

**Test Plan to Determine PEMS
Measurement Allowance for the PM
Emissions Regulated under the
Manufacturer-Run Heavy-Duty Diesel
Engine in-use Testing Program**

Test Plan to Determine PEMS Measurement Allowance for the PM Emissions Regulated under the Manufacturer-Run Heavy-Duty Diesel Engine in-use Testing Program

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

and

California Air Resources Board

and

Engine Manufacturers Association

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.

TABLE OF CONTENTS

Executive Summary	2
Table of Contents	3
List of Figures	5
List of Tables	5
1 Introduction.....	6
2 Monte Carlo Error Model and Measurement Allowance	8
2.1 Objective.....	8
2.2 Background.....	9
2.3 Methods and Materials.....	15
2.4 Simulation Procedure.....	16
2.4.1 Construction of the Error Surface.....	16
2.5 Model Considerations	24
2.5.1 Convergence	24
2.6 Simulation Output.....	24
2.6.1 Sensitivity Variation Effect.....	24
2.6.2 Sensitivity Bias Effect.....	25
3 Engine Dynamometer Laboratory Tests	26
3.1 Preliminary Audits	26
3.1.1 Objective	26
3.1.2 Background.....	26
3.1.3 On-site meeting to establish 1065 compliance requirements	26
3.1.4 Methods and Materials.....	26
3.1.5 Data Analysis	27
3.1.6 PEMS Manufacturer PM PEMS Commissioning.....	27
3.2 Bias and Precision Errors under steady state engine operation	27
3.2.1 Objective	27
3.2.2 Background.....	28
3.2.3 Methods and Materials.....	28
3.2.4 Data Analysis	30
3.3 Precision Errors under transient engine operation (dynamic response).....	31
3.3.1 Objective	31
3.3.2 Background.....	31
3.3.3 Methods and Materials.....	31
3.3.4 Data Analysis	35
3.4 ECM Torque and BSFC.....	37
3.4.1 Objective	37
3.4.2 Data Analysis	37
4 Environmental Chamber	37
4.1 Data Analysis for Environmental Tests	38
4.2 PM Generator Commissioning	39
4.3 Baseline.....	39
4.3.1 Objective	39
4.3.2 Background.....	39

4.3.3	Methods and Materials.....	40
4.3.4	Data Analysis.....	40
4.4	Electromagnetic Radiation.....	40
4.4.1	Objective.....	40
4.4.2	Methods and Materials.....	40
4.5	Atmospheric Pressure.....	41
4.5.1	Objective.....	41
4.5.2	Background.....	41
4.5.3	Methods and Materials.....	41
4.5.4	Data Analysis.....	43
4.6	Ambient Temperature and Humidity.....	44
4.6.1	Objective.....	44
4.6.2	Background.....	44
4.6.3	Methods and Materials.....	45
4.6.4	Data Analysis.....	46
4.7	Orientation and Vibration.....	46
4.7.1	Objective.....	46
5	SwRI CVS and CE-CERT Trailer Correlation.....	47
5.1	Method and Materials.....	47
6	Model Validation and Measurement Allowance Determination.....	48
6.1	Model validation.....	48
6.1.1	Objective.....	48
6.2	Measurement Allowance Determination.....	49
6.2.1	Objective.....	49
6.2.2	Background.....	49
6.2.3	Methods and Materials.....	49
6.2.4	Data Analysis.....	49
7	Time and Cost.....	50
7.1	Timeline.....	50
7.2	Cost.....	51
8	Abbreviations used in Brake Specific Equations.....	51

LIST OF FIGURES

Figure 1. Probability Density Functions For Sampling Error Surfaces	9
Figure 2. Brake-Specific PM Emissions Calculation For Method 1	11
Figure 3. Brake-Specific PM Emissions Calculation For Method 2	12
Figure 4. Brake-Specific PM Emissions Calculation For Method 3	13
Figure 5. Error Surface: PEMS Vs. LAB	17
Figure 6. Error Surface: (PEMS-LAB) Vs. LAB	18
Figure 7. Error Surface: Final Version	19
Figure 8. Overview of Monte Carlo Simulation	22
Figure 9. Example of A NTE Cycle.....	35
Figure 10. Pressure Histogram.....	41
Figure 11. Pressure-Time Environmental Test Cycle.....	43
Figure 12. temperature histogram	44
Figure 13. Time Series Chart of Ambient Temperature Test	46

LIST OF TABLES

Table 1. Allowed Modifications	6
Table 2. Example Of Selection Of Measurement Allowance At 0.02 g/hp-hr NTE Threshold	15
Table 3. Error Surfaces for the BSPM Simulation	23
Table 4. Engine, Exhaust Configuration, And Steady-State Modes.....	28
Table 5. Example Of SS Error Surface	30
Table 6. NTE Transient Cycle	32
Table 7. Dynamic response inter-NTE Events	34
Table 8. Concentration and Dilution Ratio Schedule with PM Generator	38
Table 9. Atmospheric Pressure Test Sequence	42
Table 10. Ambient Temperature test sequence.....	45
Table 11. Projected PM-PEMS Timeline	50
Table 12. projected cost estimate.....	51

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 can not 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 CO₂, 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.

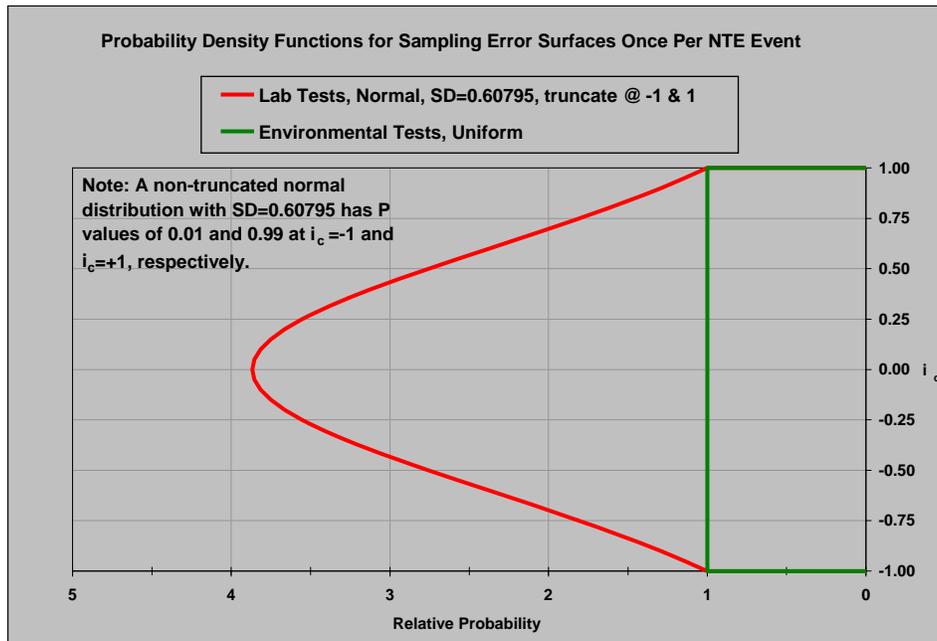


FIGURE 1. PROBABILITY DENSITY FUNCTIONS FOR SAMPLING ERROR SURFACES

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, Figure 3, and Figure 4, respectively.

For all PM PEMS:

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

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

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

$$e_{PM} (g/kW \cdot hr) = \frac{\overline{m}_{PM} \left(\frac{g}{mol} \right) * \sum_{i=1}^N \left[\dot{n}_i \left(\frac{mol}{s} \right) * \Delta t \right]}{\frac{M_C}{W_{fuel}} * \sum_{i=1}^N \frac{\dot{n}_i \left(\frac{mol}{s} \right) * \left[x_{THC_i} (ppm) * 10^{-6} + (x_{CO_i} (\%) + x_{CO_2} (\%)) * 10^{-2} \right] * \Delta t}{\left[\frac{\dot{m}_{fuel_i} \left(\frac{g}{s} \right)}{\frac{Speed_i (rpm) * T_i (N \cdot m) * 2 * 3.14159}{60 * 1000 * 3600}} \right]}}$$

Where for AVL:

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

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

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

For AVL Only:

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

$$\overline{m_{PM}} \left(\frac{g}{mol} \right) * \frac{w_{fuel}}{M_C} * \sum_{i=1}^N \left[\frac{\dot{m}_{fuel} \left(\frac{g}{s} \right)}{xTHC_i (ppm) * 10^{-6} + (xCO_i (\%) + xCO_2 (\%)) * 10^{-2}} * \Delta t \right]$$

$$\sum_{i=1}^N \left[\frac{Speed_i (rpm) * T_i (N \cdot m) * 2 * 3.14159 * \Delta t}{60 * 1000 * 3600} \right]$$

Where:

$$\overline{m_{PM}} \left(\frac{g}{mol} \right) = \frac{\frac{w_{fuel}}{M_C} * \sum_{i=1}^N \left[\frac{(mPM_i (g / mol)) * \dot{m}_{fuel} \left(\frac{g}{s} \right)}{xTHC_i (ppm) * 10^{-6} + (xCO_i (\%) + xCO_2 (\%)) * 10^{-2}} * \Delta t \right]}{\sum_{i=1}^N \left[\frac{\dot{m}_{fuel} \left(\frac{g}{s} \right)}{xTHC_i (ppm) * 10^{-6} + (xCO_i (\%) + xCO_2 (\%)) * 10^{-2}} * \Delta t \right]}$$

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:

$$\text{PM} = 0.02 \text{ g/hp-hr and } 0.03 \text{ g/hp-hr}$$

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.

Error! Reference source not found. 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

Calc. Method ==>	Allowance at Respective NTE Threshold (%)		
	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 Figure 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 upon 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.

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:

$$\text{PM_with errors} = \text{PM_ideal} + \Delta(\mu\text{g/mole})_1 + \Delta(\mu\text{g/mole})_2 + \Delta(\mu\text{g/mole})_3 + \dots$$

where,

$\Delta(\mu\text{g/mole})_1$ = PM concentration errors due to steady state bias and precision errors,

$\Delta(\mu\text{g/mole})_2$ = PM concentration errors due to ambient temperature,

$\Delta(\mu\text{g/mole})_3$ = 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 $\mu\text{g}/\text{mole}$). 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).

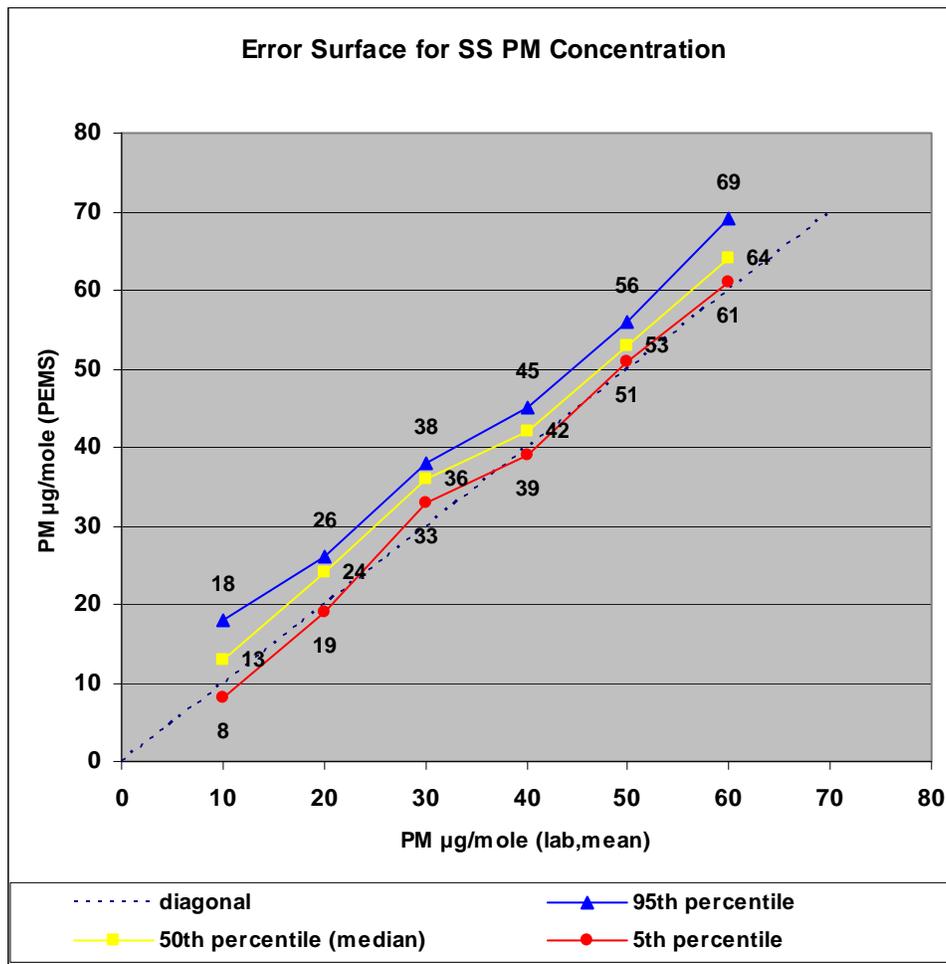


FIGURE 5. ERROR SURFACE: PEMS VS. LAB

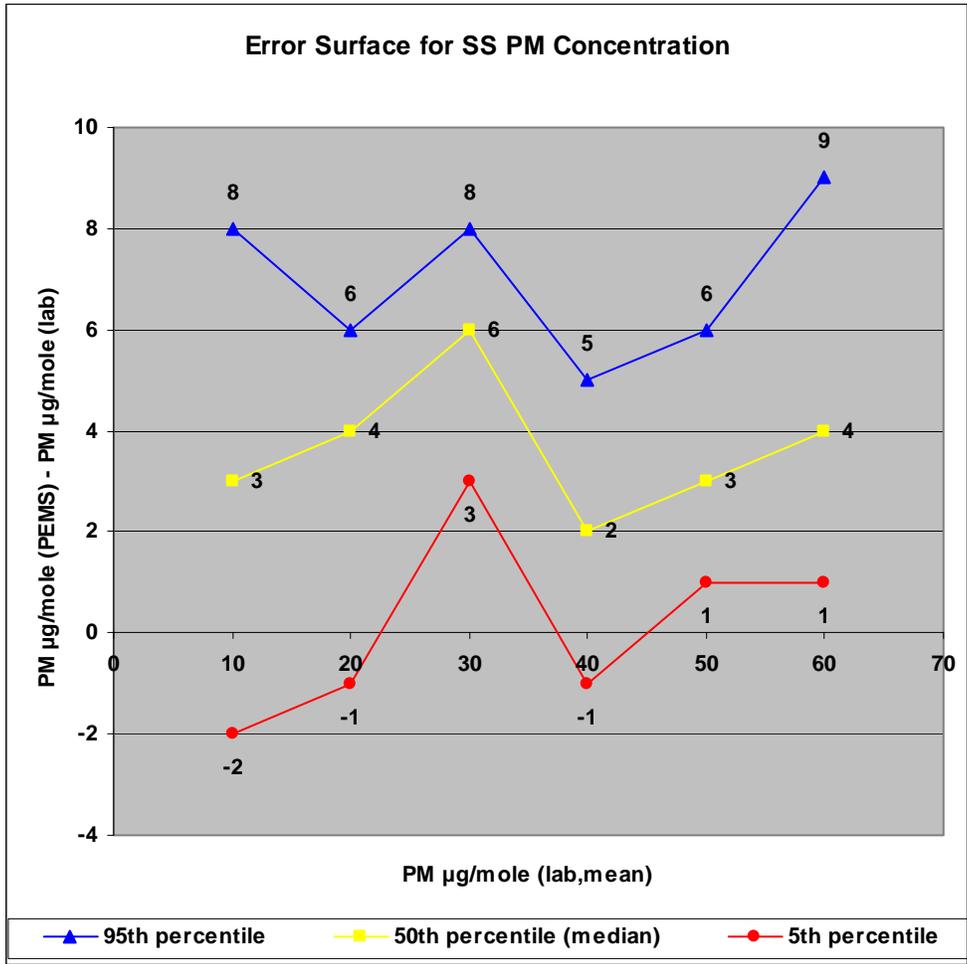


FIGURE 6. ERROR SURFACE: (PEMS-LAB) VS. LAB

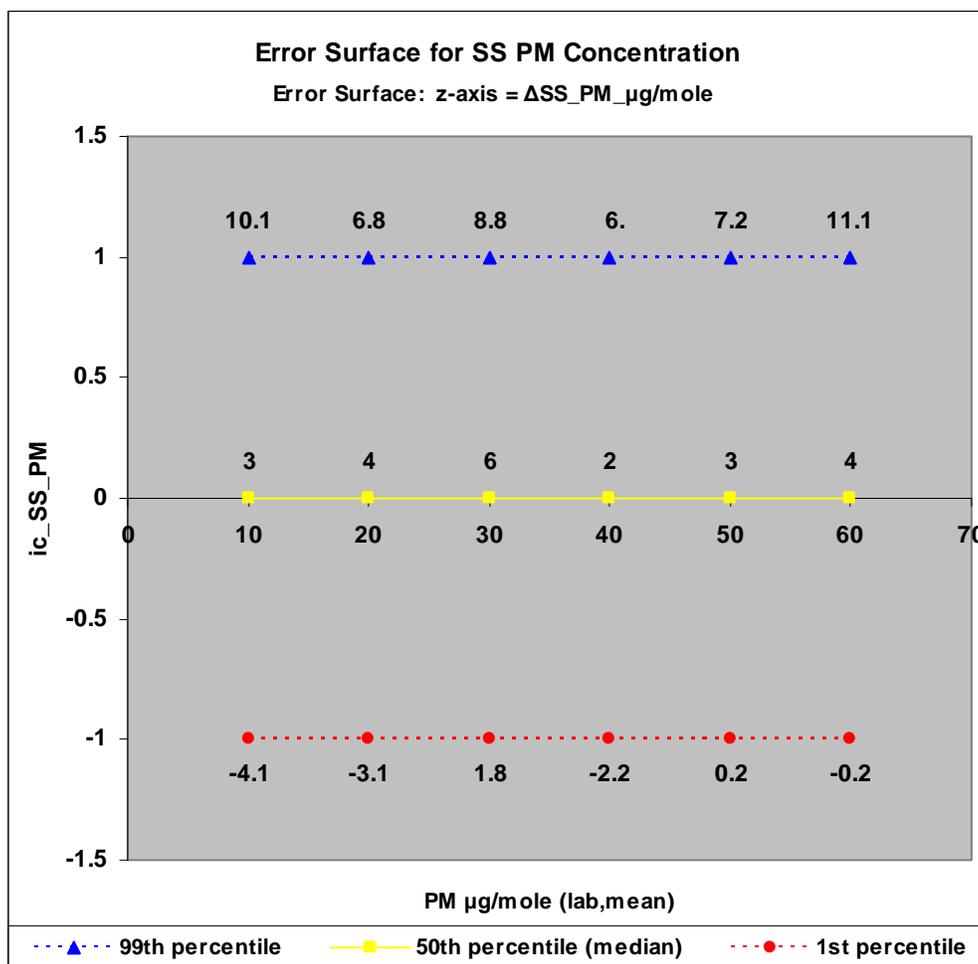


FIGURE 7. ERROR SURFACE: FINAL VERSION

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 95th, 50th, and 5th 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 1st and 99th 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 95th percentile delta error will form the upper boundary of one half of the normal distribution, and the 5th 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 1st and 99th 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 50th 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 1st percentile error from the fitted normal distributions with $i_c = -1$, the 50th percentile error with $i_c = 0$, and the 99th 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,

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

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,

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

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: $\Delta(\mu\text{g/mole})_1$, $\Delta(\mu\text{g/mole})_2$, and $\Delta(\mu\text{g/mole})_3$. 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
- $\Delta(\mu\text{g/mole})_1 = 6 \mu\text{g/mole}$
- $\Delta(\mu\text{g/mole})_2 = -2 \mu\text{g/mole}$
- $\Delta(\mu\text{g/mole})_3 = -3 \mu\text{g/mole}.$

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:

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

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 $\Delta\mu\text{g}/\text{mole}$ 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.

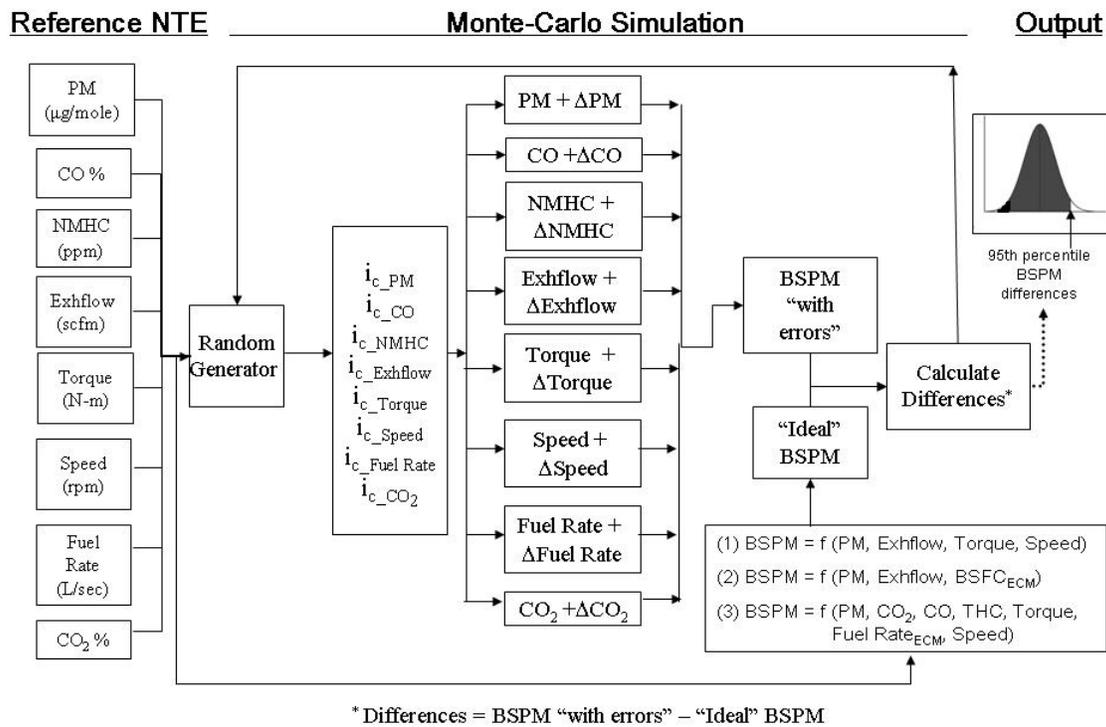


FIGURE 8. OVERVIEW OF MONTE CARLO SIMULATION

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 technique³ 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

$$n_{\text{lower}} = 0.95 * N - 1.645\sqrt{0.95 * 0.05 * N}$$

4. Identify the trial number at the upper end of the 90% confidence interval

$$n_{\text{upper}} = 0.95 * N + 1.645\sqrt{0.95 * 0.05 * N}$$

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), $6 \times 10 \times 1 \times 1 \times 3 = 180$.

Determine the $\Delta_{SS} \bar{m}_{PM} \left(\frac{g}{mol} \right)$ surface plots for the error model based upon all data pooled. Note that each brand of PEMS will have its own $\Delta_{SS} \bar{m}_{PM}$ 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 $\Delta_{SS}\bar{m}_{PM}$ 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.

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

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 setup 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 SS 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

<u>Error Surface for SS PM Concentration</u>	
-	
Figure 5	
x-axis	PM $\mu\text{g}/\text{mole}$ (lab mean at setpoint)
y-axis	PM $\mu\text{g}/\text{mole}$ (PEMS)
Figure 6	
x-axis	PM $\mu\text{g}/\text{mole}$ (lab mean at setpoint)
y-axis 5th percentile	5th [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)]
y-axis 50th percentile	50th [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)]
y-axis 95th percentile	95th [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)]
<i>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.</i>	
Figure 7	
x-axis	PM $\mu\text{g}/\text{mole}$ (lab mean at setpoint)
y-axis	i_c SS PM
z-axis = $\Delta_{SS_PM_}\mu\text{g}/\text{mole}$	<p>1st Percentile from Gaussian distribution based on 5th and 50th [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)] deltas.</p> <p>99th Percentile from Gaussian distribution based on 50th and 95th [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)] deltas.</p> <p>50th Percentile based on [PM $\mu\text{g}/\text{mole}$ (PEMS) - PM $\mu\text{g}/\text{mole}$ (lab)] deltas.</p>
i_c sample frequency	once per NTE event trial
i_c 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.

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

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.			

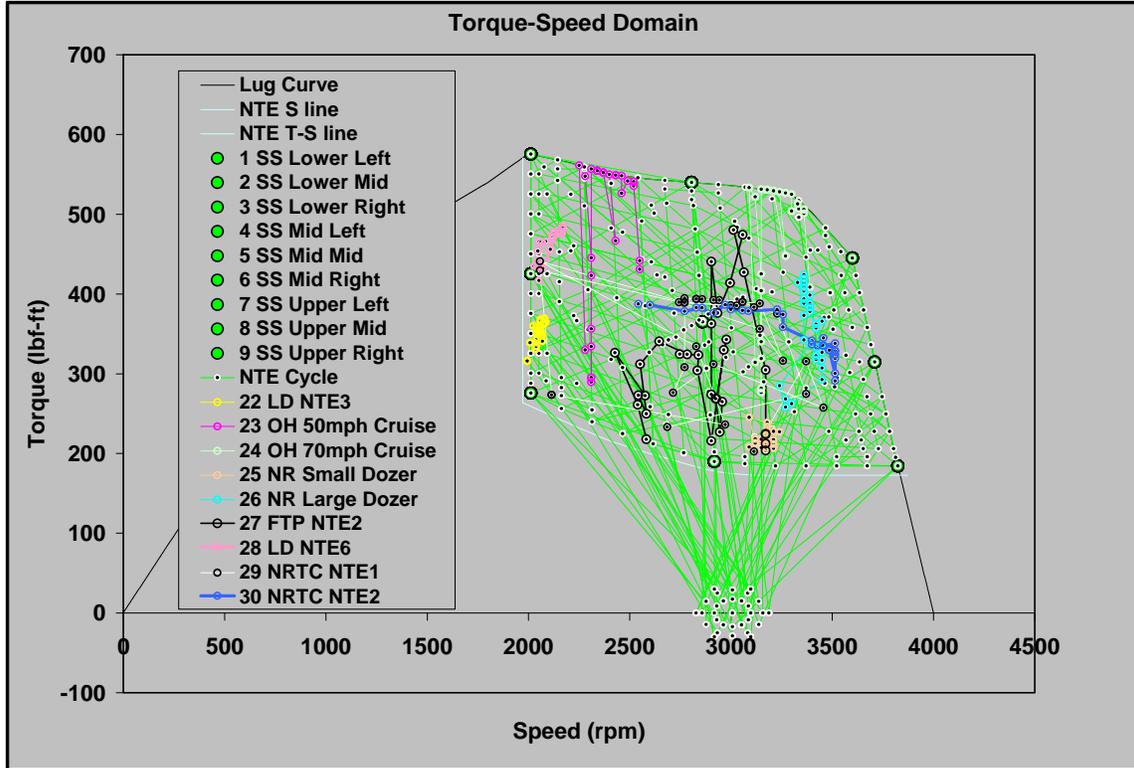


FIGURE 9. EXAMPLE OF A NTE CYCLE

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, $MAD_{TRi} = \text{median}[|NTE_{ij} - \text{median}(NTE_{ij})|]$.

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.**

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/m³, 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 .

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.

TABLE 8. CONCENTRATION AND DILUTION RATIO SCHEDULE WITH PM GENERATOR

Raw PM Concentration, $\mu\text{g}/\text{m}^3$	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

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 \bar{m}_{PM} the mean \bar{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.

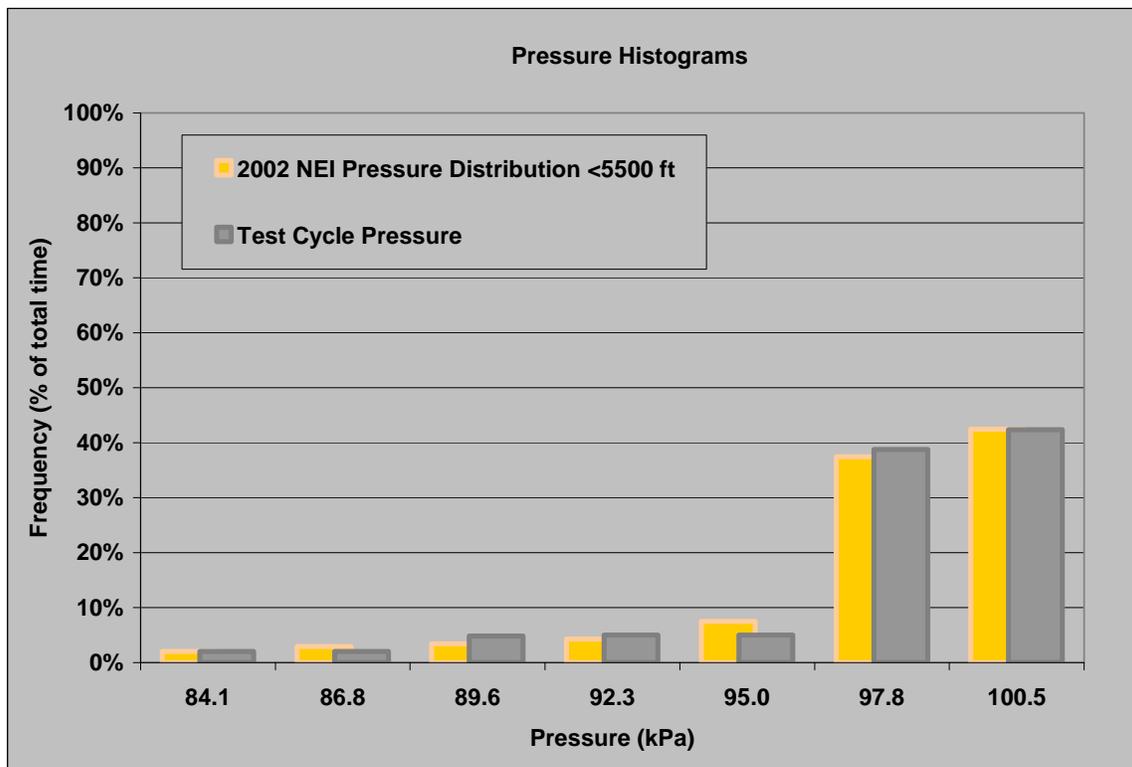


FIGURE 10. PRESSURE HISTOGRAM

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, 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					
Phase	Pressure		Time	Rate	Comments
	kPa	Alt. ft.	min	ft/min	
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

Pressure-Time Environmental Test Cycle

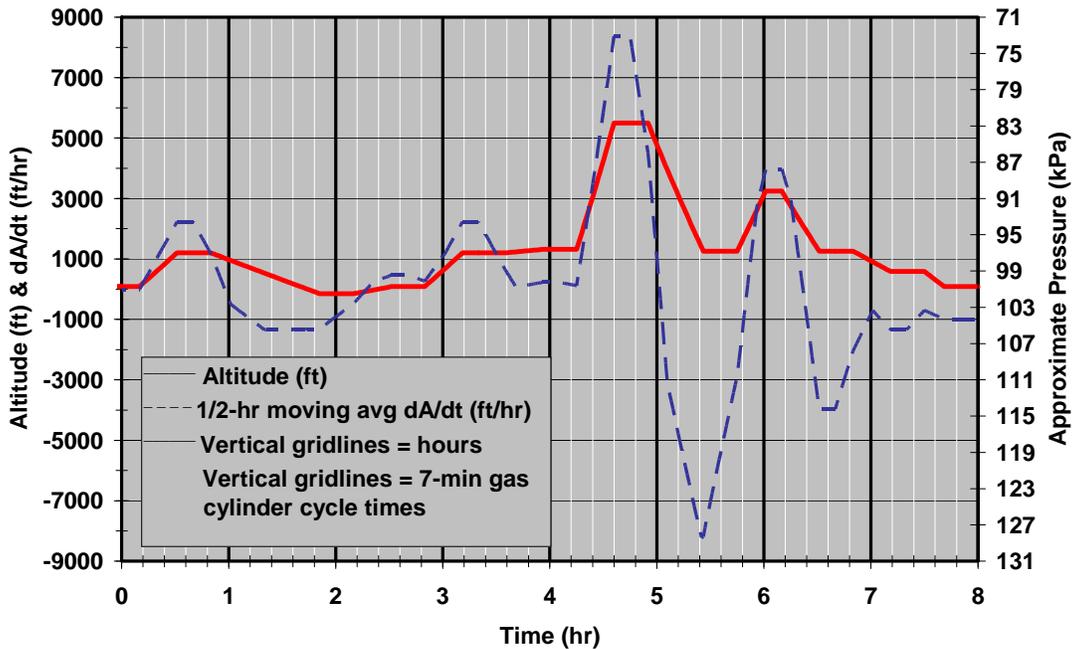


FIGURE 11. PRESSURE-TIME ENVIRONMENTAL TEST CYCLE

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.

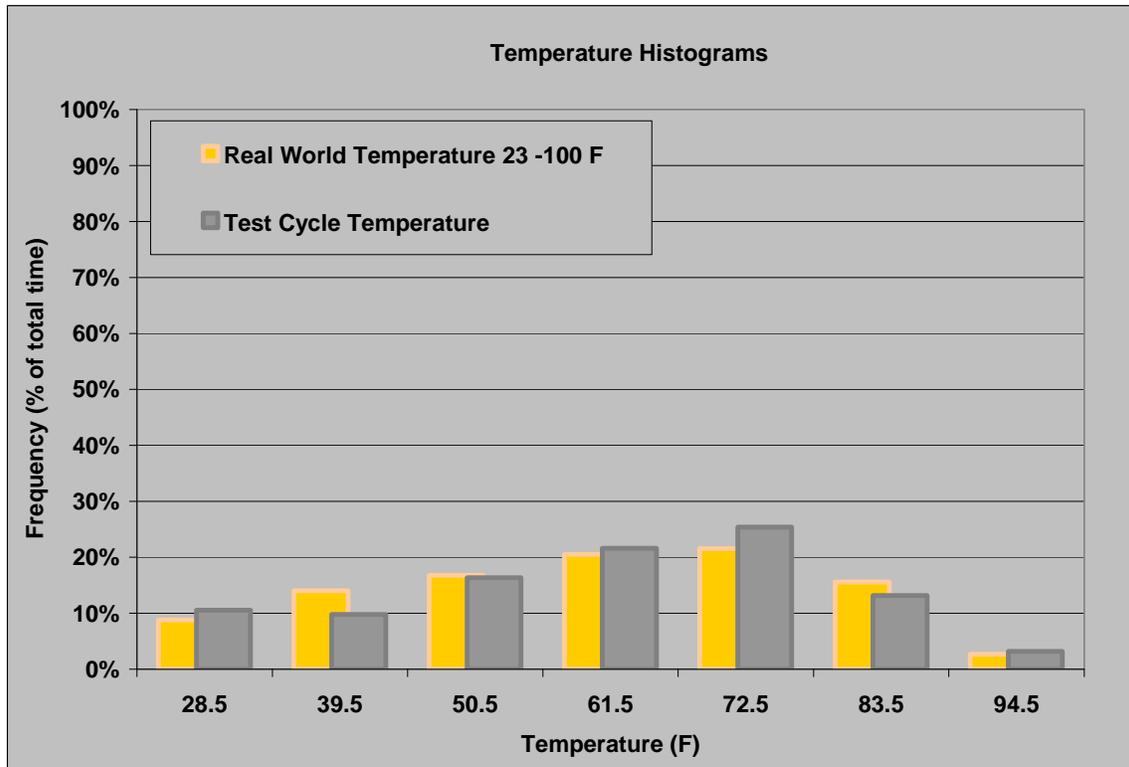


FIGURE 12. TEMPERATURE HISTOGRAM

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 times to simulate the range of real-world temperatures and changes in temperature:

TABLE 10. AMBIENT TEMPERATURE TEST SEQUENCE

Ambient Temperature Test Sequence					
Phase	Temperature		Time	Rate	Comments
	°C	°F	min	°C/min	
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

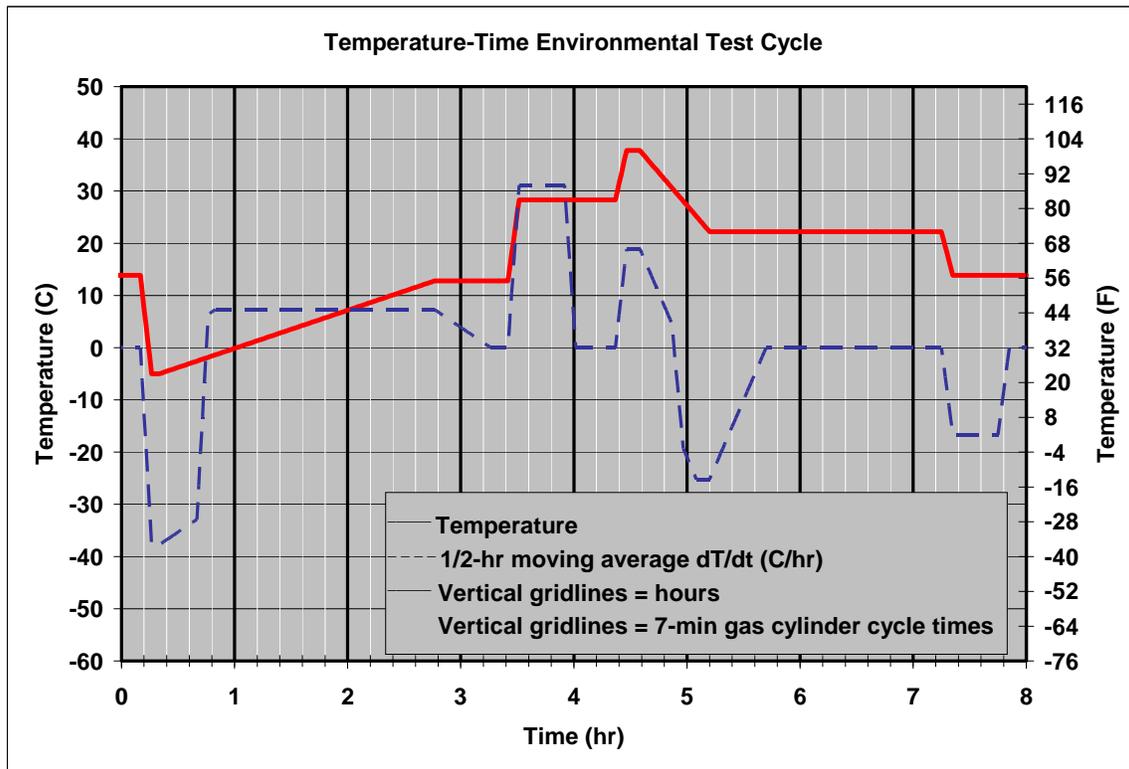


FIGURE 13. TIME SERIES CHART OF AMBIENT TEMPERATURE TEST

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.

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. 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.
8. 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.
9. Use SwRI DMM-230 and CE-CERT DMM-230 to make sure that the engine PM source is not shifting and being consistent.
10. SwRI should handle and weigh all the filters for both SwRI and CE-CERT in accordance with their protocol.
11. 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.
12. 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.

13. 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

6.1 Model validation

6.1.1 Objective

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 laboratory efforts

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) technique¹. 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 parameter² 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 is a tentative timeline 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

	Tentative Timeline																					
	2008										2009										2010	
	April	May	June	July	August	September	October	November	December	January	February	March	April	May	June	July	August	September	October	November	December	January
PEMS Audit and Engine 1 Setup	█																					
SS Experiments, Eng. 1							█															
Transient Experiments, Eng. 1								█														
Data Analysis and Reporting								█	█	█												
Environmental Chamber, etc..								█	█	█												
Data Preparation for Model								█	█	█												
Model Processing											█											
SwRI CVS/CE-CERT CVS Corr.											█											
CE-CERT In-Use Testing											█	█	█									
Data Processing and Model Validation														█								
Additional work if needed																						
Draft Final Report										█	█	█	█	█	█	█						
Review of Final Report																		█				
Final Report																			█	█		

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:

e_{PM} = 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 1 μ mol (emission constituent)/mol (exhaust) = 1ppm (part per million))

\dot{n} = amount of substance rate (mol/sec, in this case, mol (exhaust)/sec)

t = time interval (sec)

f_n = rotational frequency (shaft), rev/min

T = torque (N-m)

NOTE: The units of the numerator work out to g emission 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 1 μmol (emission constituent)/mol (exhaust) = 1 ppm (part per million))

\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)

t = time interval (sec)

MC = Atomic weight of carbon (~12 g/mol)

w_{fuel} = g (carbon)/g (fuel); Note fuel is roughly 86% carbon by mass

x_{Cproddry} = amount of carbon products on a C1 basis per dry mol of measured flow (exhaust), mol/mol, solved iteratively per 1065.655

x_{H₂O} = amount of water in measured flow, mol/mol (see 1065.645 for calculations)

e_{fuel} = 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)

w_{fuel} = 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 1 μmol (emission constituent)/mol (exhaust) = 1 ppm (part per million))

\dot{m}_{fuel} = mass rate of fuel (g/sec)

x_{H₂O} = amount of water in measured flow, mol/mol (see 1065.645 for calculations)

x_{Cproddry} = amount of carbon products on a C1 basis per dry mol of measured flow (exhaust), mol/mol

t = time interval (sec)

f_n = rotational frequency (shaft), rev/min

T = torque (N-m)

t = time interval (sec)

NOTE: The units of the numerator work out to g emission 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)