a bypass. The bypass will be "tuned" to the BSPM level requested by the committee. Initially, it is planned to tune to 0.025 g/hp-h at clean DPF condition, which could give a range of values from 0.01 to 0.04 g/hp-h depending on in-use conditions and DPF regeneration status. The use of a PM PEMS may be incorporated into this part of tuning to provide instantaneous feedback on the PM level in addition PM filters will be used to determine actual level. This tuning data will be made available to the MA SC as additional PEMs-MEL deltas, but be denoted as preliminary tuned data since values could exceed the desires of the MA program.

Long line lengths will be employed to ensure good mixing. CE-CERT will use good engineering judgment to determine if good mixing is established. CE-CERT will evaluate good mixing by measuring the real time PM with the AVL PEMS while attempting to traverse the exhaust stack. Given the limitation to work around a vehicle during in-use testing, traversing the exhaust may require some type of alternative test procedure once the bypass is fabricated. CE-CERT will work with the MA SC to determine when a suitable well mixed bypass has been achieved.

The test matrix and test costs depend on the actual number of PEMS tested, number of bypass configurations, and the number of routes. For this scope of work three model PEMS from one manufactures over three routes with one bypass setting and one vehicle will be tested. This test matrix is based on the recommendation of the SC. If a second manufacture PEMS requires testing then a new scope of work will be needed and a budget change.

The primary testing will be focused on true NTE events if practically possible and/or forced triggered events. The target level of≥ 50 ug will be set for the filter measurements by the MEL. If Horiba PEMS is chosen then the Horiba filter will be replaced one time for every 8 MEL filters to simulate an 8 hour operation for the Horiba filter. All filter weighing for both the CE-

CERT and Horiba filters (if selected) will be performed by CE-CERT using CE-CERT's weighing procedures.

For the test matrix chosen three models of one manufacture PEMS will be tested over three routes with one additional test day allocated, see Table below. One additional day is allocated for repeating a test route or for operating the PEMS in a "true" NTE mode or combination of both. The PEMS will be tested over each route/test-bypass configuration for a total of 4 test days. A total of 10 prep days are allocated for the preparation and installation of the first PEMS for each manufacturer, 5 test days are allocated for commissioning each PEMS, and 3 days are allocated for changing between PEMS of a single manufacturer. Subsequent PEMS commissioning of like models should also take less time and thus only 3 test days are allocated.

Table - Three Models of One PEMS Manufacture Test Matrix

Mfg	Unit #	Route	Test Conditions	Total test days
PEMS plus AVL	1	Palm Springs San Diego Baker	1 bypass 0.025 g/hp-h	4
PEMS plus AVL	2	Palm Springs San Diego Baker	1 bypass 0.025 g/hp-h	4
PEMS plus AVL	3	Palm Springs San Diego Baker	1 bypass 0.025 g/hp-h	4

Truck rental for extended period of time for setup and PEMS installation is included under this task. This could include a Volvo because of parts availability or a different model for ease of bypass installation.

Data analysis with engines outside of the NTE requires additional data processing for Method 2. During Method 2 calculation there is a summation of the inverse of fuel rate. The fuel rate on some conditions outside the NTE can go to zero causing the calculation to go to infinity. In these situations it was decided by the MASC to freeze the bsFC to a constant value during out-of-NTE operation using the last valid BSFC NTE value. CE-CERT will perform this bsFC freezing in the Method 2 summation during data post processing for both the PEMS and MEL. The logic to start and stop freezing will be determined by the MASC and provided to CE-CERT before processing Method 2 results.

$$Method2 = \frac{\sum g}{\sum \left[\frac{Carbon_{fuel}}{ECM_{fuel}} \times Work \right]}$$

6.1.1.1 CE-CERT Validation

The difference between the PEMS results and the CE-CERT trailer results will be compared to the error predicted by the Monte Carlo model. To validate the Monte Carlo model, data must be run through the model and the model results must predict the actual test results within a reasonable level of accuracy.

Validation will be based on the following procedure. For each reference NTE event, the Monte Carlo model will be used to generate the 5th and 95th percentiles of the simulated distribution of the brake-specific PM emission differences. In order to obtain simulations representing similar conditions to those obtained on-road, some error surfaces may need to be suppressed in the simulations since not all of them may be applicable to the on-road conditions. The choice of which error surfaces to suppress would need to be made by the Steering Committee.

Next, the 5th and 95th delta percentiles obtained from the above simulations will be separately fit to a line or curve using two chosen methods: a linear regression procedure and a local regression (loess) technique[1]. Depending on which of the resulting two fits is best for each set of data (i.e., either for the 5th percentile deltas or the 95th percentile deltas), the resulting line or curve will be used as one of the lower or upper limits for the on-road data.

To determine the best fit for a given set of delta percentiles (i.e., 5th or 95th), a simple regression line initially will be fit to the data. If a least squares linear regression of the 5th or 95th percentile deltas versus the ideal PM emission has an $r^2>0.85$ and an $SEE < 5$ % of the median ideal PM emissions, then the regression line will be used. If this set of criteria is not met, then a loess fit will be used. Since a loess regression requires the selection of a smoothing parameter[2] to smooth the data, the chosen smoothness parameter should balance the residual sum of squares against the smoothness of the fit.

The on-road delta errors, obtained from the results of collecting data on several NTE events during on-road operations, will be plotted on a graph containing the 5th and 95th percentile delta limits determined from the regression fits chosen above. The graph will consist of a plot of delta PM versus ideal PM. The number of on-road points outside these limits will be determined and expressed as a percentage of the total number on on-road data points. If this number does not exceeds 10% of the total number of on-road data, the simulation data will be considered to be valid.

6.2 MEASUREMENT ALLOWANCE DETERMINATION

6.2.1 Objective

Use the Monte Carlo simulation program developed with data from sections 2, 3 and 5, and validated with section 5.1 to determine the measurement allowance for all regulated emissions, at 2007 emissions standards.

6.2.2 Background

After the Monte Carlo model has been validated and confidence in its ability to predict errors from PEMS instrumentation, the last step in this program will be to actually calculate a single set of measurement allowance for PM.

6.2.3 Methods and Materials

Using the criteria explained in section 2.2 calculate the various levels of measurement accuracy corresponding to the three PEMS manufacturers and the brake specific PM emissions calculations. Use all the various error surfaces developed during this test program, including those provided by engine manufacturers to the EPA and ARB.

6.2.4 Data Analysis

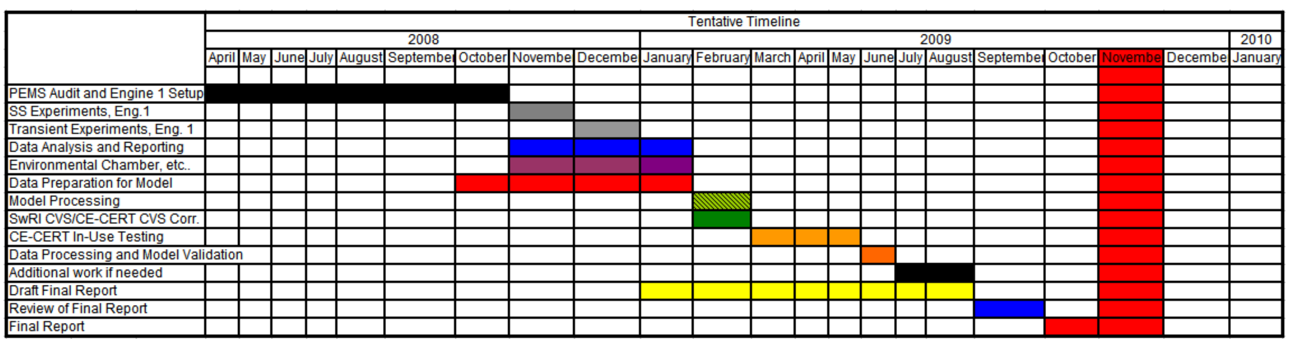
Use the methodology explained in section 2.2, and Table 2.2 to arrive at the final measurement allowance.

7 TIME AND COST

7.1 TIMELINE

Table 11 is a tentative time line projecting the major tasks to be accomplished during this program. The additional work if needed option is the work that may need to be done if the model did not validate. Otherwise, the final report will be submitted by September 30, 2009.

TABLE 11. PROJECTED PM-PEMS TIMELINE



7.2 COST

The rough estimated cost is shown in Table 12. Based on the current estimate, a $125,000 of the $200,000 is needed to complete the project.

TABLE 12. PROJECTED COST ESTIMATE

PEMS Training, Setup, Audit, and Debug	$660,000
Steady-State and Transient Experiments	$190,000.00
SwRI and CE-CERT Correlation (1 engine)	$75,000.00
PM Generator and Environmental Testing Activities	$200,000.00
Modeling Activities (Including CO_2)	$225,000.00
Data and analysis, reporting, and final report	$150,000.00
Contingency if validation fails	$100,000.00
General Contingency	$200,000.00
Grand Total	$1,800,000.00
Grand Total Without General Contingency	$1,600,000.00
Grand Total without General Contingency and Contingency if Validation Fails	$1,500,000.00

8 ABBREVIATIONS USED IN BRAKE SPECIFIC EQUATIONS

Method 1:

ePM = brake-specific emission, PM (g/hp-hr)
N = total number (of time intervals) in series
x = amount of substance fraction (mol PM/mol exhaust; note that 1µmol (emission constituent)/mol (exhaust) = 1ppm (part per million)

$\dot{n}$ = amount of substance rate (mol/sec, in this case, mol (exhaust)/sec
Δt = time interval (sec)
fn = rotational frequency (shaft), rev/min
T = torque (N-m)

NOTE: The units of the numerator work out to gemission as is. However, using the units given for the denominator (RPM * N-m * s), you would still need to divide by 1.978 to get to hp-hr (using RPM * N-m = kW * 9550, 1 hour = 3600 sec, and kW = hp*0.7457)

Method 2:

ePM = brake-specific emission, PM (g/hp-hr)
MNO2 = Molecular weight, NO2 (~46 g/mol)
N = total number (of time intervals) in series
x = amount of substance fraction (mol PM/mol exhaust; note that 1µmol (emission constituent)/mol (exhaust) = 1ppm (part per million)

$\tilde{\dot{n}}$ = amount of substance rate (mol/sec, in this case, mol (exhaust)/sec) that is linearly proportional to $\dot{n}$ (Note: this is a proportional sample, which means that you may use a flow meter that has a span error, as long as its calibration is linear)
Δt = time interval (sec)

MC = Atomic weight of carbon (~12 g/mol)
wfuel = g (carbon)/g (fuel); Note fuel is roughly 86% carbon by mass
xCproddry = amount of carbon products on a C1 basis per dry mol of measured flow (exhaust), mol/mol, solved iteratively per 1065.655
xH2O = amount of water in measured flow, mol/mol (see 1065.645 for calculations)
efuel = brake-specific fuel consumption (g (fuel)/hp-hr)

Method 3:

ePM = brake-specific emission, PM (g/hp-hr)
MNO2 = Molecular weight, NO2 (~46 g/mol)
wfuel = g (carbon)/g (fuel); Note fuel is roughly 86% carbon by mass
MC = Atomic weight of carbon (~12 g/mol)
N = total number (of time intervals) in series

x = amount of substance fraction (mol PM/mol exhaust; note that 1µmol (emission constituent)/mol (exhaust) = 1ppm (part per million)

$\dot{m}_{fuel}$ = mass rate of fuel (g/sec)
xH2O = amount of water in measured flow, mol/mol (see 1065.645 for calculations)
xCproddry = amount of carbon products on a C1 basis per dry mol of measured flow (exhaust), mol/mol
Δt = time interval (sec)
fn = rotational frequency (shaft), rev/min
T = torque (N-m)
Δt = time interval (sec)

NOTE: The units of the numerator work out to gemission as is. However, using the units given for the denominator (RPM * N-m * s), you would still need to divide by 1.978 to get to hp-hr (using RPM * N-m = kW * 9550, 1 hour = 3600 sec, and kW = hp*0.7457)

APPENDIX B

STEERING COMMITTEE MEETING MINUTES

PM Measurement Allowance Steering Committee Meeting
Meeting at CE-CERT
April 23, 24, and 25, 2008

Future Meetings:

1. May 15-16 meeting, SwRI
2. June 12 and 13 at for PM-PEMS and 10 and 11 for EMTC, ACS.
3. July 29 and 30, San Antonio, SwRI
4. August 28, 29, San Antonio, SwRI

On-Road PM PEMS Discussion and Action Items

CO_2 Activities

1. Use CO_2 data provided by CE-CERT during the gaseous program for CO_2 validation, and share the information during the May 15-16 meeting at SwRI.

Test Plan Activities

a. Explain in test plan why Horiba can't use Method 3
b. Replace BSFC in the equation of Method 2 with (fuel flow/torque *speed). Essentially, remove BSFC error surface
c. Show how (mp bar) for the AVL is calculated
d. For AVL Method 3, use a different error surface for PM.
e. For reference NTEs, use the existing reference NTEs, and PM concentrations to produce different concentration from DPF out to threshold levels.
f. Check section 2.3 with Bob Mason to make sure it is correct
g. Change the example to PM in the test plan and give an appropriate PM concentration range per mole basis.
h. Reexamine the text to explain the new equations better. No second by second for AVL
i. Change Figure 8 in the test plan to reflect the fuel flow inclusion, and remove BSFC error.
j. Change Figure 8 to update all errors that are required
k. State the time and date by when the model could be available to the group, assuming no last minute changes are required.

General Notes:

1. For AVL, use a 3 to 1 dilution ratio and change the selectable range if needed but not the dilution ratio.
2. For the NTE windowing, use the EEPS to determine the windowing sensitivity, assuming a maximum of 6 seconds delay at the beginning and end.
3. Measure the CVS dilution air temperature as close as close as possible to the exhaust and dilution air mixing point. This may require insulation of SwRI CVS system.
4. Use Whatman Teflon membrane, 2 micrometer for the entire program

5. Use the fine ambient backup screen instead of the coarse or diesel backup screen
6. List all the error surfaces in the test plan
7. Plan Training and Comissioning of the PM Generator
8. If 32 seconds NTE is not sufficient for the PM-PEMS, extend the length
9. Use 10 % difference as an acceptable difference between SwRI and CE-CERT

1065 Audit (For reference see SwRI presentation)

TSI Flow Meters

- Using reference flow meters like the TSI flow meter as a transfer standards is okay, if independently checked via a master flow meter

Sensors PPMD

a. Verify that the external and bypass flow TSI flow meter certificates are valid for duration of testing
b. Verify that the data published on their individual certificates meet the 1065 linearity thresholds

Horiba TRPM

- Use total flow and dilution air flow for Horiba and make sure they meet 1065 linearity verifications.

AVL MSS

- Meeting +/- 3 % per point on dilution ratio is acceptable.

Vibration

Perform a frequency sweep with moderate amplitude and log the real time signals from the PEMS using a fixed PM generator level. If changes occur, design a frequency cycle around that frequency range to test for delta changes in PM with and without vibration. Obtain approval on the frequency cycle selected from the MASC before proceeding. If no changes are observed during a frequency sweep, there is not a need to test for vibration.

Use two orientations vertical and horizontal for the PPMD. If there is enough space on the vibration table at SwRI, test all PEMS units at once. If not, use them one by one.

EMI

Use EMI on and off, and screen the real time response of the instrument at a specific concentration level. If a response is observed during EMI on/off switching, the MASC will decide on what the next steps are.

Environmental Chamber:

1. Temperature and Humidity cycle will be made available by Matt Spears
2. Use a high velocity fan to blow over the 4 inch inlet section of the PPMD
3. PM Generator Setup and Verification

4. How to do the environmental pressure test?

a) Use three different levels concentration at the 0.02 and 0.03 g/hp-hr
b) Run a long baseline of 8 hours using three different toggeled PM concentration levels. For baseline, toggle the process five times, and use that as a baseline, followed by the continuation of the baseline.
c) Run the temperature and humidity test using the same toggeling profile. For temperature, humidity, and pressure, start with a baseline with five repeats, and then kick off the environmental cycle.
d) A toggeling of zero, mid, and high is on the order of 15 minutes.

There is a possibility of eliminating the zero and add one concentration level, and randomly sample from all the deltas generated. We need to talk to Bob Mason about this.

Use just one of each of the PEMS for environmental activities.

Finally, changes were made to the test plan during discussions. Also, SwRI presented that attached document on the test plan. More test plan discussions will take place in the next meeting on May 15 and 16, at SwRI.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI
May 15-16, 2008

Day 1

1. Tim French indicates that there are several issues came up with the PM-PEMS onboard testing performed at CE-CERT before the CE-CERT meeting was presented.

2. Kent's presentation, posted on FTP website:

   Some highlights, but see presentation for more details:

   a. Problems with valve timing opening and closing consistency and long delays over 3 seconds.
   b. There was one crystal that was very noisy but the software did not reject it, and reported data using it.
   c. A drop in frequency but an increase in mass deposit. (This is a non-issue)
   d. Semtech DS 10[1].09 SP2 b5. This beta J1939 includes filtering and was able to include NTEs.
   e. Post test J1939 filtering versus real time J 1939 filtering. Post test captured different start up NTE than the real time filtering one. Essentially, post processing software needs to be scrutinized.
   f. NTE yield produced by PPMD was low. Some of the valid NTE that was captured in PPMD post processing was rejected, after carefully reviewing the data.
   g. Others. See presentation.

3. SwRI update:

   a. Horiba linearity check was resolved by using the Gilibrator directlty
   b. Engine A, B, C, and D 80 steady-state testing was complete
   c. Engine A was tested for 40 SS points in sub-NTE runs
   d. International engine was also tested
   e. All above will be posted on the website after careful review

4. Janet and Bob Presentation, please see website.

   Bill Martin questioned the idea of excluding the 95th to 100th data twice. One in the error surfaces, and the other in the measurement allowance. He was concerned whether such practice will lead to truncation of the distribution. Janet will show in the next meeting that such practice will not lead to any truncation of data or it will effect the shape of the error distribution.

5. General Discussion and Action Items:

   a. Find ways to load up the can bus during the actual testing to simulate real world operation by making the can bus communication busy.

b. Keep using the gaseous error surfaces for Method 2 and Method 3 on the PM-PEMS.

c. Environmental Chamber:

1. Use a 9 minute cycle for the environmental chamber and go into three concentration levels, 3 minutes per level. Sample for a period of 35 seconds from each level.
2. Use five levels of dilution ratio ranging from 6 to 50.
3. Check with Sensors to see if they accept an exhaust flow meter analog input.

For Model output, keep the 95th as the measurement allowance. However, if it did not validate consider the potential of using other than the 95th, if the MASC reaches an agreement on that.

Day 2:

1. Move forward with the International Engine
2. Communicate via J1939 to load the engine can bus during testing. Use only the J1939 communication with the heavy-heavy duty diesel engine
3. Accept the idea that Horiba will use test cell engine speed and load analog output signals
4. The right to remove outliers using good engineering judgement.
5. Starting on June 2nd with commissioning
6. Spend one week of commissioning before we start.

Plot:

x-axis percent of max torque or fuel rate
y-axis absolute difference over max torque or fuel rate

Matt's Discussion:

Model Validation Testing at CE-CERT

a. Number of engines/vehicles
b. Number of bypass conditions, at least two, maybe 3
c. Number of PEMS: at least two of each, highly desirable three
d. Number of NTE events: total 100-200 per PEMS
e. Number of route repeats: 1 to 3
f. Types of NTE events
    i. CE-CERT limits
        1. Minimum filter loading: 50 micrograms

Gaseous plus PM. But PM set priorities. Sensors goes first.

	NTE Events	**Route**	**Bypass**	**Repeat**
Horiba plus AVL	30-50	Palm Springs	1	One-Run
Sensors plus AVL	30-50	Palm Springs	1, review	One-Run
Horiba plus AVL	30-50	San Diego	1 or change	One-Run
Sensors plus AVL	30-50	San Diego	1	One-Run
Horiba plus AVL	30-50	Baker	1	One-Run
Sensors plus AVL	30-50	Baker	1	One-Run

PM Measurement Allowance Steering Committee Meeting
Meeting in Madison, Wisconsin
June 12-13, 2008

The meeting started by reviewing and approving the last meeting minutes.

PPMD Commissioning

a. Following the meeting minutes, Imad Khalek gave a presentation on the status of the PPMD commissioning at SwRI. The presentation was sent to the MASC, but was not posted on the website.

b. David Booker also gave a presentation on the SwRI commissioning activities. The presentation was sent to the MASC, but was not posted on the website at the request of Sensors.

c. As a result of these two presentations, the MASC decided to give Sensors a chance to fix some of the problems encountered and come back to SwRI for additional commissioning during the week of June 16. Also, the MASC requested that a conference call should take place on Friday, June 20, and SwRI should give a status update on whether or not the Semtech-DS/PPMD issues were fixed to a satisfactory level so the program can proceed.

d. The MASC also made the following points on the PPMD:

    i. It is up to Sensors to decide on the quartz crystal equilibration time, after a crystal goes into a invalid NTE window.
    ii. It is requested that when all crystals are locked out, and one of them becomes available during an NTE, the crystal should wait until the current NTE terminates, and a new NTE starts before it samples from an NTE.

PM-PEMS Engine Selection

Imad Khalek pointed out to the MASC the fact that the PM-PEMS program is moving forward with some deficiencies related to the Horiba system inability to communicate with the Navistar engine ECM ISO protocol. It was recommended to the MASC that a heavy-heavy duty diesel engine be installed in the test cell first so the Horiba system can communicate with the engine ECM using the J1939 protocol. In addition, this will give a chance for Horiba to upgrade their system in preparation for the Navistar engine after a heavy heavy-duty diesel engine.

EMA agreed to take a look at the possibility of providing a heavy heavy-duty diesel engine in a timely manner. EMA agreed to make a final decision on this issue by the June 20 conference call.

Horiba Concern

Horiba was concerned about the fact that Sensors brought a new model of the PPMD to be used on the PM-PEMS-MA program. They wanted to have a chance to update their system as well.

The MASC decided to give Horiba a chance to work and upgrade their systems. It was decided that SwRI should ship back to Horiba one of their system present at SwRI, and give them until July 14 to ship back the system.

Horiba was also given until September 15 to upgrade their system so it can communicate with the Navistar ECM protocol using ISO-15765.

Bill Martin made comments about the difficulty he sees in the Horiba system meeting 1065 requirements. Matt indicated that EPA would enter an allowance for Horiba specifically, at the time of Direct Final Rule (DFR), through the alternate procedure approval.

AVL Presentation

Bill Silvis presented results on the MSS, where a compensation algorithm is added to account for organic carbon and sulfate. No copy of the presentation was given to SwRI for distribution. Matt Spears was not convinced that such compensation will be acceptable for EPA approval due to the significant correction required and due to the MSS principle itself. SwRI also had some technical reservation about the process due to its technical complexity. Essentially, the problem is not trivial and more thorough work and understanding is still needed.

AVL was encouraged to continue working on this issue and refine it. It is understood that they will submit the compensating algorithms prior to the start of steady-state testing. They may also submit their compensating algorithms at any time for the MASC to have analyzed by SwRI or CE-CERT.

Rey Agama suggested that time would be the best window of opportunity for AVL to be included via DFR through alternate procedure approval.

SwRI Test Cell

The MASC requested the following:

- SwRI should install all PM-PEMS as close as practically possible to the entry of the CVS. This will reduce any particle losses between the point of measurement among the PM-PEMS and also relative to the CVS. Furthermore, this will minimize the backpressure experienced by the PPMD, by shortening the length of exhaust piping present downstream of the PPMD, prior to entry to the CVS. The target backpressure is (-1 to +4 kpa)
- SwRI should try to maintain temperature of 35°C ± 5°C in the vicinity of the PM-PEMS inside the test cell.

CE-CERT Presentation

Kent Johnson gave a presentation on the temperature distribution on various location of the MEL such as behind the CAB, under MEL trail, and under passenger door. Kent's presentation is posted on the website. One of intriguing highlights of the presentation is that the temperature profile can reach as high as 60 °C to 90 °C during in-use in the vicinity of the PM-PEMS. This triggers the idea of changing the environmental temperature profile that was used during the gaseous PEMS program that was based on ambient temperature. Matt spears will be modifying the existing environmental chamber temperature profile, taking into account Kent's finding.

Budget

CE-CERT presented their budget with some options. The overall impression was that the total budget for both SwRI and CE-CERT is beyond the funding level available for this program. Below are some of the options entertained that will be discussed during the next meeting at SwRI starting on July 21st.

1. Reduce the scope of work by cutting the number of routes and the number of PEMS used by CE-CERT
2. Reduce the scope of work at SwRI by reducing the number of engines to be tested from two engines to one engine
3. Increase the overall budget by eliminating this year EMA pilot program requirement, and add funding to the MA program instead, assuming that the funding will be cost shared among EMA, EPA, and CARB

Additional Comments and Action Items:

1. If PPMD and OBS200, both, resulted in negative allowance, e.g. -0.01 to -0.02 g/hp-hr, the MA will be zero, essentially one MA for the entire program and for all the PM-PEMS used. Under such circumstances, both instruments will be allowed to be used with a zero MA.
2. Keep aware of alignment issues. One may want to investigate the brake-specific emission value reported by PM-PEMS by shifting the numerator and denominators relative to one another and relative to absolute time. This could be done with initial transient test results with bypass.
3. Sensors will provide a VI to simulate the exhaust flow rate so we can exercise the multiple dilution ratios in the environmental chamber.
4. SwRI will need to resubmit some budget options of doing the work with one engine versus two engines.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
July 21-23, 2008

July 21

The meeting started at 1:00 PM. It started by reviewing and approving the previous minutes, and also by discussing future meeting schedules, which were already sent by EMA as future meeting notices. The next meeting is scheduled for August 27 (starts at 2:00 PM), 28, and 29 (ends at 2:00 PM).

Imad Khalek started a presentation, posted on FTP website, on project status update. He showed a comparison between laboratory-based exhaust flow and the 4-inch Sensors exhaust flow that was used on the Navistar engine. The slope of the correlation was too high at 1.27. As a result of the discussions, the MASC decided on the following with the current 5-inch exhaust flow meters used with the Mack engine, which the first engine to be used as a part of the official measurement allowance work.

- Check laboratory-based exhaust flow rate with Horiba and Sensors 5-inch exhaust flow meters. If a problem is obvious or the slope of the correlation differs by more than +/- 0.05 from a slope of 1, then send the flow meters back to the manufacturers to check on the calibration.

After finishing a part of the presentation, Janet Buckingham and Bob Mason showed up for a scheduled presentation at 3:00 PM. The presentation is posted on the FTP website and addressed the double truncation issue raised by Bill Martin at the 5th and 95th percentile. The presentation is posted on the FTP website. Based on the presented work, the following was agreed upon:

a. The 95th percentile is still desired for the measurement allowance
b. The 5th and 95th are still acceptable to bound the validation range.
c. There was still a remaining unresolved issue about where you assign the -1, 0,1 on the error surfaces for the delta change between lab and PEMS. It was decided that this issue should be addressed during the last day of the meeting, but that was never brought up again. There was a proposal by Bill Martin to fit both sides of the error distribution independently using a normal distribution fit. The median of such distribution will be the median based on previous practice along with 95th for one side and 5th for the other side. When each side of the distribution is fitted using the above boundary conditions, one can then expand the data picked from the error surfaces to cover 1 % to 99 % of the data or even 0.1 % to 99.9 %. No decision has been made on this issue yet. This topic will require more discussion during the next meeting.

July 22

A significant part of the day was allocated for budget discussion. The different budget scenarios are posted in the FTP website. Below are some of the highlights:

For budget cutting purposes, one engine will be used for the measurement allowance at SwRI. In addition, work will be performed with one bypass setting that gives brake specific PM emissions levels between the two thresholds of 0.02 and 0.03 g/hp-hr. For CE-CERT, choose the PEMS with the lowest positive measurement allowance. If one PEMS clearly shows a lower measurement allowance than the rest, and both are positive, pick the one with the low measurement allowance for the rest of the validation testing.
If one allowance is positive by one PEMS, and if the other one is negative, then, in principle, choose the positive allowance if it slightly positive. (no clear cut agreement yet).

After the budget discussion, Tim French from EMA walked the group (via phone) through the EMA proposal, posted on FTP website, to substitute year 1 pilot program and to also provide some supplemental funding on the order of $200 K to inject more funding into the measurement allowance program. The overall EMA budget funding was projected to be on the order of $500 K to $700 K. Most or all the proposed activities will be performed in-use by hiring a third party that is not part of EMA and does not belong to one of the engine manufacturer to conduct the testing. As a result of the EMA proposal the following will take place:

- Matt Spears will speak with EPA upper-management to consider the EMA proposal in the context of the one year pilot program.
- EPA will also make a final determination on whether to use the shortened version of the measurement allowance program. E.g. one versus two engines, by-pass, no-bypass, etc…

After the budget discussions, Imad Khalek continued his presentation that was started on the first day. The work showed the different torque and fuel errors surfaces determined between the laboratory and the engine ECM public broadcast. The data covered a total of five engines (four heavy-heavy and one light-heavy) that included a DDC Series 60, CAT C13, Cummins ISM, Mack MP7, and Navistar 6.4 liter engine.

Also the work covered sub-NTE fuel flow errors. Based the sub-NTE results, it was decided that for forced NTEs, if the engine operation falls below NTE, use the last BSFC value observed within the NTE. Use that only for Method 2 calculations.

After this presentation, Imad Khalek refreshed the memory of the group by giving a status update presentation, posted on the FTP website, based on the last commissioning work done at SwRI. The presentation was posted on the FTP website. After that, Kent Johnson from CE-CERT shared some observations about the Sensors data produced by SwRI during commissioning. There was no conflict between SwRI and CE-CERT reporting on the results. Kent's Word document that was shared with the group will be posted at the FTP website when it becomes available to SwRI.

July 23, 2008

The focus of this day was on the Test Plan, particularly the environmental testing. However, at the beginning of this day, the idea brought by SwRI earlier of adding short NTE windows for the laboratory transient testing, along with some low or medium idle operation prior to the NTE transient cycle was discussed.

- It was decided that Short NTE windows should be added to the thirty 32-seconds NTE cycle, in the inter time. A total of 10 short NTEs will be added as follows:

    1. 4 five seconds NTEs, with two back to back within an inter-time
    2. 3 10 seconds NTEs
    3. 3 18 seconds NTEs

    Position two five seconds NTEs back to back in the inter-NTEs. For Horiba, they need about 2 to 3 seconds to exit an NTE. Thus, place the short NTEs at least five seconds after the end of a valid NTE to avoid continuous sampling with Horiba.

- On the conditioning prior to the start of a transient NTE, start with five to 10 minutes at medium idle time before the NTE transient cycle to observe if there is an effect on the laboratory PM emissions results. If there is and effect, then propose an idle time or something similar prior to starting the NTE transient cycle. (Note that before each NTE transient cycle, the plan is to force-regenerate the DPF first, medium speed idle will then be added after the forced regeneration).

EMI/RFI/Shock &Vibration

1. For EMI/RFI, expose the PM PEMS to EMI/RFI using HEPA filtered air, similar to the gaseous program. Then decide with the MASC after reviewing the results, what is the next step. As an option, we could use the PM generator to perform this work. One PEMS from each manufacturer will be used for these activities.
2. Vibration and Orientation (non-road only)
    a. On the orientation, ask PEMS manufacturers on the worst orientation scenario postion. Use such orientation at 45^{o} with the appropriate orientation, and survey the worst case scenario for all gaseous and for PPMD, and TRPM.
    b. Perform a frequency sweep, with a very moderate amplitude, then share with MASC to decide on how to go forward. Eric should propose the sweep frequency, amplitude and duration. Do two repeats. One of each instrument will be used. This is only for nonroad. Outside the scope of the program.

3. As for shock, ask Eric about a recommended on-highway profile for shock.

Temperature/Humidity chamber and Pressure Chamber

For both temperature and humidity and pressure chamber work, use three PM concentration levels around the two threshold levels such as 4000, 5000, and 6000 μg/m³. Use a total of four dilution ratios of 6, 12, 20 and 30. At each dilution ratio, stabilize for 4.5 minutes at each concentration level and measure for 30 seconds before you go to the next concentration level to do the same. E.g.

1. Set the dilution ratio to 6, stabilize at 4000 μg/m³ for a 4.5 minutes
2. Measure PM using PEMS for 30 seconds
3. Move to next concentration level of 5,000 μg/m³ and stabilize for 4.5 minutes
4. Measure PM using PEMS for 30 seconds
5. Move to the next concentration level of 6,000 μg/m³

6. Measure PM using PEMS for 30 seconds
7. Repeat 1 through 6 at different dilution ratio

A spreadsheet on PM concentration and loading was originally made by Matt Spears during the meeting and was very slightly modified by Imad is posted to the FTP website

As a result of the proposed scenario above, Sensors PPMD will require a secondary dilution using MPS2 to perform an 8 hours of activities using the above scenarios. In case of Horiba, either we need to allow higher dilution ratio than those adheres to 1065 or we need to allow more loading on the filter past a 0.4 mg. More discussions on this will need to take place during the next meeting.

The PM cycle to run by the PM generator contains five 15 minutes cycle to be used as a baseline. E.g. Run the first five 15 minutes at normal temperature, use those as a baseline line, then proceed for the rest of the day to capture an eight hours of similar repeats. Do the same thing prior to starting the Temperature/Humidity profile and well as the Pressure Chamber profile. One of the remaining issues that has not been resolved around this topic is how do we capture the baseline information with the Horiba system without the need to change the filter. More discussion on this subject is needed during the next meeting.

New Temperature Profile

Take the mean of CE-CERT Cab minus ambient and add it to original temperature profile, and solve for new temperature and humidity profile that maintains derived from the real world data.

Perform a Fourier transform on the CE-CERT Cab data, eliminate frequency content that are similar to the base ambient profile, and use a magic synthesizer to superimpose the frequency on top of the new temperature profile. Matt Spears is assigned to do this task.

Pressure Chamber

We resolve the logistical issue of the pressure chamber work by placing the PM generator inside the chamber. Matt will need to send me some dimension on the PM generator to see if it fits in the Chamber. Other gases as well as 30 amp circuits should all be accommodated.

For Horiba, heat trace the segment of the transition to 250 ^{o}C, similar to the PM generator outlet temperature for both the Horiba and AVL.

Use each instrument separately for these tests.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
August 27,28, & 29, 2008

Meetings

October: 9,10-at EPA
Nov: 12,13, and 14-at SwRI
Dec.: 10,11,12-at SwRI

Discussion Points and Decisions Made

- For the error distribution choose the 1st and 99th at -1 and 1, based on a normal distribution fitting to extrapolate down to the 1st and 99th. For the height of the median, if there is a discontinuity, choose the average or randomly pick one or the other.
- Recheck the 4 inch flowmeter calibration that was on the International engine
- For Horiba, filter loading is allowed to go beyond 400 microgram up to 700 microgram or beyond as long as the flow is controlled.
- For Horiba, do the five cycle baseline at the beginning for humidity and temperature and do it at the end for the pressure. This will require changing the filter. For the pressure, if it can be done within an hour than do it at the beginning, otherwise, do it at the end.
- Which of the three units are acceptable to be used in the pilot program:
    - PPMD is approved
    - Horiba might be approved
    - AVL will have to make the case at EPA to see if approved
    - EMA would like to know what instrument would be acceptable for pilot one program
    - Can EMA combine pilot efforts within companies
    - EMA will fund the additional funding required that will be required to do the intermediate testing that involves:
        - One bypass setting, one engine at SwRI
        - Three PEMS, one manufacturer with CE-CERT
- We should move forward on RMI, RFI, and vibration sweep, as soon as we start the official testing
- Due to spikes, we may revisit the post processing of the Horiba results, especially during the NTE transient test. As of right now, Horiba first correlates the entire EAD signal (including spike) with the filter weight (not including spikes), then apply the relationship for the NTE window portion of the cycle.

SwRI Presentation and Action Items

During the meeting, SwRI gave a status update via a presentation, see enclosed presentation (Update 6), on the PPMD, MSS, and TrPM. SwRI, also discussed the bypass tuning for using 10 NTE transient cycle, 80 points steady-state using MSS, and projected filter mass concentration, using a relationship between the filter and the MSS. In addition, the bypass mixing was shown qualitatively. Furthermore, the transient concentration trace with the MSS was presented for the 10 NTE transient cycle.

As a result of the work reported several action items were born:

- Make sure that the filter-based steady-state projected concentration is consistent with the filter-based measured for the six steady-state points selected. Thus, perform an experiment to determine the filter-based measured concentration for the six points selected and share the results with MASC
- Instead of showing a qualitative results on the mixing, provide some quantitative assessment such as a T-test.
- Based on the high spikes observed with the MSS, check if the PPMD results in a low bias due to the fact that it may be missing the early spike. For these experiments, pick the transient NTE window with the highest spike and create a cycle that consists of 10 repeats of that same window. During this exercise, use only three working crystals and vary the PPMD trigger into the NTE with time advancement of 1,2 and 3 seconds, time delay of 1 second, no time delay, and ECM trigger

The above work and the problems encountered were presented to the MASC via two conference calls that were done on September 12 and September 30, 2008. The presentations are also enclosed as Update 7, and Update 8.

PM Measurement Allowance Steering Committee Meeting
Meeting at EPA, Ann Arbor
October 9 and 10, 2008

SwRI gave a status update on the progress of testing. See enclosed presentation.

There was a concern about the predicted lasting time of the PPMD in the field, which was predicted to be on the order of 1 hour, using an average NTE threshold of 0.02 g/hp-hr. There was a desire to extend the running time of the PPMD to at least 2 hours. This is indeed met by the instrument if one takes into account overall collection efficiency of the instrument. In the example given, it was assumed that the collection efficiency was a 100 %, where in reality it was on the order of 50 %. Thus the one hour of lasting time reported is in reality two hours.

A decision was made to move forward with testing using only the MPS1, as shown below, after final commissioning of the PPMD by Sensors. Actually, David Booker from Sensors flew to SwRI late on October 9 to be at SwRI on October 10.

1. Test on MPS1 only, as its currently configured at one microgram.
2. Okay to use external trigger for steady-state testing
3. For steady-state testing:
    a. Target 100 microgram on the filter
    b. 50 microgram for TRPM
    c. 0.66 microgram for PPMD

Do not clean crystals until it is apparent that the next run will likely overload the filter.

The second day of the meeting was spent at Sensors. Matt Spears gave a presentation on the PM generator. Later, he showed the PM generator setup, and explained to the group the various elements of the PM generator and the equipment used. A copy of Matt's presentation is enclosed. Also, a copy of Matt's note is shown below, particularly to 1065 PEMS changes:

Matt's Note:

1. Review minutes from last meeting
2. Discuss 1065 changes required for PM PEMS
3. Update from SwRI on recent activities
4. Update from PEMS manufacturers regarding recent phone conference
5. Friday afternoon @ Sensors
    a. SUN conference presentation
    b. PM Generator
6. Discuss 1065 changes required for ****PEMS field testing only****
    a. Dilution Air
        i. Temperature control
            1. 1065 = 25±5 °C

        2. PM PEMS= no direct feedback control from a dilution air temperature measurement required-- use good engineering judgment; if directly and actively controlled then target 25 °C .
    ii. You may use a fixed molar mass of the diluted exhaust mixture for all PEMS field testing, as determined by engineering analysis.
b. “Filter”
    i. Media
        1. PTFE membrane or TX-40
    ii. Face velocity
        1. 1065= target near 100 cm/s actual, unless overloading
        2. PM PEMS
            a. Flow-through media: (10 to 100) cm/s actual, which can be verified by engineering analysis
            b. Non-flow through media: no specification
    iii. Temperature
        1. 1065 is 47±5 °C
        2. PM PEMS target (42 to 52) at all times, with a minimum tolerance of 32 °C and a maximum tolerance of 62 °C, where the tolerances apply only during filter sampling.
    iv. Conditions during mass determination
        1. 1065=see subpart B
        2. PM PEMS
            a. If mass is not determined in-situ—i.e. within the PEMS—then the sample collection media must be pre and post analyzed according to 1065.190x.
            b. If mass is determined in-situ, follow .195.
            c. In subpart J, have no requirement to hold to dewpoint specs for in-situ analyzers.
c. Absolute reference for inertial balance
    i. Current status: QCM OEM stated specs are assumed.
    ii. For 1065 measurement allowance audit we had Sensors verify frequency measurement circuit.
    iii. No immediate solution available
d. Cleanup 915 table for inertial **batch** PM analyzers: no freq, or rise/fall time specs. Recommend a process for determining noise, accuracy, and repeatability
e. 1065 Subpart J needs to state that field testing applies at any ambient temperature, pressure and humidity, unless otherwise specified in the standard setting part.
f. State that EPA approves of electrostatic deposition technique for PM collection. Must meet 95% collection efficiency, as stated by the manufacturer.
g. Overall PEMS test requirement should be reread and edited to be applicable to batch analyzers. For example describe how to use a combination of steady-state and transient test modes to determine accuracy and repeatability separately; like what we’re doing in the measurement allowance.
h. 1065.308-09: also required for continuous PM analyzers—read and edit accordingly
i. 1065 clarify that options after 400 ug loading are optional
j. Clarify whether or not ambient air may be used for zero air for PEMS, including for hangup check.

   k. Drift: allow any drift that doesn't affect your ability to demonstrate compliance with the applicable standard.
7. Timetable
   a. Next meetings
8. Test Plan-documentation reflecting the latest agreements
   a. Validation—get from CE-CERT
   b. Modeling
9. For PEMS testing set dilution ratio based on manufacturers literature regarding maximum exhaust flow. You may also use other manufacturer information to perform an engineering analysis to estimate the maximum.
10. There will be no dilution ratio verification.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
November 12 and 14, 2008

Flow Alignment in PEMS

In case of continuous sampling, use a step function to measure the delay from the probe to the instrument.

In case of batch sampling, use the geometry to account for time delay from the probe to the batch sampler

The above is done to align the flow or to account for time delay.

Leave alone any time alignment between exhaust flow and ECM torque and speed. Use the ECM torque and speed to determine the integral over the NTE.

Loss Correction

a. The principle of PM loss corrections for PM PEMS is agreed upon by the steering committee
b. EMA desires a legal construct in 1065 for allowing the use of PM loss corrections
   i. Open up 1065.295 to allow more types of compensating algorithms, based upon other variables
   ii. Utilize Subpart J overall approval test to validate entire PM PEMS, including its loss corrections.

The PEMS manufacturers will be allowed to use compensation algorithms.

- Horiba decided to use no particle loss algorithm.
- AVL presented a loss algorithm to correct for thermophoresis. The loss correction is already defined and will be implemented via a post processor provided by AVL
- Sensors plans to correct for particle loss and will share the process with MASC during the next meeting

As of today, no filter data can be shared with Sensors unless the loss correction is shared with the MASC.

Test Matrix, DPF out

Full day no QCM cleaning or filter changing

Storage, high speed, light load
Release at peak torque, run for 20 minutes
Store again at high speed, light load
Release at rated power

Do another storage at low idle, equivalent

Cycle the PEMS every one minute to sample into NTE.
Cycle the PEMS every 32 seconds
5 second dwell time in between the NTEs

PEMS Daily Checks Tolerance

Slope of 0.96 is acceptable by Sensors
For Horiba, 3% on filter flow, and 3 percent at a dilution ratio of 5, and 5 percent at a dilution ratio of 15, and Mike will reconfirm.
We will get a feedback from AVL on the accepted tolerance for a dilution ratio of 5.f

Milestones

Milestone for the Model dry run
PM generator milestone for commissioning, week of January 5
Milestone for the fuel flow error surface delivery by the engine manufacturers (EMA will target the end of February for these data to be available. The eight or nine engines that are available now will be used for the dry run).

Fixed date for the delivery of environmental chamber kit by the PEMS manufacturer.
Ship it on the 19th of January by Sensors and Horiba.

We will schedule EMI, RFI, on the 26th of January, and shock and vibration on the following week.

Matt Spears' Note:

Wednesday

1. Upcoming meetings, December, January, and March all at SwRI
    a. December 10-12 at SwRI (10th 2pm start, 12 2pm close)
    b. January 28th – 30th (28th 2pm start, 30th 2pm close)
    c. March 18th – 20th (18th 2pm start, 20th 2pm close)
2. Review October meeting minutes
3. EPA / SwRI / CE-CERT PM filter round-robin
    a. Initial results
4. Temperature-Humidity test cycle
    a. EPA cycle
    b. SwRI addition of CE-CERT frequency content
5. Status and progress at SwRI since last meeting
    a. Update on mission time projections
        i. Relook at projections to see if it is possible to collect 20 failed NTE events (0.02 g/bhp-hr) in one mission
    b. Test plan review
    c. Decisions for MASC
6. Budget update
    a. Arrangements for EPA/EMA/ARB

Thursday

7. PEMS PM loss algorithms
    a. AVL
    b. Sensors
    c. Horiba
8. Test plan development
    a. Inclination discussion
9. Continue if necessary: Status and progress at SwRI since last meeting
    a. Decisions for MASC

Friday

10. Continue PM PEMS related Part 1065 changes
11. Other meetings during our November meetings
    a. Wednesday
        i. Wrap-up by 5:30pm due to another room reservation
    b. Thursday
        i. 12:00pm EMA, Rey Agama – break for lunch at 12:00pm
        ii. 1:00pm – 2:00pm, Shirish Shimpi, continue meeting
    c. Friday
        i. Matt Spears 10:00am to 10:45am, continue meeting
12. Loss corrections resolutions
    a. The principle of PM loss corrections for PM PEMS is agreed upon by the steering committee, including EMA, EPA, ARB.
    b. EMA desires a legal construct in 1065 for allowing the use of PM loss corrections
        i. Open up 1065.295 to allow more types of compensating algorithms, based upon other variables.
        ii. EPA agrees that PM loss corrections will not be applied to certification testing. If in the future EPA desires to apply PM loss corrections to certification testing, such a provision would be proposed as part of a notice of proposed rulemaking because EPA acknowledges that such a change would cause a change in the stringency of the certification standard.
        iii. EPA will be the approving body with respect to PM PEMS PM loss correction.
            1. May make case-by-case approvals, based upon specific PM PEMS manufacturer circumstances, such as, but not limited to submitted, models, theory, validation data, or even simply the magnitude of the correction.
            2. May utilize Subpart J overall approval test to validate entire PM PEMS, including its loss corrections.
            3. May develop (with consultation with EMA) other procedures for codification within Part 1065.
13. Sensors will provide an advance copy of Sensors' December presentation, requesting EMA question consolidation ahead of meeting.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
December 10-12, 2008

SwRI presented the steady-state testing results, and the storage and release and regeneration results. The presentations were posted on the FTP site.

Sensors presented their approach to particle loss correction. A presentation is available at the FTP site.

Craig Kazmierczak presented some in-use PM-PEMS work that was done on one of DDC trucks using the PM-PEMS equipment. The work was done by Sensors and presented by Craig.

The MASC requested that the reference crystal be used during SwRI laboratory activities, if that is to be used on the road.

The testing done by SwRI so far is acceptable. For the particular PPMD used, disable the reference crystal, and use a working crystal to be a reference. Essentially, operate with six working crystals, and use one for reference.

Sensors intends to use the reference crystal for correction, but they are going to use a logic to decide whether or not it will be used in the post processor.

The post processor should be available before January 23, 2009. The post processor should include any loss correction intended or any reference crystal correction model, remove all Part 1065 excursions, and all other miscellaneous items that will make a measurement invalid.

In the current AVL post processor, thermophoretic loss was capped at 25 %. AVL wants to change that to include the full range of the model, and remove the 25 % cap. Both corrected and uncorrected data will be provided in the output of the post processor.

We agreed to use the paired analysis for steady-state and for model validation.
We agreed to use 5 % COV at a 1 sigma standard deviation for the CVS at 100 microgram filter loading.

The above subject was tabled for further discussion on how to subtract the CVS error contribution. Bill Martin will send his proposal to Bob and Imad.

How to account for a regeneration in the field:

NTE event > 30 seconds to be valid

1-Discrete
2-Triggered by ECM
3-The regen is defined between two regen flags
4-If the regen occurs during an NTE event, and the length between two consecutive NTE flag x 2 is shorter than the NTE event, then the regeneration is counted

5-If the regen occurs before an NTE event, and end outside the NTE event, the NTE will count.

Tim French mentioned that the subject of regeneration and its inclusion in NTE need to be discussed in a different forum.

Blow-By and how it will be computed for the measurement allowance. Next meeting

As of now, the results reported for storage and release and for regeneration will not impact the MA program.

Matt will share the filter results during the next meeting.

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
January 28-30, 2009

The last minutes was reviewed and approved. The scheduling for future meetings and conference calls was as follows:

Conference Call, Thursday, Feb. 26, 2009, 9:00 am Central, length will be decided on Friday.

Next MA-SC, April 1^{st} (2:00 to 6:00), 2^{nd} (9:00 to 5:00) and 3^{rd} (8:00 to 2:00), San Antonio.

Week of the 18^{th} of May for EMTC and MASC (May 20, 21, 22, same as the April meeting)

- Some of the in-use testing performed by Ce-Cert will include regeneration events. No action will be taken on modifying the test plan at SwRI. The test plan will remain the same and it will not include active regeneration.

- Bill Martin explained his proposal on the CVS variability addition to SS delta data. Bill Martin presented the analysis on how to assign the CVS variability into the delta between PM-PEMS and CVS in order to shrink the 95^{th} and 5^{th} A copy of his write-up is on the FTP website

- SwRI presented work on the progress made. A copy of the presentations is posted on the FTP website

- Rey Agama presented an argument about using standard deviation instead of MAD for the data analysis. Matt Spears suggested that the MAD should be used, and if no validation was observed at the end of the program, other possibilities can be considered. The group agreed to move forward with this approach. Rey asked that we apply a normality test on the data, and he will consult with Bob Mason on that. This is in relation to applying a MAD or SD for the model. Bob Mason will present some material on the normality criteria during the next meeting.

- The contribution of blow-by will be a constant based on the data presented from the four ACES engines at 0.00042 g/hp-hr. If the crankcase is vented to the atmosphere, this value will be added to every NTE emissions value. If the crankcase is closed loop, the blow-by contribution of 0.00042 g/hp-hr will not be added to the NTE emission values.

- Horiba was allowed to fix a bug in their system in relation to delays between engine and OBS and OBS and TRPM

- Horiba was allowed to make modifications on the ion trap voltage of the EAD for the third TRPM unit.

- The engine manufacturers agreed to submit the ECM/Lab Torque and Fuel Flow by March 31st, 2009. The data will not be linked to a particular manufacturer.

- The instrument manufacturers needs to submit the latest post processor by Friday, March 6, 2009

- The MASC agreed that the AVL measurement allowance will be performed based on data measured plus thermophoretic correction. The MASC agrees to also see data from the AVL MSS total PM prediction on a non-interference basis from the core of the measurement allowance program.

- The MASC was updated on the PM generator via a laboratory tour. The PM generator is currently set up at SwRI Particle Laboratory.

Below is the unedited Matt Spears' minutes:

1. January meeting agenda

    a. Next meetings?
    b. EPA participation/management in MASC
    c. Review of Meeting minutes
    d. Regen in NTE discussion
    e. Bill Martin's paired testing proposal
    f. SwRI data
        i. Transient
        ii. 2nd set of PEMS
        iii. Lessons learned, problems?
        iv. Analysis of MSS with sulfate and HC corrections
        v. ECM vs test cell torque and BSFC error surface update
            1. SwRI approach
    g. PM Generator update
    h. Environmental chamber update
        i. PEMS mfr readiness
        ii. SwRI readiness & schedule
        iii. PM Generator readiness
    i. Next face-to-face meeting: April 1 afternoon, to April 3rd afternoon—SwRI
    j. May 13-15, placeholder-SwRI
    k. Bypass sizing for model validation work
        i. DDC engine
    l. Filter results

    m. Friday Schedule
        i. 9:00am start
        ii. Review test plan timeline
        iii. Environmental chamber update
            1. PEMS mfr readiness
            2. SwRI readiness & schedule
            3. PM Generator readiness

iv. AVL data with corrections

v. Horiba general topic

vi. Finalize agenda for February 26th meeting—finalized, finalize time. 9am central. 4 hrs. 12:00pm CST – 4:00pm CST (1pm-5pm EST) Shirish travelling to NRMM in Ispra Feb 26th

    1. Agenda

        a. Make this a LiveMeeting, this is ok w SwRI

        b. Update on PEMS manufacturer post processors: 1-hr

        c. Timeline update—SwRI: test cell and environmental chamber testing: 30 min

        d. CE-CERT update on ability to come to SwRI for correlation testing & progress on bypass: 30 min

        e. SwRI data

            i. PEMS set number 2: steady-state & perhaps transient results—summary only: anything remarkably different than the 1st set of PM PEMS: 1-hr

            ii. Any new issues or difficulties: 30 min

        f.

vii. PM Generator / nanoparticle lab tour

viii. Engine manufacturers to submit ECM/test cell torque/fuel rate data by March 31st meeting

ix. Rudy's for lunch

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
April 1-3, 2009

PM-PEMS Meeting: April 1-3, 2009.

Wednesday, 2:00-6:00 PM

- Meeting Minutes from previous meeting were reviewed
- Practice measurement allowance on incomplete set of data was presented by Janet, see presentation on website
- The viability of using Method 3 was discussed. There was a general agreement that this method needs to be dropped out mainly because the lack of information on time alignment between ECM fuel flow and gas-based fuel flow, but such decision needs to be reconfirmed during the next meeting.

Thursday, 9:00-5:00 PM

- The normality test requirement was discussed by Bob Mason, see presentation on website. The decision for now is not to assume normal distribution and use the MAD instead of SD. If the MAD failed to produce a validated measurement allowance, the SD will be revisited.
- David Booker from Sensors presented the features of the new PPMD post processor, see presentation on website
- Mike Akard from Horiba gave an update on the status of Horiba's post processor, see presentation on website
- SwRI gave a presentation on the following (see presentation on FTP website):
  - Status update and project progress
  - SS data from all the PM-PEMS
  - Transient data with and without engine drift from all the PM-PEMS
  - OC/EC data for SS
  - EEPS data for SS
  - Some MSS corrected data for sulfate and HC
  - Reference NTE using method 3 gave different values than Method 1 and 2, and decision will need to be made on Method 3 during the next meeting.

Friday, 8:00-2:00

- Vibration for offroad was discussed. SwRI plans to do a vibration sweep similar to on-highway but while the PEMS sitting at the vibration table at 45 degree angle. SwRI will present a cost estimate for this additional activities when the vibration activities start.
- SwRI showed the fuel and torque data submitted by all engine manufacturers that included Caterpillar, Cummins, Detroit Diesel, Navistar, and Volvo Powertrain. SwRI will present all data together during the next meeting.

Some of the decisions/action items made during this meeting were as follows:

- A decision on whether or not Method 3 should be used (AVL only) needs to be made
- Reference NTEs will be tweaked so the main distribution of events will be between 0.015 g/hp-hr and 0.035 g/hp-hr
- SS error surfaces will be presented during the next meeting
- Transient data was drift corrected using the CVS, but the MASC desired to look at the integrated AVL data as compared with the CVS to look at the possibility of using real time AVL data for drift correction. The integrated AVL for the NTE cycles will be compared with the integrated CVS during the next meeting, before making a final okay on the CVS drift correction method
- EPA was to provide some information on temperatures experienced during off-road in-use activities so it can be incorporated with temperature and humidity profile during environmental testing. EPA was to propose a final temperature and humidity profile for the program, after incorporating the CE-CERT and off-road data
- Off-road vibration tests will be added at 45 degree angle
- Fuel and torque errors using the engine manufacturers' submitted fuel and torque needs to be presented during the next meeting

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, San Antonio
May 20-22, 2009

PM-PEMS Meeting, May 20-22, Meeting Agenda

1. Review of last meeting minutes
2. Next Meeting Schedule
3. Overall Project Status Update
4. CE-CERT and SwRI Correlation
5. Update on EMI and RFI Testing
6. Update on Environmental Chamber Testing
7. SS Error Surfaces and Adjusted Reference NTE events
8. Other agenda items and questions

- The last meeting minutes were reviewed
- The next meeting schedule was set to July 15-17 in Indianapolis
- The overall project status we presented. See presentation by SwRI
- CE-CERT and SwRI Correlation was presented. See presentation by SwRI
- EMI and RFI testing results were presented. See presentation by SwRI. No error surfaces will be generated. The problems mainly affected instrument functions.
    i. Horiba will investigate the issue related to Bulk Current Injection effect on the Horiba exhaust flow
    ii. Sensors will demonstrate a fix to the exhaust flow problem during the next meeting. Sensors will conduct their own testing if necessary.
- SS error surfaces were presented. Sensors data were not fully analyzed because the new post processor was not provided to SwRI. Sensors promised to provide a new post processor resolving the issues identified by SwRI during the last meeting to increase data yield. Sensors later provided the new post processor, and the SS error surfaces were presented during a conference call that took place on June 29, 2009. See SwRI presentation for the June 29 conference call.
- The transient errors were also discussed, and the approach for the transient error surface will be presented during the next meeting in Indianapolis, along with a final recommendation
- Sensitivity on fuel flow and CO_2 flow for Method 2 and Method 3 will be discussed during the next meeting in Indianapolis

PM Measurement Allowance Steering Committee Meeting
Meeting at SwRI, Indianapolis
July 14-17, 2009

1. Last Minute Review
2. SwRI Presentation
    a. Project Update
    b. SS and Transient Error Surfaces treatment and results
    c. Environmental Testing (Atmospheric Pressure, Temperature and Humidity) Results and Discussion
        i. Three approaches were presented on how to treat the error surfaces for the environmental testing.
        ii. Approach 3 was used. The steering committee agreed with using approach 3
        iii. No error surfaces were obtained for Horiba and Sensors for environmental testing
        iv. Error surfaces for AVL, but anything below the lowest MAD, set to a constant equal to the lowest MAD, and anything above the highest MAD set to a constant equals to the highest MAD
    d. For Method 3, and for the reference NTEs, we agreed that the gas based fuel flow will be advanced in order to match the ECM fuel flow.
3. Rules on Measurement Allowance:
    a. Pick the positive measurement allowance that is closet to zero based on the Horiba's and Sensors' PEMS.
    b. If both Horiba's and Sensors' PEMS have a negative measurement allowance, pick the one that is closest to zero.
4. Preliminary conference call scheduled for August 20, 2009. We will confirm it tomorrow. At the August's conference call a decision on the measurement allowance will be made and an instrument will be selected to go to CE-CERT. After that, SwRI will ship the units to CE-CERT to arrive at CE-CERT earlier than September 1^{st}
5. Meeting at CE-CERT on September 22^{nd} to observe and check PEMS installation by CE-CERT.

PM Measurement Allowance Steering Committee LiveMeeting
August 20, September 11, 2009

1. SwRI presented the Monte Carlo Simulation (See Presented at FTP website)
2. The measurement allowance was determined based on Method 2 using Sensors' PPMD
3. The measurement allowance was 0.00605 g/hp-hr
4. Sensors' PPMD was chosen for CE-CERT in-use testing
5. It was agreed by the MASC that the AVL MSS will also participate in in-use testing along with the PPMD, just like it was done in the laboratory
6. The MASC requested the following from SwRI
    a. plot the Sensors and Horiba 95^{th} delta on the same plot
    b. show the results of the simulation based on reference data available within the concentration range obtained in the laboratory
    c. plot the 95^{th}, 50^{th}, and 5^{th}, for the validation
    d. Refreshment on the regression rules for the validation deltas
7. Address Item 6 above in a Livemeeting on September 11
8. The requests in Item 6 above were addressed in a livemeeting on September 11 (see presentation on FTP website)
    a. The MASC requested that the validation deltas for the 95^{th}, 50^{th}, and 5^{th} be regressed using the LOESS fitting rule since the criteria set for linear regression is not met.
    b. The LOESS fit should be done on Sensors' validation deltas based on Method 1 and Method 2.
    c. SwRI should present the regression the CE-CERT September 22 meeting.

PM Measurement Allowance Steering Committee Meeting
February 17-18, 2010, US EPA, Ann Arbor

Sensors gave a presentation, proposing a correction factor for the exhaust flow.

- Sensors calibrated the flow meter in house with the same wrong pressure configuration in the field
- Sensors determined a correction factor of 1.52 for exhaust flow correction for Unit 3. This correction factor was accepted by the MASC
- A similar calibration will be done on Unit 2 to determine the exhaust flow correction factor to be used for this unit

Sensors indicated that additional corrections related to bypass flow that was not corrected for during the in-use testing is needed:

- The sample flow during NTE is determined as the difference between bypass flow before sampling and bypass flow during sampling.
- If the bypass flow is not corrected for barometric pressure during sampling, and the barometric changes during the long NTEs, then there would be an error introduced to the sample flow.

AVL discussed the approach they took to calculate the brake-specific PM emissions using Method 2. The ECM broadcast fuel term in the equation was essentially frozen if it went below 5% of the max fuel flow encountered during the test. However, to move forward with Method 2 calculation, the MASC agreed that to the following:

- The MAX fuel flow provided by the engine manufacturer should be used not the max fuel determined during a test. Thus, the engine manufacturer of the CE-CERT vehicle should provide the information to CE-CERT to do proper Method 2 calculation
- The fuel flow along with the gas concentration terms in the equation will be frozen if the ECM fuel flow dipped below 10% of the MAX fuel flow.

CE-CERT gave a presentation on the different exhaust flow correction attempts they made. See CE-CERT presentation at the FTP website.

SwRI presented validation for PPMD Unit 2 and 3 using Method 1 with an exhaust flow correction of 1.52. The PPMD based on Method 1 failed the validation criteria. SwRI also showed different scenarios for the AVL, including Method 1, 2, and 3. The presentation is listed on the FTP website.

Below is a summary of the action items for CE-CERT and SwRI as a results of this meeting. These action items were compiled by Chris Laroo:

Follow-up Work to Finish PM MA Test Program

1) Agreed to exhaust flow correction factor of 1.52 for unit #3.

2) Will use exhaust flow correction factor for unit #2 that comes out of Sensors check of the unit #2 flow meter on their flow stand (value anticipated to be at or near 1.52 but needs to be determined). Value is anticipated to be known the week of March 1st.

3) Correct PPMD data for incorrect setting in QCM bypass flow. Software setting change from 0 to 1.

4) Use Semtech DS barometric pressure readings to account for altitude change effects on data. If it is determined that the PPMD barometric pressure reading is faulty, we will request that Sensors upgrade the sensor to the quality used in the DS. This could be deemed a special source of error and accounted for via a future hardware improvement.

5) PPMD Unit #1 data will be reported for single crystal use only to reflect that fact that the Mass Sensitivity was incorrectly entered into the software during testing. This single crystal use data will then be pooled with the multi-crystal use results from units #2 and #3 to determine the final validation % results.

6) Report PPMD Unit #2 and #3 deltas for single crystal use only as a probing exercise to see if multiple crystal use has an effect on mass loss. The intent of this exercise is to gauge the effectiveness of proposed fixes by Sensors to eliminate the PPMD low bias for future pilot and compliance program testing. This data will be pooled with the unit #1 single crystal use results for plotting in the validation window for experimental purposes only. These results will not be used to determine validation.

7) Method #2, if the fuel flow rate drops below 10% of manufacturer declared maximum fuel rate value, then the ratio of the emission concentration terms and the ECM broadcast fuel rate will be frozen at that value.

8) CE-CERT will reprocess all PPMD and MSS data with correct factors.

9) CE-CERT will write a final report to be reviewed by the steering committee before finalization.

10) SwRI will place revised CE-CERT data in validation windows and calculate new validation percentages. CE-CERT should have the data to SwRI by the end of March.

11) SwRI will also place revised CE-CERT single crystal usage data in validation windows and calculate new validation percentages (for experimental purposes only). This again will help gauge whether or not there is an effect on mass loss from multiple crystal usage.

12) SwRI will write a final report to be reviewed by the steering committee before finalization.

APPENDIX C

CRYSTAL BALL OUTPUT FILE DESCRIPTIONS

EXTRACT DATA FILES

1.0 Simulation Variables

The simulation variables listed in Table B-1 were extracted at the completion of the Monte Carlo simulation run for each reference NTE event. Crystal Ball classifies variables into two categories: assumptions and forecasts. Assumptions are the estimated inputs into the simulation model such as the variability indices used to sample each error surface. Assumption variables in this study are identified by an "i_c" at the beginning of the variable name, or by "Delta" at the beginning of the variable name. The "i_c" variables are the simulation error model inputs such as "01_ic_SS_PM". The "Delta" variables serve as switches that turn a given error surface on or off in the model, e.g. "Delta PM SS". The Delta switch variables when turned on and off during a simulation are applied in post-simulation analysis to determine sensitivity of results to the particular error surfaces. Forecasts are values calculated by a forecast formula in the spreadsheet cells. Examples of forecast variables used in this study are "001AVL_DePM (g/hp-hr), Method 1" and "005AVL_Valid DePM (g/hp-hr), Method 2".

TABLE B-1. SIMULATION VARIABLES

Variable Name	Description
001AVL_DePM (g/hp-hr), Method 1	MC Delta PM Method 1 for AVL PEMS
001Horiba_DePM (g/hp-hr), Method 1	MC Delta PM Method 1 for Horiba PEMS
001Sensors_DePM (g/hp-hr), Method 1	MC Delta PM Method 1 for Sensors PEMS
002AVL_DePM (g/hp-hr), Method 2	MC Delta PM Method 2 for AVL PEMS
002Horiba_DePM (g/hp-hr), Method 2	MC Delta PM Method 2 for Horiba PEMS
002Sensors_DePM (g/hp-hr), Method 2	MC Delta PM Method 2 for Sensors PEMS
003AVL_DePM (g/hp-hr), Method 3	MC Delta PM Method 3 for AVL PEMS
004AVL_Valid DePM (g/hp-hr), Method 1	Validation MC Delta PM Method 1 for AVL PEMS
004Horiba_Valid DePM (g/hp-hr), Method 1	Validation MC Delta PM Method 1 for Horiba PEMS
004Sensors_Valid DePM (g/hp-hr), Method 1	Validation MC Delta PM Method 1 for Sensors PEMS
005AVL_Valid DePM (g/hp-hr), Method 2	Validation MC Delta PM Method 2 for AVL PEMS
005Horiba_118_Valid DePM (g/hp-hr), Method 2	Validation MC Delta PM Method 2 for Horiba PEMS
005Sensors_Valid DePM (g/hp-hr), Method 2	Validation MC Delta PM Method 2 for Sensors PEMS
006AVL_Valid DePM (g/hp-hr), Method 3	Validation MC Delta PM Method 3 for AVL PEMS
01_ic_SS_PM	Random Sampling Variability Index for SS PM Error Surface, applied to AVL, Horiba and Sensors PEMS
02_ic_TR_PM	Random Sampling Variability Index for Transient PM Error Surface, applied to AVL, Horiba and Sensors PEMS
04_ic_Atm.Pres_PM_AVL	Random Sampling Variability Index for PM Atmospheric Pressure Error Surface, applied to AVL PEMS

05_ic_Amb.Temp_PM_AVL	Random Sampling Variability Index for PM Temperature Error Surface, applied to AVL PEMS
07_ic_SS_CO	Random Sampling Variability Index for SS CO
10_ic_Pressure_CO	Random Sampling Variability Index for CO Pressure
11_ic_Temperature_CO	Random Sampling Variability Index for CO Temperature
13_ic_SS_NMHC	Random Sampling Variability Index for SS NMHC
14_ic_TR_NMHC	Random Sampling Variability Index for Transient NMHC
16_ic_Pressure_NMHC	Random Sampling Variability Index for NMHC Pressure
17_ic_Temperature_NMHC	Random Sampling Variability Index for NMHC Temperature
19_ic_NMHC_Ambient	Random Sampling Variability Index for Ambient NMHC
20_ic_SS_flow	Random Sampling Variability Index for SS Exhaust Flow
21_ic_TR_Flowrate	Random Sampling Variability Index for Transient Exhaust Flow
22_ic_Pulsation_flow	Random Sampling Variability Index for Exhaust Flow Pulsation
23_ic_Swirl_flow	Random Sampling Variability Index for Exhaust Flow Swirl
25_ic_Radiation_Exhaust Flow	Random Sampling Variability Index for Exhaust Flow EMI/RFI Radiation
27_ic_Temperature_Exhaust Flow	Random Sampling Variability Index for Exhaust Flow Temperature
28_ic_Pressure_Exhaust Flow	Random Sampling Variability Index for Exhaust Flow Pressure
29_ic_TR_Torque	Random Sampling Variability Index for Dynamic Torque
30_ic_Torque_DOE	Random Sampling Variability Index for Torque Design of Experiments Testing
31_ic_Torque_Warm	Random Sampling Variability Index for Torque Warm-up
32_ic_Torque_IP	Random Sampling Variability Index for Torque Independent Parameters Humidity and Fuel
34_ic_Torque_Interpolation	Random Sampling Variability Index for Torque Interpolation
35_ic_Torque_Engine Manufacturers	Random Sampling Variability Index for Torque Engine Manufacturers
42_ic_Fuel_Engine Manufacturers	Random Sampling Variability Index for Fuel Engine Manufacturers
43_ic_TR_Speed	Random Sampling Variability Index for Dynamic Speed
44_ic_TR_Fuel Rate	Random Sampling Variability Index for

	Dynamic Fuel Rate
45_ic_SS_CO2	Random Sampling Variability Index for SS CO2
46_ic_TR_CO2	Random Sampling Variability Index for Transient CO2
49_ic_Temperature_CO2	Random Sampling Variability Index for CO2 Temperature
Delta PM SS	Model switch controlling PM SS error surface application
Delta PM Transient	Model switch controlling PM Transient error surface application
Delta PM Atmospheric Pressure	Model switch controlling PM Atmospheric Pressure error surface application
Delta PM Ambient Temperature	Model switch controlling PM Ambient Temperature error surface application
Delta CO SS	Model switch controlling CO SS error surface application
Delta CO Atmospheric Pressure	Model switch controlling CO Atmospheric Pressure error surface application
Delta CO Ambient Temperature	Model switch controlling CO Ambient Temperature error surface application
Delta NMHC SS	Model switch controlling NMHC SS error surface application
Delta NMHC Transient	Model switch controlling NMHC Transient error surface application
Delta NMHC Atmospheric Pressure	Model switch controlling NMHC Atmospheric Pressure error surface application
Delta NMHC Ambient Temperature	Model switch controlling NMHC Ambient Temperature error surface application
Delta Ambient NMHC	Model switch controlling Ambient NMHC error surface application
Delta Exhaust Flow SS	Model switch controlling Exhaust Flow SS error surface application
Delta Exhaust Flow Transient	Model switch controlling Exhaust Flow Transient error surface application
Delta Exhaust Flow Pulsation	Model switch controlling Exhaust Flow Pulsation error surface application
Delta Exhaust Flow Swirl	Model switch controlling Exhaust Flow Swirl error surface application
Delta Exhaust EMI/RFI	Model switch controlling Exhaust EMI/RFI error surface application
Delta Exhaust Temperature	Model switch controlling Exhaust Temperature error surface application
Delta Exhaust Pressure	Model switch controlling Exhaust Pressure error surface application
Delta Dynamic Torque	Model switch controlling Dynamic Torque error surface application
Delta Torque DOE Testing	Model switch controlling Torque DOE Testing error surface application
Delta Torque Warm-up	Model switch controlling Torque Warm-up

	error surface application
Delta Torque Humidity	Model switch controlling Torque Humidity error surface application
Delta Torque Interpolation	Model s witch c ontrolling T orque Interpolation error surface application
Delta Torque Engine Manuf	Model s witch c ontrolling Torque (Engine Manufacturer) error surface application
Delta Fuel Engine Manuf	Model s witch c ontrolling F uel (Engine Manufacturer) error surface application
Delta Dynamic Speed	Model s witch c ontrolling D ynamic Speed error surface application
Delta Dynamic Fuel Rate	Model s witch c ontrolling Dynamic F uel Rate error surface application
Delta CO2 SS	Model s witch controlling C O2 S S error surface application
Delta CO2 Transient	Model s witch c ontrolling C O2 Transient error surface application
Delta CO2 Ambient Temperature	Model s witch controlling C O2 A mbient Temperature error surface application

2.0 Statistics

Descriptive statistics summarizing the values obtained during a single reference NTE event simulation are provided in Table B-2.

TABLE B-2. DESCRIPTIVE STATISTICS FOR SIMULATION VARIABLES

Statistic	Definition
Trials	Number of times the simulation was repeated
Mean	Arithmetic average
Median	The va lue midw ay b etween the s mallest va lue a nd the la rgest value
Mode	Value that occurs most often
Standard Deviation	Measurement of variability of a distribution. The square root of the variance
Variance	The a verage of t he s quares of t he de viations of a num ber of values from their mean
Skewness	A measure of the degree of deviation of a distribution from the norm of a symmetric distribution
Kurtosis	A measure of the degree of peakedness of a distribution
Coefficient of Variability	Standard deviation/Mean
Minimum	Smallest value
Maximum	Largest value
Range Width	Largest value – smallest value
Mean Standard Error	Standard deviation of the distribution of possible sample means

3.0 Percentiles

Percentiles are the probability of achieving values below a particular percentage in the following increments: 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, and 100%. Percentiles are computed for each of the simulation variables described in Table.

4.0 Sensitivity Data

Sensitivity data are provided by computing the rank correlation coefficient for all error surfaces and all simulation variables. The EXTRACT data file contains the absolute value of the rank correlation. In post-simulation processing, values of control variable Delta PM SS in the simulation results were applied to dichotomize the data.

5.0 Trial Values

The value for all simulation variables is provided at each trial of the simulation.

REPORT FILES

1.0 Report Summary

This section includes the simulation start date and time, stop date and time, number of trials run, sampling type (Monte Carlo), random seed used, and run statistics.

2.0 Forecasts

Descriptive statistics, percentiles, and a frequency histogram are provided for forecast variables 001AVL_DePM (g/hp-hr), Method 1 through 006AVL_Valid DePM (g/hp-hr), Method 3 (see Table).

3.0 Assumptions

Descriptive statistics, percentiles, distribution parameters, and a distribution chart are provided for assumption variables 01_ic_SS_PM through 49_ic_Temperature_CO2 (see Table).

4.0 Sensitivity Charts

Sensitivity charts are provided for forecast variables 001AVL_DePM (g/hp-hr), Method 1 through 006AVL_Valid DePM (g/hp-hr), Method 3 (see Table). Crystal Ball calculates sensitivity by computing rank correlation coefficients between every assumption (error surface) and forecast (delta BSPM emissions) while the simulation is running. Positive rank correlations indicate that an increase in the assumption is associated with an increase in the forecast. The larger the absolute value of the rank correlation the stronger the relationship.

The sensitivity charts developed during the MC simulation are displayed as 'Contribution to Variance" charts which are calculated by squaring the rank correlation coefficients for all assumptions used in a particular forecast and then normalizing them to 100%. Figure displays a sensitivity chart for the AVL delta PM Method #1. The assumptions with the highest contribution to variance (in absolute value) are plotted at the top of the chart. This example shows a typical dominant effect of the PM SS error surface represented by the 79.5% negative effect of Delta PM SS. As seen in the example in Figure B-1, as you increase the SS PM there is an increase in the delta PM Method #1 values represented by the 7.6 % positive effect of ic_SS_PM, and as you increase the torque warm-up there is a decrease in the delta PM Method #1 values represented by the 2.8 % negative effect of ic_Torque_Warm. Only the top eight assumptions are plotted in this sensitivity chart.

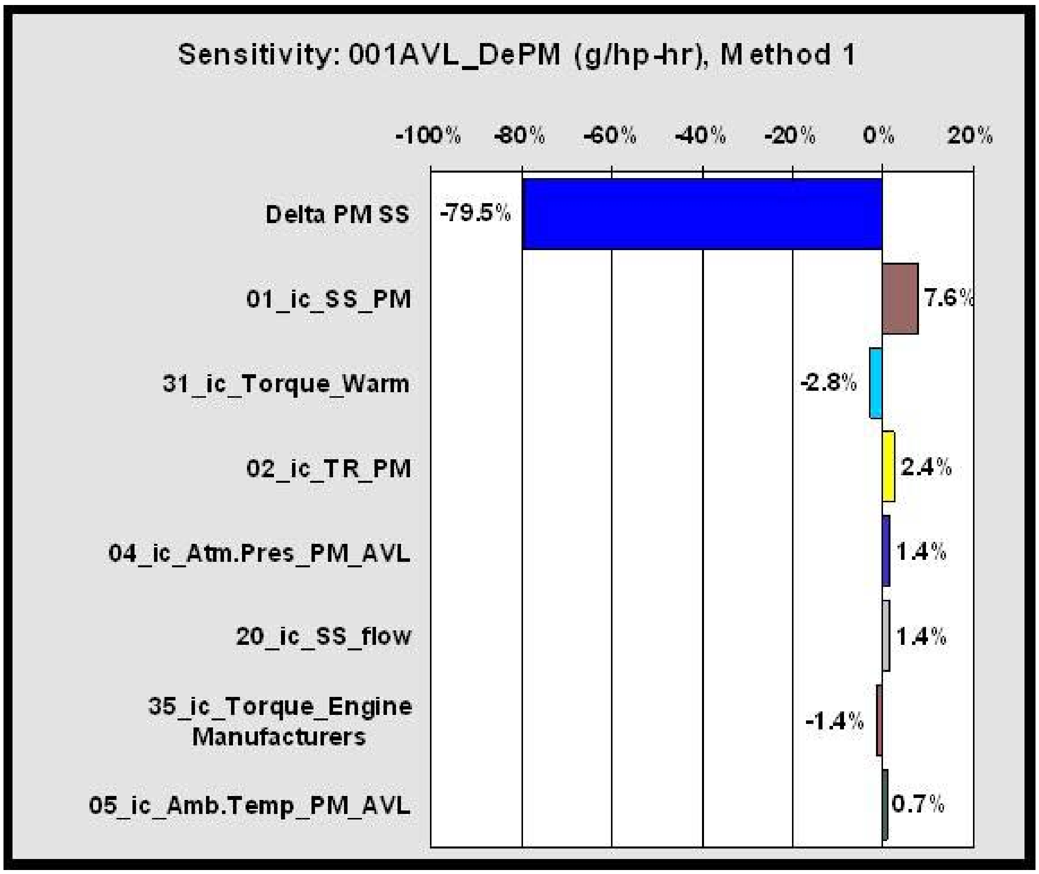


FIGURE B-1. SENSITIVITY CHART FOR AVL DELTA PM METHOD 1

APPENDIX D

MONTE CARLO SPREADSHEET COMPUTATIONS

1.0 DESCRIPTION OF ASSUMPTIONS

The following assumptions were made in running the Monte Carlo model:

- Only one reference NTE event can be run at a time through the Monte Carlo simulation workbook. However, NTE event cases can be stacked and run in a batch mode.

- Uniform (1 second in duration) time steps are used in the reference NTE events.

- Standard format and engineering units for reference NTE data established for the project are observed, and applied to the reference NTE event before the NTE event is entered in the Error Model workbook for Monte Carlo simulation.

- Any wet – dry matter conversions, if not negligible, have been performed on the appropriate reference NTE event values before the reference NTE event was entered in the Error Model workbook for Monte Carlo simulation. No wet – dry conversions are performed in the workbook.

- Any reference NTE event normalizations to produce similar emissions brake-specific results from the three emissions calculation methods have been appropriately performed before the reference NTE event was entered in the Error Model workbook for Monte Carlo simulation. No normalizations among the three methods are performed in the workbook.

- PM emissions models for three calculation methods are computed for the AVL PEMS. Only calculation methods 1 and 2 are computed for the Horiba and Sensors PEMS.

- Error surface models and supporting data were approved by the Steering Committee.

- The error model spreadsheet has been correctly implemented, and its interaction with Monte Carlo tools like Crystal Ball is correctly understood.

- Random number generation by a Monte Carlo tool like Crystal Ball is correct.

- Convergence of the completed MC simulation was processed and checked outside of the simulation workbook. Benchmark checks on the convergence calculations were made using a SAS® computer program.

2.0 WORKSHEET DESCRIPTIONS

2.1 Macro Description

The Macro can be viewed in the Excel spreadsheet 'Batch Control' with the menu selections Tools>Macros>Macro1>Edit. The purpose of Macro1 is to control NTE event batch processing of stacked cases. For each NTE event case processed, the macro expedites clearing extra cells below the reference NTE event in the spreadsheet 'Error Model' Methods worksheet and deletes extra rows in the Delta error worksheets. The macro also performs Mode 0 calculations and stores resultant 'ideal emissions' values for application in subsequent Monte Carlo simulation.

The user must begin with the starter version of the 'Error Model' Excel file which has 300 rows of equations in columns X - CF and in rows 52 - 351 in the Methods worksheet. The starter spreadsheet also has 300 rows of equations below charts in columns B – F, or B – L, in applicable Delta worksheets. The user (when not under automatic batch control) copies the reference NTE event into columns A – V, row 52 and down, in the Methods worksheet. It is can then be confirmed that cell J45 in the Methods worksheet displays the correct number of rows of the reference NTE event.

Macro execution can be accomplished through the menu selections Tools>Macros>Macro1>Run. Note that this macro clears cells without deleting rows in the Methods worksheet, and deletes rows in the Delta worksheets. This macro will not work if the reference NTE event has only one row. For a reference NTE event with exactly two rows, this macro will corrupt the second "check" values in columns B-F type Delta worksheets. Check values are not used in the simulation, but are provided as a diagnostic aid. Apply the macro for reference NTE events with no more than 300 rows.

The reader can follow the description of execution that follows by viewing the macro and observing the comment rows provided throughout the macro text. In execution, the macro first reads the contents of J45 in the Methods worksheet. It uses the number of rows in the reference NTE event defined by J45 to determine how many rows to clear and delete in the spreadsheet. It checks that the number of rows is between 2 and 299, inclusive. It will also execute correctly for 300 rows.

Next, the macro clears cell contents in columns X – CF below the reference NTE event in the Methods worksheet. Note the macro, as written, will not execute properly if the starter spreadsheet has been revised with row insertion or deletion in certain areas of the spreadsheet. As written, the macro initiates in cell X52, counts down through the NTE Event rows, and clears contents in the range from there in column X through cell CF351.

Next, the macro deletes extra rows below the reference NTE event, where applicable, for example in Delta worksheet 07. For Delta worksheet 07 it initiates in cell B79 and counts down through the rows of the reference NTE event to the first row to be deleted. It selects the range of rows from there down through row 378, deletes the rows, copies some equations and a value to the last row in the range the charts use, and returns the cursor to cell F68 leaving the display more or less centered on the charts in the worksheet.

Subsequently, the macro performs similar operations in other Delta worksheets; however, the initiating cell and final row differ among the worksheets. The Delta worksheets processed in this way are 7, 10, 11, 16, 17, 20, 21, 22, 23, 29, 30, 43, 44, 45, 46 and 49.

Following the row deletion operations in the Delta worksheets, or directly when the reference NTE event has 300 rows, the macro prepares for the Mode 0 (ideal emissions) calculation. First, in the Methods worksheet it copies the equations in row 52, columns X through CF, to the last row in the reference NTE event. This clears any errors introduced in the last row; however, it assumes that row 52 is correct. The last cell in column AC (Δt) is cleared for aesthetics, since the Δt values are not applied in the model calculations.

The Mode 0 calculation is performed by the macro by changing the value in cell A6 of the Summary worksheet to 0. Then in the Methods worksheet, the values from cells CU22 through CU30 are pasted (values only) to cells O22 through O30 where they are referenced by formulas during Monte Carlo simulation. The macro changes the value of A6 in the Summary worksheet to 2 in preparation for the Monte Carlo simulation, and moves the cursor to cell CT18 of the Methods worksheet.

Additional comments regarding the macro operation are presented in the following section descriptions of the model spreadsheet.

2.2 Worksheet 1: ErrorControl

The ErrorControl worksheet of the Error Model workbook implements 31 logic switch functions. The user enters a numerical "1" in column AD in each row corresponding to error surfaces to be included in the calculation. A numerical "0" is applied to error surfaces to be excluded in the calculation. Corresponding random variables for error-surface on-off switch random effects sensitivity modeling are implemented in column W under Crystal Ball control.

Error surfaces are numbered 1 through 49. The numbered error surfaces are defined in columns A – C, and information pertinent to their usage is presented in columns E – V of the worksheet. Column E displays warning messages when an unusual value is monitored in column D.

The control switch elements in the worksheet are deliberately placed on rows in the worksheet corresponding to the error surfaces to expedite equation checking in the Methods worksheet where the control switch variables are applied in conjunction with error surfaces from the correspondingly numbered "Delta" worksheets

The numbered error surfaces and time alignment controls that have been implemented are defined in the following Table C-1.

TABLE C-1. ERROR SURFACES USED IN SIMULATION

Component	No.	Error Surface
Delta PM	1	Delta PM SS
	2	Delta PM Transient
	4	Delta PM Atmospheric Pressure
	5	Delta PM Ambient Temperature
Delta CO	7	Delta CO SS
	10	Delta CO Atmospheric Pressure
	11	Delta CO Ambient Temperature
Delta NMHC	13	Delta NMHC SS
NMHC = 0.98*THC	14	Delta NMHC Transient
	16	Delta NMHC Atmospheric Pressure
	17	Delta NMHC Ambient Temperature
	19	Delta Ambient NMHC
Delta Exhaust Flow	20	Delta Exhaust Flow SS
	21	Delta Exhaust Flow Transient
	22	Delta Exhaust Flow Pulsation
	23	Delta Exhaust Flow Swirl
	25	Delta Exhaust EMI/RFI
	27	Delta Exhaust Temperature
	28	Delta Exhaust Pressure
Delta Torque	29	Delta Dynamic Torque
	30	Delta Torque DOE Testing (Interacting Parameters Test)
	31	Delta Torque Warm-up(Interacting Parameters Test)
	32	Delta Torque Humidity / Fuel(Independent Parameters Test)
	34	Delta Torque Interpolation
	35	Delta Torque Engine Manufacturers
Delta Fuel	42	Delta Fuel Engine Manufacturers
Delta Speed	43	Delta Dynamic Speed
Delta Fuel Rate	44	Delta Dynamic Fuel Rate
Delta CO_2	45	Delta CO_2 SS
	46	Delta CO_2 Transient
	49	Delta CO_2 Ambient Temperature

The thirty-one (31) error surfaces that have been implemented are included or excluded by the controls numbered 1 – 49 identified in Table. When all 31 error controls are on (included in calculation), the sum of column D in the worksheet ErrorControl is 31.

2.3 Worksheet 2: Summary

The Summary worksheet in the Error Model workbook comprises input mode control in rows 4 – 10 and output summary in rows 88 and 119. Other rows in this worksheet are available for diagnostic purposes.

The calculation mode control is accomplished with cell A6 where the user normally confirms that a numerical value of "2" is designated. Mode 2 designates emissions calculation with all errors applied. Mode 1 corresponds to a calculation of emissions with all errors applied except environmental errors. Mode 0 designates an "ideal" emissions calculation with no errors applied. In Monte Carlo error model simulation performed in this study Mode 2 was used.

Mode 0 is used prior to Monte Carlo simulation to generate the "ideal" emissions for a given reference NTE event. The Mode 0 values are calculated by entering a value of "0" in cell A6. The Mode 0 calculation and subsequent storing of the "ideal" emissions results may be accomplished manually (as described above) or by exercising a provided macro. The macro automatically sets the value in cell A6 to zero, calculates and saves the "ideal" emissions values, and returns the value in A6 to "2" in preparation for the Monte Carlo simulation. The locations where the reference NTE event must be entered manually, and the locations where the "ideal" emissions must be saved (done automatically if the macro is used) are described in the Methods worksheet section.

Mode 1 in cell A6 is not typically used but can be applied for diagnostic purposes.

The output summary section of the Summary worksheet in rows 88 and 119 presents numerically and descriptively labeled outputs of the emissions and emissions error calculations.
In the output summary, the cells that are highlighted in turquoise color are designated by Crystal Ball as "Forecast" (or output) random variables.

A total of 14 outputs ("Forecasts") are designated in the Summary worksheet rows 88 and 119 covering the number of output values from PM emission, three calculation methods (Methods 1, 2 and 3) for the AVL PEMS and two methods (Methods 1 and 2) for the Horiba and Sensors PEMS, for the full error model and for the validation model (designated Valid in Summary worksheet variable labels). All of these "Forecasts" are provided in units of grams/hp-hr. This variety of calculations was accomplished with the Methods worksheet.

2.4 Worksheet 3: Methods

The Methods worksheet of the Error Model workbook comprises the following areas:

- Notes and diagnostic guides are located principally in rows 1 – 21 in columns A – CF, continuing on row 5 through column DD.

- Reference NTE event data are located in rows 35 - 351 of columns A – W. Actual reference NTE event data must be entered manually (or automatically under batch control) starting on row 52 in columns A – V. Cell W52 data must be entered, and is provided for special case study where the Method 3 flow-weighted PM concentration may differ from Methods 1 and 2. One to 300 rows of reference NTE event data are allowed. Uniform (one second interval) time steps are assumed represented by the reference NTE data.

- Parameters calculated are located in rows 35 – 351 of columns X – CF. The number of rows of these parameter equations must match the number of rows in the reference NTE event. Excess cells in these columns may be cleared manually or automatically during execution of the macro.

- Mode 0, Ideal Emissions for this reference NTE event are stored in column O rows 22 – 30 (either manually or automatically by the macro). Related data on the same rows are located in columns CT – DD.

- Input i_c random variable distributions (Crystal Ball uses the terminology "Assumptions" for these inputs) are located in rows 26 – 32 of columns AG - CC.

- Emissions calculations by three methods are located in rows 6 - 81 of columns CH – CJ (Method 1), CL – CN (Method 2) and CP (Method 3). This part of the worksheet calculates full model and validation model.

2.5 Methods Worksheet: Notes and Diagnostic Guide

In rows 1 – 22 for columns A – CF, several descriptive labels and references are defined for use in navigating through the worksheet. Row 5, columns A -DD, contains column identification numbers referenced in rows 7 through 22 (depending on the column). For example, in column H the values 65 on row 8 indicates that the values in column H (rows 52 and following rows) are applied in column 65 (BM) labeled on row 5. If the user scrolls to cell BM52 it is observed that the spreadsheet formula in the cell refers to values from column H. The information in the notes and diagnostic guide was not applied by the spreadsheet in any of the emissions calculations. It was included with the intent to simplify diagnostics by providing information on locations where spreadsheet values were applied elsewhere in the spreadsheet. Outside the areas indicated above, some other notes, comments and diagnostic guides may be found in other areas of the spreadsheet.

2.5.1 Methods Worksheet: Reference NTE Event

The reference NTE event used in the simulation was entered in rows 35-351 of columns A – W. Actual reference NTE event data must be entered manually starting on row 52 in columns A – V. Cell W52 data must be entered, and is provided for special case study where the Method 3 flow-weighted PM concentration may differ from Methods 1 and 2. A minimum of one and a maximum of 300 rows of reference NTE event data are allowed. Equal time steps (1 second intervals) are assumed in the reference NTE data rows. The standard format and engineering units of reference NTE event data established for this project must be observed. These are described in the column headings on rows 47 – 51, columns A – V.

2.5.2 Methods Worksheet: Parameters

Parameters applied in the three emissions methods are calculated in rows 35 – 351 of columns X – CF. The number of rows of these parameter equations must match the number of rows in the reference NTE event. Excess cells in these columns may be cleared manually or automatically during execution of the macro.

The formulas applied in rows 52 and down in columns X – CF have been produced by normal edit-copy (typically of row 52 in these columns) and edit-paste to rows 53 and following rows in these columns. The Δt values displayed in column AC are not used in any calculation, but are displayed so a user can confirm uniform reference NTE event time sampling. The last cell in column AC can be cleared (done automatically by the macro). Note that excess cells in these columns must be cleared, and row deletion operations should not be applied since this would affect other areas in the Methods worksheet.

Certain sums are performed in several columns over the Parameter rows (range of the reference NTE event). These are accomplished in row 46 in columns AI, AW, AX, BO, BQ, BU and CA. Flow-weighted PM concentration SS and TR errors are consolidated, with and without environmental errors, in the area of cells AN40:AB47. Certain constants applied in the calculation are stored in cells AW42, BC42, BI42, BP40 and BP42. Other constants or conversion factors are incorporated numerically in spreadsheet formulas. Typical of these is "0.01" to convert a percentage to a fraction.

Specific parameters or variables are calculated in the various columns for application in all three methods, full model and validation model. Table C-2 lists the parameters used in the Methods worksheet, the columns where they are computed and a brief description of the parameters.

TABLEC-2. METHODS WORKSHEET PARAMETER COLUMN DESCRIPTIONS

Methods Worksheet Parameters Column Descriptions		
Subject	**Column**	**Description**
Engine operating state percentages	X – AB	Convert NTE Event variables to percentages: speed, torque, fuel rate, exhaust flow
ΔTime	AC	Displays Δt between NTE Event rows
NMHC	AD	Calculate NMHC ppm as 0.98 of THC ppm
Fuel Rate	AE	Calculate fuel rate g/s based on fuel density of 851 g/L
Exhaust Flow Calculations	AF	Convert exhaust flow SCFM to mol/s
	AG	Sum exhaust flow errors from Delta tabs 20, 21, 22, 23, 25 27 and 28 expressed in % of mol/s maximum. Respective ErrorControl tab switches are applied.
	AH	Convert the total exhaust flow error in % of maximum mol/s to mol/s
	AI	Add the mol/s exhaust flow error to the exhaust flow in mol/s. Mode control logic is applied.
Speed with error	AJ	Add engine speed error from Delta tab 43 expressed as % of engine range converted to engine speed in rpm. Mode control logic and ErrorControl switch are applied.
Fuel rate with error	AK	Combine Delta tab 42 Fuel (engine manufacturer) with fuel rate from Delta tab 44 expressed as % of maximum fuel rate converted to g/s to engine fuel rate in g/s. Mode control logic and ErrorControl switch are applied.
Torque	AL	Sum torque errors from Delta tabs 29, 30, 31, 32, 34 expressed as % of peak torque, and from Delta tab 35 expressed as % of NTE point torque converted to % of peak torque. ErrorControl switches are applied.
	AM	Add the total torque error expressed as % of peak torque converted to N·m to engine torque in N·m. Mode control logic is applied.
PM, μg/mol	AN42, AN43	Sum PM SS and TR errors from Delta tabs 1 and 2 for AVL PEMS expressed as μg/mol, AN 42 for Methods 1 and 2, AN43 for Method 3. ErrorControl switches are applied.
	AO42	Sum PM SS and TR errors from Delta tabs 1 and 2 for Horiba PEMS expressed as μg/mol, for Methods 1 and 2. ErrorControl switches are applied.
	AP42	Sum PM SS and TR errors from Delta tabs 1 and 2 for Sensors PEMS expressed as μg/mol, for Methods 1 and 2. ErrorControl switches are applied.
	AQ42, AQ43	Sum AVL flow-weighted PM concentration to all errors except environmental PM errors, AQ 42 for Methods 1 and 2, AQ43 for Method 3. Mode control logic is applied.
	AR42	Sum Horiba flow-weighted PM concentration to all errors except environmental PM

		errors. Mode control logic is applied.
	AS42	Sum Sensors flow-weighted PM concentration to all errors except environmental PM errors. Mode control logic is applied.
	AQ46, AQ47	Sum AVL flow-weighted PM concentration to all errors including environmental PM errors Delta tabs 4 and 5, AQ 46 for Methods 1 and 2, AQ47 for Method 3. Mode control logic is applied.
	AR46	Same formula as AR42 as no environmental PM error model applied to Horiba flow-weighted PM concentration.
	AS46	Same formula as AS42 as no environmental PM error model applied to Sensors flow-weighted PM concentration.
Speed · Torque	AW	Form product of Speed (rpm, all errors case, column AJ) and Torque (N·m, all errors case, column AM) for application in Methods 1 and 3. Convert rpm to radians/sec with 2 πradians/revolution, minutes to seconds with 60sec/min, N·m/sec to watt hr with 3600Joules/watt hr, and watt to kw with 1000w/kw.
	AX	Form product of Speed (rpm, no errors for validation case, column O) and Torque (N·m, no errors for validation case, column T) for application in Methods 1 and 3. Convert rpm to radians/sec with 2 πradians/revolution, minutes to seconds with 60sec/min, N·m/sec to watt hr with 3600Joules/watt hr, and watt to kw with 1000w/kw.
CO and ΔCO, %	AY	Sum environmental CO errors including errors from Delta tabs 10 and 11.
	AZ	Sum other CO errors. Error from Delta tab 7 is the only one developed.
	BA	Add the total CO errors expressed as % to engine CO in %. Mode control logic is applied.
NMHC and ΔNMHC, ppm	BE	Sum environmental NMHC errors including errors from Delta tabs 16, 17 and 19.
	BF	Sum other NMHC errors including errors from Delta tabs 13 and 14.
	BG	Add the total NMHC errors expressed as ppm to engine NMHC in PPM. Mode control logic is applied.
CO_2 and ΔCO_2, %	BK	Sum environmental CO_2 errors. Error from Delta tab 49 is the only one developed.
	BL	Sum other CO_2 errors including errors from Delta tabs 45 and 46.
	BM	Add the total CO_2 errors expressed as % to engine CO_2 in %. Mode control logic is applied.
Exhaust Flow · [NMHC + (CO +CO_2)] / [fuel mass flow rate / Speed · Torque]	BO	Form product of hydrocarbons fraction plus CO and CO_2 fractions (all errors case, columns BG, BA and BM) and exhaust flow (mol/s, column AI) divided by ratio of fuel rate (g/s, all errors case, column AK) to speed-torque product (all errors case, column AW) for application in PM Method 2.
	BQ	Form product of NMHC fraction plus CO and CO_2 fractions (all errors case, columns BG, BA and BM) and exhaust flow (mol/s, column AI) divided by ratio of fuel rate (g/s, no errors case, column AE) to speed-torque product (no errors case, column AX) for application in PM Method 2 validation.
NMHC + (CO+CO_2)	BS	Form sum of NMHC fraction plus CO and CO_2 fractions (all errors case, columns BG, BA and BM) for application in Method 3.
Fuel Rate / [NMHC + (CO+CO_2)]	BU	Form quotient, Fuel Rate (g/s, all errors case, column AK) divided by sum of NMHC fraction plus CO and CO_2 fractions (all errors case, column BS) for application in Method 3.
Fuel Rate / [NMHC + (CO+CO_2)]	CA	Form quotient, Fuel Rate (g/s, no errors case, column AE) divided by sum of NMHC fraction plus CO and CO_2 fractions (all errors case, column BS) for application in Method 3 validation.

2.5.3 Methods Worksheet: Mode 0 Ideal Emissions

For the reference NTE event in rows 52 and down in columns A – V, an ideal emissions value must be calculated and stored for application in the emissions difference calculations. The ideal case can be calculated either manually, or automatically by the macro. Following the calculation, the ideal values are stored by edit-copy edit-paste-special-values operation to the cells in column O, rows 22 – 30. The manual operations described below are performed automatically by the macro, if executed, after manually entering the reference NTE event.

After manually entering the reference NTE event to be simulated and checking that the number of rows of equations in the Parameters section matches the rows in the reference NTE event, a numerical "0" can be entered in cell A6 of the Summary worksheet. The Methods worksheet should have calculated Mode 0 results using the reference NTE event. If error messages like "#VALUE or #DIV/0!" are displayed, there is probably still a mismatch between the rows of the reference NTE event and Parameter equations. When calculated properly (with 0 in Summary A6), the values displayed in the Methods worksheet columns CU, CV and DB will be equal on each of the rows 22 – 30. The values in column CX are not yet equal (unless previously calculated and stored for this reference NTE event) because they reflect the values stored in Methods worksheet column O, rows 22 – 30. The next manual step is to edit-copy column CU, rows 22 - 30, and store the values by edit-paste-special-values in column O, rows 22 - 30. Now in rows 22 - 30 the columns CU, CV, CX and DB should be equal. The final step is to return to Summary worksheet cell A6 and change the value from 0 to 2. At this point the spreadsheet could be run in Monte Carlo simulation to produce properly sampled values. However, if the user desires to monitor charts provided in the Delta worksheets during the simulation, further row-matching to the reference NTE event is required in most of the Delta worksheets.

The manual operations described in the previous paragraph are intended to explain how the Mode 0 ideal emissions are calculated and stored for use in the Monte Carlo simulation when Δemissions values are calculated using the ideal emissions results stored in O22 – O30. The reference NTE event must be entered with an operation such as a manual edit-copy and edit-paste or edit-paste-special-values operation. The macro automatically performs the mode 0 calculation, stores the mode 0 results in O22 – O30, and changes Summary A6 back to mode 2.

The macro also deletes extraneous rows from all the appropriate Delta worksheets so the charts therein display properly. It is important to copy the reference NTE event into a fully 'loaded' starter file with equations filled on 300 rows in the Parameters area, and with full 300 row complement of equation-rows in each of the appropriate Delta worksheets for the macro to modify the spreadsheet properly.

2.5.4 Methods Worksheet: Input ic Random Variable Distributions

Probability distribution parameters are applied, and simulation trial values of the inputs are generated in rows 26 – 32 of columns AG - CC. Rows 26 and 27 are used to input distribution parameters. Rows 28 and 29 contain descriptive labels brought from the appropriate Delta worksheet. Row 30 is an information-only number, row 31 contains the name label applied in Monte Carlo simulation to the input i_c, and row 32 is where the Monte Carlo simulation tool places generated randomly-sampled values during simulation. The values in row 32 are referenced by formula in the respective Delta worksheets where they are used for interpolation on the error surfaces.

The Monte Carlo tool in Crystal Ball uses the terminology "Assumptions" for these inputs. Two distribution forms are applied: truncated normal (Gaussian), and discrete uniform. For the normal distribution, the applied standard deviation is in row 27. In Crystal Ball, the standard deviation cell on row 27 and the label cell on row 31 were referenced by equation in the Crystal Ball assumption setup window, the mean was input as 0, and the distribution was truncated at -1.414319083 and at +1.414319083. Since all the truncated normal i_c distributions are identical (although the sampled trial values from each will be random in the Monte Carlo simulation), the Crystal Ball define-copy data and define-paste data operations were applied to define the truncated normal distributions for other i_c variables once the first one had been defined.

For the discrete uniform distributions, the minimum discrete value (1 in all cases) was applied in row 26, the maximum discrete value was applied in row 27 and the other row descriptions are the same as before. Again, one of these inputs was setup with Crystal Ball "define assumption" and then applied with Crystal Ball define-copy data and define-paste data operations to other i_c cells on row 32 where a discrete uniform distribution was applied. When Crystal Ball "Assumptions" were defined, Crystal Ball colored each input cell bright green

During a Monte Carlo simulation, the Monte Carlo tool (e.g. Crystal Ball) placed a numerical value in each of the i_c cells on row 32. Then the spreadsheet was exercised to perform interpolations in all the Delta worksheets. The resulting error sample values for the entire reference NTE event were returned to the Methods worksheet Parameters area, and then the Methods worksheet Emission Calculations section computes Δemissions using three methods, full model and validation to generate one set of the 14 output values described in the Summary section. The simulation tool stores the set of random input values from row 32 as well as the output values in an Excel data base from which the corresponding sets of values can later be extracted. Once each trial was completed, the simulation tool randomly sampled a second set of input values from the respective probability distributions, placed the values in the cells on row 32, exercised the spreadsheet again, stored the input and output values, and went to a third trial, etc. Typically 40,000 to 65,000 trials, depending on the reference NTE event, were used in this project with this Error Model workbook.

Note that there are three ways the user can control the effect of the i_c values in the emissions calculations:

Mode control in Summary A6,
Include / exclude switches in ErrorControl column AD, and
Specification of input random variables ("Assumptions") and their probability distributions in the Methods worksheet row 32.

These three ways of controlling the i_c values are independent, but the effects are interdependent as follows. Mode control determines what categories of errors are added into the calculations. Mode controls categories of errors are classified as:

1. Mode 0 - no errors included
2. Mode 1 - "all" but 'environmental' errors included
3. Mode 2 - "all" errors added into the calculations

"All" in this context represents those error surfaces turned on by the switches in the ErrorControl worksheet. The input random variable distribution controls the distribution of the sampled i_c values applied during Monte Carlo simulation for the several Delta error surfaces. Mode and ErrorControl switches must be appropriately turned on for the effects of the sampled i_c values to be included in the emissions difference results. These controls affect the calculations in the Methods worksheet Parameters and Emission Calculations sections.

2.5.5 Methods Worksheet: Emission Calculations

In the area of rows 6 - 81 of columns CH – CP the brake-specific emissions and Δemissions calculations are performed using the variables and parameters generated in the Parameters section. Three sets of columns, structured similarly, calculate the full model, validation model, time alignment and drift correction for the following methods:

1. Method 1 calculations are applied in columns CH – CJ,

2. Method 2 calculations are applied in columns CL – CN, and

3. Method 3 calculations are in columns CP.

Columns CH - CJ for Method 1 are typical of the methods where the structure is the same, but the formulas are a little different. Column CH performs the PM emission calculations for the AVL PEMS, column CI performs for the Horiba PEMS and column CJ for the Sensors PEMS. The structure of the three columns is the same. Formulas implemented in the three columns are the same, but the equations implementing the formulas apply variables and parameters appropriate to the respective PEMS.

As an example of the calculation for PM Method 1 we will examine column CH in detail. The full model calculation was accomplished in cells CH48 – CH54. The ideal emissions result was brought into the area by equation in CH51. Full model PM emissions (ePM) in g/kw-hr were calculated in CH54. Cells CH55 – CH59 are information-only diagnostic aids. The full model Method 1 result in CH54 is calculated by the formulas in Figure C-1.

$\overline{m_{PM}}$ is a flow weighted particulate matter exhaust concentration in g/mol

$$e_{PM}\left(g/kW\cdot hr\right)=\frac{\overline{m_{PM}}\left(\frac{g}{mol}\right)*\sum_{i=1}^{N}\left[\dot{n}_i\left(\frac{mol}{s}\right)*\Delta t\right]}{\sum_{i=1}^{N}\left[\frac{Speed_i(rpm)*T_i(N\cdot m)*2*3.14159*\Delta t}{60*1000*3600}\right]}$$

FIGURE C-1. BRAKE-SPECIFIC PM BY METHOD 1

In the formula for the full model mode 2, delta error values sampled from the Delta worksheets 1, 2, 4 and 5 have been added in $\overline{m_{PM}}$. Similarly, delta error values sampled from Delta worksheets 20-23, 25, 27 and 28 have been added to the exhaust flow, delta errors sampled from worksheets 29-32 and 34-35 were added to torque, and worksheet 43 deltas were added to speed. The Δt values are equal (1 second) and therefore cancel out of the equation.

The validation model calculation was accomplished in the cells CH79 – CH81. Validation model PM emissions (g/kW-hr) was calculated in cell CH81.

Calculations for PM by Method 1 described above for the AVL PEMS in column CH are similar for the Horiba and Sensors PEMS by Method 1 in columns CI and CJ, respectively. Similar calculations for PM by Method 2 are presented in columns CL – CN, and by Method 3 in column CP.

2.6 Worksheet 4: Constants and Equations

The Constants&Eqns tab was strictly a snapshot of equations used in the brake-specific emissions calculations. It displayed the equations and constants implemented in spreadsheet formulas of the Methods worksheet

2.7 Worksheet 5: SS PM Error Surface

The 7 Delta CO SS worksheet is a typical Delta worksheet. Its functional structure, formulas, charts and operation are very similar to the following worksheets:

- 20 Delta Exhaust Flow SS
- 22 Delta Exhaust Flow Pulsation
- 23 Delta Exhaust Flow Swirl
- 30 Delta Torque DOE Testing
- 45 Delta CO2 SS
-

With minor changes in charts and structure, its function, formulas and operation are also similar to the following worksheets:

- 1 AVL Delta PM SS
- 1 Horiba Delta PM SS
- 1 Sensors Delta PM SS
- 2 AVL Delta PM Transient
- 2 Horiba Delta PM Transient
- 2 Sensors Delta PM Transient
- 4 AVL Delta PM AtmosPressure
- 5 AVL Delta PM Ambient Temp
- 13 Delta NMHC SS
- 14 Delta NMHC Transient
- 19 Delta Ambient NMHC
- 21 Delta Exhaust Flow Transient
- 25 Delta Exhaust EMI-RFI
- 29 Delta Dynamic Torque
- 31 Delta Torque Warm-up
- 32 Delta Torque Humidity
- 34 Delta Torque Interpolation
- 35 Delta Torque Engine Manuf
- 42 Delta Fuel Engine Manuf
- 43 Delta Dynamic Speed
- 44 Delta Dynamic Fuel Rate

- 46 Delta CO2 Transient

The following provides a brief summary of the 7 Delta CO SS worksheet:

- Rows 1 – 7 contain descriptive information about the error surface implemented in the worksheet.
- Rows 8 - 42 present the error surface in columns A – L. Other columns, M – W, on these rows generate a lookup table used with an interpolation routine.
- Figures A, B and C follow.
- Rows 76 – 379 calculate the ΔCO SS error values for each row of the reference NTE event. These values were returned to the Methods tab Parameters section.

The following paragraphs describe in further detail functions in the 7 Delta CO SS worksheet:

Data from the error surface (rows 13 – 42, columns A – L, in this Delta worksheet) must be entered in sorted order (sorted on Lab Nominal column C in ascending order) for proper operation of the x-lookup-interpolation function. The three figures chart the error function. Figure A, in similar Delta tabs, may plot several data sets versus the x-value, Lab Nominal (column C). Figure A y-values are CO % Lab Nominal (column C), and may also plot 99th percentile, 50th percentile (median) and 1st percentile.

Related error surface data are plotted in Figure B. Figure B plots several data sets versus the same x-value, Lab Nominal (column C). Figure B y-values are the difference, CO % (PEMS) – CO % (lab, nom). The differences plotted may not correspond exactly to the values shown in Figure A because of the statistical procedure applied in calculating the differences shown in Figure B. Figure B plots the 99th percentile (column I), the 50th percentile (median) (column H) and the 1st percentile (column G). In addition to the error surface data, Figure B also shows the interpolation line designated i_c = xx (column V), and the reference NTE event values on the interpolation line (column F rows 80 through end of the reference NTE event versus Lab Nominal x-values in column B rows 80 through end of the reference NTE event). When i_c = +1.414319083, the interpolation line plots on the 99th percentile. When i_c = 0, the interpolation line plots on the 50th percentile. When i_c = -1.414319083, the interpolation line plots on the 1st percentile. The reference NTE event always plots on the interpolation line, with points at the x-values in the reference NTE event.

The error surface data were also plotted in the format of Figure C. Again the x-axis was the same Lab nominal (column C). This time the y-axis data are the i_c values. Thus, the 99th percentile plots at +1.414319083, the 50th percentile plots at 0 and the 1st percentile plots at -1.414319083. The interpolation line plots at the value of i_c, and the reference NTE event plots on the interpolation line at the x-values in the reference NTE event. If appropriate value labels were displayed in Figure C, the values would represent the error surface plotted on a z-axis above the two-dimensional x-y plane. These error surface values are displayed graphically in Figure B.

Now consider inner rows 13 – 41 in the look-up table in columns T – W. Column T is a repetition of the x-value from column C. Column U calculates a row-to-row Δ for the x-values in column T for use in interpolation. Column V computes the interpolation line linearly interpolated according to the value of i_c between the median and the 99th percentile if $i_c > 0$ (on median if $i_c = 0$ and on 99th percentile if i_c = +1.414319083); and between the median and the 1st

percentile if $i_c < 0$ (on median if $i_c = 0$ and on 1st percentile if $i_c = -1.414319083$). Only one i_c value (from cell E80) is applied in this calculation of the interpolation line. The Microsoft Excel vertical lookup function VLOOKUP is applied to the table in rows 12 – 42 in columns T – W. This is done in rows 80 and down in column F. Because of the way the VLOOKUP function operates, the first row cells T12 and V12, and the last row cell W42 (all three cells distinguished by darker line borders) contain formulas or values different from the formulas of the inner rows. The formula in cell T12 assures that the lookup function can always find an x-value in its table. The formula in V12 and the value in W12 assure that the interpolation in cells F80 to the end of the reference NTE event data returns the nearest ΔCO SS value on the interpolation line if the x-value is outside the range of the error surface lab nominal values.

Before going to the interpolation accomplished in F80 and down, consider briefly the formulation on rows 12 – 43 in columns O – R. This formulation considers one x-value from the reference NTE event, the first one, in cell B80 and selects the two adjacent rows in the error surface between which to interpolate on the B80 x-value. The result is formed on row 43 in these columns and then the "check" cell G80 accomplishes the i_c controlled interpolation. This provides an alternative calculation check on one row in the reference NTE event.

Now consider the interpolation for each point in the reference NTE event. Column B, row 80 and down, brings the lab nominal x-value from the Methods worksheet reference NTE event. For this Delta worksheet, that x-value is CO % (lab,nom). The out-of-range flags are information-only indicating points in the reference NTE event with x-value out of the range of the error surface lab nominal. The i_c value for this Delta worksheet was brought into cell E80 from the Methods worksheet i_c area. Each point in the reference NTE event was interpolated with the same i_c value, but with its own x-value. Recalling that the interpolation line in column V was computed with this one i_c value, the x-interpolation between the appropriate two adjacent rows in the error surface can now be accomplished. This requires using the x-value on each row in column B, B80 and down, in the VLOOKUP function, and performing the required calculation using the looked-up values and deltas from the look-up table. The calculation is done with the formulas in cell F80 and down. The values computed in column F, cell F80 and down through the reference NTE event, could be considered elements of a column matrix or vector, and are returned to the Methods worksheet Parameters section.

In the Monte Carlo simulation, the Methods worksheet combines this reference NTE event result vector from the 7 Delta CO SS worksheet with similar results from other error surfaces, calculates Δemissions by three methods, full model and validation to produce a set of 14 output values ("Forecasts" in Crystal Ball terminology) described in the Summary worksheet section. This was done having input i_c values (including one i_c value for this Delta CO SS) all chosen by random sample from the appropriate truncated normal or uniform distribution as explained in the Methods worksheet section. Then another sample set of randomly sampled values was input (only one i_c value coming to this Delta function again). The reference NTE event CO SS vector was recomputed with the one new i_c value, returned to Methods worksheet and another set of 14 output values was produced. This process was repeated many times until a statistical convergence criterion, described in Section 2, was satisfied. Typically, 40,000 to 65,000 sets of input values and 14 output values were produced to satisfy the convergence criterion with this Error Model spreadsheet.

The number of rows in the Delta worksheet reference NTE event area (rows 80 and down) should match the number of rows in the reference NTE event applied in the Methods worksheet for proper function of Figures B and C. The starter spreadsheet has been set up with the range of charted reference NTE event series extending through row 379 in this Delta worksheet. The balance of the spreadsheet should calculate correctly when a reference NTE event is properly entered in the Methods tab and Parameters formulas properly aligned, although figures like B and C will not display properly until the last row of the reference NTE event is coincident with the end of the range of the charted reference NTE event series. This could be done manually in each Delta worksheet where needed, however, the macro was designed to convert the fully 'loaded' starter workbook after the reference NTE event was entered in the Methods worksheet. The macro uses the row count in the reference NTE event, aligns formulas in the Methods worksheet Parameters area, and eliminates extra rows in the reference NTE event area of each appropriate Delta worksheet. Again, the macro will do the operations correctly only on a fully 'loaded' starter workbook set up with 300 rows of formulas in the Methods worksheet Parameter area, and in each of the Delta worksheets using the reference NTE event.

APPENDIX E

EMS OPERATION LOG

Date	PEMS	Description	Reason	Solution
2/25/2008	Horiba	Lost communication with TRPM laptop on a regular basis	Standard ethernet cable does not fit properly into this laptop	A industrial grade ethernet cable was provided by Horiba which solved this problem
2/28/2008	Horiba 1	Could not control dilution ratio if external flow meter is not connected	Unknown	Horiba fixed the problem
2/28/2008	Horiba 2	Java software does not display the measured values that are in the Labview software	Unknown	Software update fixed the problem
3/3/2008	Horiba 2	Dilution air flow not stable	Dilution air pressure too high	Performed a dilution air flow adjustment per Horiba
3/4/2008	Sensors 1	Lookup table for MPS2 repeatedly failed	Unknown	Sensors said the criteria is too stringent and it is fine as long as it visually looks good
3/4/2008	Horiba 1	Dilution Ratio control is still somewhat erratic	Bad PID constants	Adjusted PID constants to new values suggested by Horiba
3/14/2008	Horiba 1	Pressure transducer Pt1 would not respond to calibration	Pressure transducer was broken	Replaced with new part from Horiba
3/21/2008	Horiba 1,2,&3	Unable to pass Part 1065 sample flow linearity verification	Sample flow is an inferred not measured value	Linearity verification performed on dilution and total flow at MASC request
3/24/2008	Horiba 1,2,&3	Sample flow failed Horiba check with provided external flow meter	Flow calibrations needed updating	Flow coefficients updated for all three units
3/26/2008	Horiba 1,2,&3	Unable to pass Part 1065 dilution flow linearity verification	Dilution flow coefficients needed updating	Performed "Dilution Ratio Accuracy Adjustment" as instructed by Horiba

Date	PEMS	Description	Reason	Solution
4/14/2008	Horiba 3	Java software freezes when loading	Wrong parameters set in a config file	AVL programmed an offset into their software to account for this, laterit appeared to be a grounding problem in the Semtech DS
4/22/2008	Horiba 3	Java softare is not communicating with the Labview software	Improper software configuation	Parameters adjusted to fix the problem
6/13/2008	Horiba 2200	Horiba system is unable to log the ISO-1576 ECM broadcast from the International Engine	Software did not have this capability	International engine was replaced with a heavy-duty Volvo engine that uses J1939 broadcast
6/19/2008	Horiba 1	TRPM software not reading the same exhaust flow as OBS-2200 software	Calibration coefficient is wrong	Manually adjust the calibration coefficient to get the readings to match
6/28/2008	Sensors 1	Sample valve for crystal remains in "transient" state every time it attempts to sample	Stepper motor attempting to turn too quickly (not enough torque)	Sensors readjusted the stepper motor speed
7/31/2008	Horiba 2	The OBS-2200 software would not trigger the OBS-TRPM to start sampling during an NTE	Connector wired incorrectly	Reduced the speed of the stepper motor
8/8/2008	Horiba 2	Dilution flow is too low		Replaced with connector from second unit
8/12/2008	Horiba 2200	OBS-2200 software unable to read the reference torque value from J1939 broadcast	Unable to enter the proper data bit location	Perform dilution flow adjustment using internal pressure regulator
8/14/2008	Sensors 2	Could not get any of the crystals to oscillate	Power supply in CQCM head was likely burnt out	Enter the reference torque value manually
8/15/2008	Horiba 2200	OBS-2200 laptop would not boot up	Unknown	Hard drive was placed in another identical laptop, broken laptop was shipped back to Horiba

Date	PEMS	Description	Reason	Solution
8/18/2008	Sensors 1	Bypass flow was not updating		
8/21/2008	Sensors 1	Crystal frequencies, corona currents, and voltages were dropping out	High temperature causing communication problems	Attempted to reduce test cell temperature, but problem persisted
8/26/2008	AVL 1	Unit switched into Zero Check in the middle of the test	Uknown, possibly a pressure out of limit	Unit switched back into sample after approx. 30 seconds
8/27/2008	Horiba 1	OBS-2200 laptop failed, would no longer boot	Laptop broken	New laptop provided by Horiba
8/27/2008	Horiba 1	OBS-2200 laptop would not read J1939	Unknown	Sent back to Horiba for repair
8/27/2008	Horiba 1	TPA would not zero	Zero function tied to gas analyzers, looking for gas flow	Use the CAL function instead of the ZERO to just zero TPA
8/27/2008	Horiba 1	TRPM Java software unable to log exhaust flow (Labview works)	Error in software	Installed new version of Java software
8/27/2008	Horiba 1	EAD check will fail repeatedly	Tolerances are too tight for test cell operation, tolerances relaxed.	Ignored tolerances set in software for check
8/27/2008	AVL 1	Analog output signal to MSS would clip at 2 mg/m³ range	Soot concentration too high	Output switched to 0-10 mg/m³, DR setpoint increased from 3 to 6
8/27/2008	AVL 1	DR would occasionally stop controlling	Too much moisture in the system	Unit purged for moisture overnight, and firmware upgraded
8/27/2008	Sensors 1	PPMD internal temperature was out of limit	Test cell temperature too hot	A new back panel was installed with two fans to promote cooling
8/27/2008	Sensors 1	Bypass flow from TSI flowmeter was not reading in software	Faulty com cable	Replaced TSI cable

Date	PEMS	Description	Reason	Solution
8/27/2008	Sensors 1	CQCM communication dropped out during testing	CQCM power supply failed	Power supply replaced
8/27/2008	Sensors 1	CQCM communication dropped out during testing	Unknown	CQCM comm chip replaced with a newer model
8/27/2008	Sensors 1	Corona needle high voltage erratic	Unknown	Fixing the comm issue resolved this problem
8/27/2008	Sensors 1	PPMD communication was dropping out	High internal temperature	Directed cooling air at PPMD
9/10/2008	Horiba 1	Compressor tripped breaker, turned off AVL unit	Combining AVL and compressor on same 15A circuit was too much current	Horiba compressor moved to dedicated 15A circuit
9/10/2008	Horiba 1	Make up air flow was 0.7 lpm instead of 2.3 lpm	PID constants incorrect	Modified PID constants
9/12/2008	AVL 1	Analog output signal to MSS would still briefly clip at 10 mg/m³ range	Soot concentration too high	Logarithmic analog output added as a firmware update
9/12/2008	Sensors 1	Negative emissions reported even at high emission levels on NTE	High dilution, crystal saturation (no grease), crystal stabilization	Do not use MPS2, grease crystals, wait longer for PPMD to warm up
9/18/2008	Sensors 1	The bypass flow would increase when crystal 1 on PPMD1 would sample	Crystal may be installed backwards so that it is always sampling	Set crystal 1 to be the reference crystal
9/18/2008	Sensors 1	Sample flow drifting during steady state engine operation	Temperature estimate is based on mixing of two flows, if the estimate is off temperature will change the flow	Adjusted the parameters in the temperature estimate

Date	PEMS	Description	Reason	Solution
9/18/2008	Sensors 1	No corona current was measured for two crystals	Crystals were shorted to ground	Crystals were replaced
9/18/2008	Sensors 1	High voltage reading was low on two crystals	Corona needles were too close to the crystals	Needles repositioned
9/20/2008	Sensors 1	Sample flow measurement was too low	Sample flow TC was in excess flow return, which had low flow due to connection to CVS	TC moved into the main exhaust
9/26/2008	AVL 1	Error: MFD Temperature out of Spec	Test cell temperature too hot	Repositioned chiller air to blow on the AVL unit
9/30/2008	Sensors 1	Lower than expected emissions for the PPMD	Inaccurate sample flow temp causing low sample flow meas, corona needles not positioned properly	Reposition the sample flow thermocouple, adjust corona needle
10/9/2008	Sensors 1	PPMD sampling delayed several seconds after trigger	Delay in communications	Increased residcence time inside PPMD up to 3 seconds
10/9/2008	Sensors 1	Inaccuracies in flow measurement	System uses an assumed inlet pressure for MPS2	Added pressure measurement downstream of MPS1 to account for changes in pressure due to MPS2
10/9/2008	Sensors 1	Crystal sampling as soon as it becomes available, including in an NTE event	Software logic	Software modified so that an available crystal waits for the start of the next NTE event
10/9/2008	Horiba 1	Compressor supplying dilution air stops working in middle of test (2 units)	Unit shutting off due to overheat protection	Cool air provided to the compressor (temporary solution)

Date	PEMS	Description	Reason	Solution
10/9/2008	AVL 1	MSS concentration reporting too high in Sensors software	Sensors not correcting concentration from 0°C to 20°C (~8%)	Semtech DS software updated to include the log range and volume correction
10/10/2008	Sensors 1	Bypass flow too low	Flow leaking through the carbon filter connection	Tightened the carbon filter
10/15/2008	Sensors 1	PPMD emission results were inconsistent	Booker had decreased the crystal flow from 0.4 to 0.2 slpm to increase loading time	Final crystal sample flow set at 0.5 slpm
10/15/2008	Sensors 1	PPMD emissions were lower than expected	Uknown	Crystal sensitivity adjusted from 125 hz/µg to 100 hz/µg (increasing sensitivity by 25%)
10/15/2008	Sensors 1	PPMD wouldn't sample when external trigger activates on Semtech DS	Unknown	Powered off hardware and laptop and restarted, problem was resolved
10/16/2008	Sensors 1	PPMD unable to communicate with DS	Unknown	Triggered the PPMD manually through Host software (unofficial testing)
10/28/2008	Horiba 1	Dilution flow inaccurate	Unknown	Recalibrated VFM
11/3/2008	Sensors 1	PPMD block pressure low	Uknown, block pressures were activated in the software	Aborted cycle, powered down the PPMD and restarted, problem was fixed
11/4/2008	Sensors 1	Multiple crystals stopped oscillating, when one was enabled another would disable	Grease loading slightly too high?	Re cleaned and greased crystals
11/4/2008	Horiba 1	Unable to maintain setpoint for total flow near end of the cycle	High filter loading	Adjusted the valve on the total flow pump to allow more flow

Date	PEMS	Description	Reason	Solution
11/5/2008	Horiba 1	Sample flow accuracy is out of spec	Caused by inaccurate dilution flow measurement (cause of this uknown)	Recalibrated VFM
11/6/2008	Horiba 1	Dilution flow is still inaccurate	Unknown	Recalibrated VFM
11/7/2008	Sensors 1	MPS Dilution Flow Major audit could not pass	Overheated	None, cycle voided
11/7/2008	Horiba 1	External compressor stopped working	Overheated	None, cycle voided
11/7/2008	Horiba 1	External compressor stopped working	Overheated	None, cycle voided, installed 2nd compressor in parallel
11/12/2008	Sensors 1	PPMD results not included in the DS results file	Descrepancies in the time stamps	Never resolved
11/12/2008	Horiba 1	Dilution compressor still stopping sometimes	Overheating	Connected two compressors in parallel, so the 2nd will run if the first stops
11/12/2008	Sensors 1	Slope on flow for daily audits sometimes fails to 0.97 or 1.03	Monthly tolerances too tight for daily checks	Tolerances relaxed slightly for daily checks to save time
11/12/2008	Horiba 1	Sample flow check is sometimes not within tolerance	Monthly tolerances too tight for daily checks	Tolerances relaxed slightly for daily checks to save time
11/24/2008	Horiba 1	Sample flow accuracy is out of spec	Inaccurate dilution flow measurement	Recalibrated VFM
11/25/2008	AVL 1	MSS failed the external DR audit repeatedly	Unknown - all internal checks passed	Requirement of performing external audit on daily basis was removed

Date	PEMS	Description	Reason	Solution
12/1/2008	Sensors 1	EFM reading inaccurate at the end of each test	Solenoid not switching properly during the 1 hour autozero, EFM zeroing while open to flow	Solenoid fixed, auto zero disabled?
12/1/2008	Horiba 1	Newest compressor that was shipped still stopping sometimes	Overheating	Continued to use two compressors in parallel, a new compressor was shipped from Horiba
12/1/2008	Horiba 1	Post processor file size too big for Excel (>200 MB)	Steady state data processed at 1Hz instead of 10Hz	Continued to use two compressors in parallel
12/11/2008	Horiba 1	DCS signal flat lined during testing	Uknown	Problem did not occur again when system was restarted
12/15/2008	Horiba 1	TRPM data filed was not saved by Java software	Unknown	None, cycle was void
12/16/2008	Horiba 1	External compressor stopped working	Overheated	None, cycle voided
12/18/2008	Horiba 1	External compressor stopped working	Overheated	None, cycle voided
1/14/2009	Horiba 1	Sample flow accuracy is out of spec	Caused by inaccurate dilution flow measurement (cause of this uknown)	Recalibrated VFM
1/14/2009	Horiba 1	Dilution flow inaccurate	Unknown	Recalibrated VFM
1/26/2009	Sensors 2	Semtech DS lost communication with laptop	Unknown	Couldn't monitor data, but data was still recorded on compact flash card
1/28/2009	Horiba 2	TPA switched from measure to standby at the start of the test	Software glitch?	Did not occur again

Date	PEMS	Description	Reason	Solution
1/28/2009	Horiba 2	TRPM would switch out of filter sample mode once 30 seconds had elapsed	Faulty software logic	Software modified so that filter will never switch out of sample mode while in an NTE event
1/28/2009	Horiba 2	Filter sampling was beginning 10 sec after start of NTE instead of 5	OBS-2200 is delayed 5 seconds in its response	Horiba chose not to make any changes
1/30/2009	AVL 2	Error: No dilution air available	On-board pump was leaking	Pump was replaced with new part shipped from AVL
2/2/2009	Sensors 2	Semtech DS lost communication with laptop, could not reconnect	Unknown	Powered down unit, recovered data the next day
2/5/2009	Sensors 2	Semtech DS was losing communication with laptop	Unknown	Couldn't monitor data, but data was still recorded on compact flash card
2/18/2009	Horiba 2	External compressor stopped working	Overheated	None, cycle voided
3/2/2009	Horiba 3	Software zero pressure transducer function would not work after repeated attempts	Unknown	Shut down equipment attempted it again several hours later and it worked
3/3/2009	Horiba 3	External compressor stopped working	Overheated	None, cycle voided
3/5/2009	Sensors 3	Semtech DS lost communication with laptop	Unknown	Couldn't monitor data, but data was still recorded on compact flash card
3/6/2009	Horiba 3	External compressor stopped working	Overheated	None, cycle voided
3/23/2009	Horiba 2200	OBS-2200 software locked up during test	Unknown	Software worked when rebooted, but data for the cycle was lost
3/24/2009	Sensors DS	Couldn't connect to the Semtech DS repeatedly	LAN circuit board was likely damaged	Unit sent back to Sensors for repair

Date	PEMS	Description	Reason	Solution
3/25/2009	Sensors 3	PPMD wouldn't sample when NTE trigger activates on the Semtech DS	Unknown	Turning the unit off and back on fixed the problem
4/3/2009	AVL 1	There is a voltage offset between what the AVL unit outputs and the Semtech DS reads	Unknown	Switched constants
4/13/2009	AVL 2	Power inverter shut down during radiated immunity test	EMI/RFI Test	Replaced bypass pump
4/15/2009	Sensors 2	Communication with the laptop dropped out repeatedly during bulk current injection	EMI/RFI Test	Head sent back for repair
4/20/2009	Sensors 2	Communication with the laptop dropped out during radiated immunity	EMI/RFI Test	Replaced with bracket from other unit
4/21/2009	AVL 2	Power inverter shut down during conducted transient test	EMI/RFI Test	No corrective action taken
4/21/2009	AVL 2	Power inverter shut down, then start smoking during conducted transient	EMI/RFI Test	Unit was shipped back to AVL, replaced with other unit, problem was not observed again
4/21/2009	Sensors 2	PPMD shut down completely several times during conducted transient tests	EMI/RFI Test	No corrective action taken
4/24/2009	Horiba 3	Flow was erratic during bulk current injection test	EMI/RFI Test	No corrective action taken
4/27/2009	Horiba 3	Exhaust flow was reading very high during bulk current injection test	EMI/RFI Test	No corrective action taken
4/28/2009	Horiba 3	Lost communication with laptop during radiated immunity test	EMI/RFI Test	Inverter replaced with backup, test was not repeated

Date	PEMS	Description	Reason	Solution
4/28/2009	Horiba 3	Exhaust flow was reading very high during radiated immunity test	EMI/RFI Test	No corrective action taken
5/15/2009	AVL 3	AVL PEMS blew a fuse when trying to power up after 1st pressure test	Uknown	Replaced with AVL 2
7/15/2009	Sensors 3	PPMD reported a barometric pressure increase when altitude chamber was at vacuum	Constants in the software were backwards for the barometric pressure	No corrective action taken
7/15/2009	Sensors 3	PPMD could not maintain a bypass flow of 4 slpm	Bypass pump was dying	No corrective action taken
7/21/2009	AVL 2	Soot concentration reading erratic during vibration (all orientations)	Vibration	Rebooted hardware to reconnect
7/22/2009	Horiba 3	L-bracket holding filter in ME box broke during vibration testing	Vibration	Did not continue with more extreme tests to prevent damage
7/22/2009	Horiba 3	Total Pi pressure transducer would not read correctly after problem with L-bracket occurred	Vibration Test	Pressure transducer was replaced
7/24/2009	Sensors 2	PPMD could not maintain total flow due to moisture traps opening	Vibration Test	No corrective action taken