Test Plan to Determine PEMS Measurement Allowances for the Gaseous Emissions Regulated under the Manufacturer-Run Heavy-Duty Diesel Engine In-Use Testing Program

Developed by:

United States Environmental Protection Agency,
California Air Resources Board, and
Engine Manufacturers Association

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Executive Summary

This test plan sets forth the agreed upon processes and methodologies to be utilized to develop additive, brake-specific, data-driven measurement allowances for gaseous emissions measured by PEMS (NOx, NMHC and CO) as required under the HDIUT regulatory program. A separate test plan will be developed and agreed upon for the determination of the PM measurement allowance.

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 allowances. Namely, the allowances are 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, sampled over 30-second durations will be subtracted from the PEMS error associated with measuring heavy-duty engine emissions utilizing PEMS over 30-second transient NTE sampling events under a broad range of environmental conditions. This subtraction will yield "PEMS minus laboratory" measurement allowances. The error model will not subtract any laboratory accuracy or precision that is determined from laboratory measurements of transient 30-second NTE events. 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 allowances for each of the gaseous emissions, namely NOx, NMHC, and CO.

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

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

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

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1 Introduction

This test plan will establish PEMS measurement allowances for the gaseous emissions regulated by the manufacturer-run on-highway heavy-duty diesel engine in-use test program. The measurement allowances will be established in units of brake-specific emissions (g/hp-hr), and they will be added to the final NTE standard for a given emission, after all the other additive and multiplicative allowances have been applied. This test plan will establish three measurement allowances; one for NOx, one for NMHC, and one for CO.

This test plan first describes a 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 a 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 nominal PEMS data set upon which it statistically applies all the errors, calculates results, and saves the results. Then the model will be run with all errors set to zero. The difference between the NTE result with errors and the case without any errors will be a brake-specific difference that is recorded for later use. Then the process repeats using the same nominal data set to which different errors are applied, and thus different differences are calculated. As the model continues to iterate and generate more and more results, patterns should appear in the output data. These patterns will be the distributions of differences, based upon the error that was statistically and repeatedly applied to the nominal data set. Many difference distributions will be determined; for each NTE event, for each regulated emission, for each calculation method, and for each PEMS manufacturer. It has been agreed that the 95th percentile value of these distributions will be taken as reasonable "worst case" results. Details on how all these distributions will be reduced to determine individual measurement allowances are given in the "Error Model" section of this test plan.

Finally, the test plan describes how the computer model will be validated against real-world over-the-road in-use PEMS operation. PEMS emissions measurements will be conducted, while at the same time a reference laboratory will be towed along to measure

the same emissions. Data from this final experiment 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.

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 nominal NTE events. Determine the pollutant-specific brake-specific additive measurement allowances for NOx, NMHC, and CO.

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: lab tests, and Section 4: environmental tests. The lab test error surfaces cover the domain of normalized error versus the magnitude of the signal to which the error is to be applied (i.e. range of error vs. concentration, flow, torque, etc.). This is illustrated later in this section. The environmental test error surfaces cover the domain of environmental test cycle time versus the magnitude of the signal to which the error is to be applied (i.e. range of error vs. concentration, flow, torque, etc.).   Details on how each surface is generated are given in each of the respective sections. These surfaces will already represent PEMS error incremental to lab error; therefore, these surfaces are sampled directly by the model.

Note that each PEMS manufacturer will be assigned unique error surfaces, depending upon the performance of the respective PEMS. For determining error surfaces for a single PEMS manufacturer, the results from the three PEMS of a given PEMS manufacturer will be pooled prior to generating the error surfaces.

The error model will use two different probability density functions (PDFs) to sample the error surfaces, depending upon which experiment the surface represents. Change this section to reflect decisions to use different PDFs for EMI/RFI and S&Vib environmental tests. To sample error surfaces that are generated from the laboratory test results (Section 3); the model will use a truncated normal PDF because the laboratory tests are designed to evenly cover the full, but finite, range of engine operation. Have A statistician review the proposed normal distribution standard deviation in Figure 2.2-a.

Fig 2.4-a. PDF.
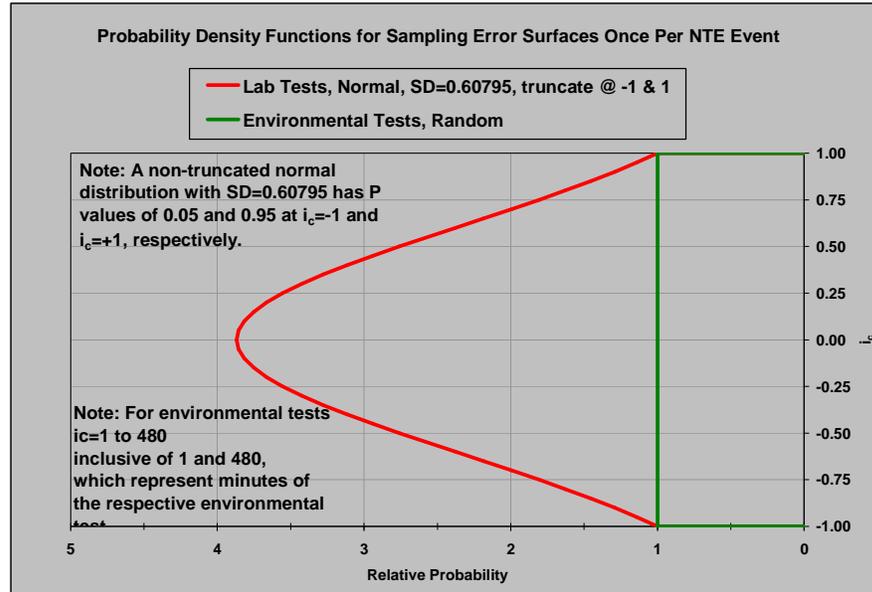
To sample error surfaces that are generated from the environmental test results (Section 4); the model will use a random PDF because the environmental tests are already designed to cover the typical range and frequency of the environmental conditions. Note that the lab's normal PDF samples i_c, from -1 to 1, including -1 and 1, and the environmental tests' random PDF samples test time in minutes from 1 to 480 minutes, including minutes 1 and 480. For the lab PDF, the PDF will be aligned with the error surface such that the 50th percentile value of the error surface crosses the median of the PDF and the 5th and 95th percentile values of the error surface 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 PDF axis once per NTE event. A line perpendicular to the error axis at the sampled error location (i_c) will be used along the surface to determine the error corresponding to the magnitude of the nominal signal. Each error will be added or subtracted, depending upon sign (+/-), to the nominal value on a second-by-second basis.

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.

The set of nominal values to which all the errors are added will be a large data set of engine operation over a wide range of NTE events. The nominal data set will be initially generated from collections of real-world PEMS data sets. Parameters in the nominal 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 nominal data set.

After the errors of each PEMS manufacturer are applied separately to the nominal data set, NTE brake-specific emissions results are calculated for each PEMS manufacturer, using each of the three agreed-upon NTE calculation methods. Next, the NTE events are calculated by each of the three calculation methods, but with no error sampled or applied. These results are considered the "true" values of the NTE events. These true values are subtracted from each NTE event, and the difference is recorded. Then a new set of errors are sampled, applied to the original input data file, and the NTE results are calculated again. The "true" values are again subtracted, and the difference is recorded. This is repeated thousands or even millions of times so that the model converges upon distributions of brake-specific differences for each of the original NTE events in the input data file. [We need to have A statistician explain how convergence of all 18 distributions, triggers the end of running the Monte Carlo model. What statistical test indicates that the distributions are sufficiently populated by the Monte Carlo model for determining 95th percentile values of each of the distributions.]

Then the 95th percentile difference value is determined for each NTE event's distributions of brake-specific differences for each emission (NOx, NMHC, and CO) for each calculation method and for each PEMS. At this point there are eighteen distributions of 95th percentile differences, where all the NTE events are pooled by the three emissions (NOx, CO, NMHC) times three different calculation methods (torque-speed, fuel-specific * brake-specific, and ECM fuel rate) times two PEMS manufacturers. Each 95th percentile distribution represents a range of possible measurement allowances.

From each of these eighteen distributions of possible measurement allowances, one measurement allowance per distribution must be determined. First the correlation between measurement allowance values versus the true NTE values is tested. For each data set, if the linear regression of measurement allowance versus true NTE value has an $r^2 > 0.9$ and an *SEE* < 5 % Check these with Bob Mason of the mean true NTE value, then use the linear regression equation to determine the measurement allowance for that data set at the following NTE thresholds:
NOx = 2.0 g/hp-hr
NMHC = 0.21 g/hp-hr
CO = 19.4 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 true NTE that is closest to the NTE threshold, not extrapolated to the NTE threshold itself.

If the linear regression did not pass the aforementioned r^2 and *SEE* statistics, then the arithmetic mean value of the distribution is used as the single measurement allowance for that distribution. Once all data distributions are evaluated, there will be eighteen measurement allowances for three emissions times three calculation methods times two PEMS manufacturers.

The calculation method and PEMS are now selected. First the eighteen measurement allowances are normalized by their respective NTE thresholds and expressed as a percent of that threshold.

Table 2.2-a below illustrates the selection of PEMS and calculation method for measurement allowance. The example is based on a hypothetical set of eighteen measurement allowances for the three emissions, two PEMS and three calculation methods. The calculation method and PEMS are selected by first picking the maximum allowances of all the emissions for each of the given calculation methods and PEMS (highlighted in yellow). For each column the maximum value is selected. Then the minimum of these maximums is used to select the best method for each PEMS (highlighted in blue). Finally, the lower of these two values determines which PEMS and its associated calculation method is the one used to determine all of the final measurement allowances. In this hypothetical case, PEMS #2 with the torque-speed calculation would have been the selected one.

Therefore, 16%, 17%, and 2% would be selected as the best measurement allowances for NOx, NMHC, and CO, respectively. And the brake-specific measurement allowances would be:

NOx   = 16% * 2.0 g/hp-hr   =   0.32 g/hp-hr
NMHC   = 17 % * 0.21 g/hp-hr =   0.0357 g/hp-hr
CO   = 2%   * 19.4 g/hp-hr =   0.388 g/hp-hr

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

Note that if any measurement allowance is determined to have a value less than zero, then the measurement allowance will be set equal to zero.

Table 2.2-a: Example of Calculation/Selection of Measurement Allowance						
	Measurement Errors at respective NTE threshold (%)					
	PEMS #1			PEMS #2		
Calc. Method ==>	Torque-Speed	BSFC	ECM fuel specific	Torque-Speed	BSFC	ECM fuel specific
BSNOx	15%	18%	20%	16%	18%	20%
BSNMHC	20%	16%	14%	17%	15%	12%
BSCO	3.00%	2%	1%	2%	2%	1%
max error ==>	20%	18%	20%	17%	18%	20%
min of max ==>		18%		17%		
min of PEMS ==>				17%		

selected method==>	PEMS#2, using "torque-speed" method

2.3 Methods and Materials

Note 1: Exercise the model using three different calculation methods: a) torque and speed method, b) BSFC method, and c) ECM - fuel specific method. Determine which calculation method is the most accurate, and use it to estimate the measurement allowance. Each calculation method is described in Table 3.3.4-a
Note 2: Exercise the model separately for each of the two PEMS manufacturers, so that the best instrument is selected.

Initial discussions have been carried out with a statistician from the contractor facility. The contractor proposes to prepare an Excel spreadsheet model for use with Crystal Ball Monte Carlo software for error analysis of brake specific emissions, BSE, as outlined in section 2.4. It is recognized that minor changes to the model's specifications may be requested as agreed upon by the steering committee, and the contractor will accommodate such change requests. The contractor will prepare the spreadsheet in a modular structure following the specified model outline, and will make provisions for identified calculation modules, such as ambient pressure-ambient temperature correlation, for which alternative modeling approaches may be implemented in the future. Additionally, the input random variables will be clearly identified and easily located to facilitate any revisions that may become necessary for user's who want to exercise the model with other Monte Carlo add-ins such as @Risk or the newest versions of Crystal Ball. The spreadsheet will be tested with controlled test cases of simplified input distributions with the Crystal Ball add-on to confirm correct model implementation in accordance with this test plan. At least one typical analysis case will be run as an additional confirmation.

The contractor will deliver the electronic spreadsheet; and a brief report describing the model, presenting the test cases and describing pertinent information including the Crystal Ball version, Excel version, operating system and computer. Standard spreadsheet calculations will be used and no serious difficulties are anticipated regarding application in other spreadsheet
versions. The basic development is planned to be tested using Crystal Ball 2000. Test cases will be executed using Excel 97 and Excel 2003.

The contractor will control revisions of the spreadsheet model using descriptive file names. Extensive revisions or testing with other software versions beyond that initially proposed will be re-proposed when a need for such additional work is identified.

2.4 Data Analysis
For each of the measurement errors in section 3, an error surface is created and sampled according to the aforementioned normal PDF. Each error surface represents an additive error—or a subtractive error if the sign is negative—to the nominal value.   Figures 2.4-

(a),(b), and (c) serve as a hypothetical example of how these error surfaces should be created for every error in section 3. The example applies to the error module for steady state bias and precision NOx concentration errors (section 3.2). The plots shown correspond to hypothetical NOx emissions concentration data acquired with 3 PEMS, all from the same manufacturer (data pooled together). These figures will be referenced by each "Data Analysis" section, for the various errors discussed in this test plan.

For each of the measurement errors in section 4, an error surface is created and sampled according to the aforementioned random PDF. Each error surface represents an additive error—or a subtractive error if the sign is negative—to the nominal value. Refer to section 4 for details on how these error surfaces are sampled.

Errors from Sections 3 and 4 are combined by adding all of the sampled error once per NTE event. For example, in order to assess the errors in NOx concentration, several modules will be created such that:

$$\text{NOx PPM} = \text{NOx PPM \_nominal} + \Delta(PPM)_1 + \Delta(PPM)_2 + \Delta(PPM)_3 + \dots$$

Where,

$\Delta(PPM)_1$ = NOx concentration errors due to steady state bias and precision errors

$\Delta(PPM)_2$ = NOx concentration errors due to ambient temperature

$\Delta(PPM)_3$ = NOx concentration errors due to ambient pressure, etc…

Fig 2.4-a: raw data PEMS vs NOMINAL (Lab):

Acquire raw data with the PEMS at various average concentration levels (NOx ppm) as per section 3.2. Plot "PEMS" concentrations against "nominal" levels measured with the Lab grade equipment. This plot pools all bias and precision errors for all 3 PEMS of a given PEMS manufacturer. Shown are the 5th 50th and 95th percentiles at each measured concentration level (note that distribution 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 concentration level sampled. The example shows only 6 discrete concentration levels (ranging from 100-350ppm). However the actual number of discrete levels will be

Figures 2.4 a, b, and c: Construction of an Error Surface
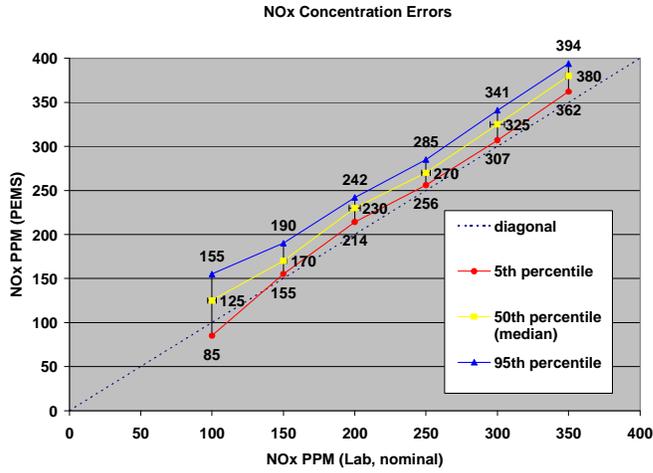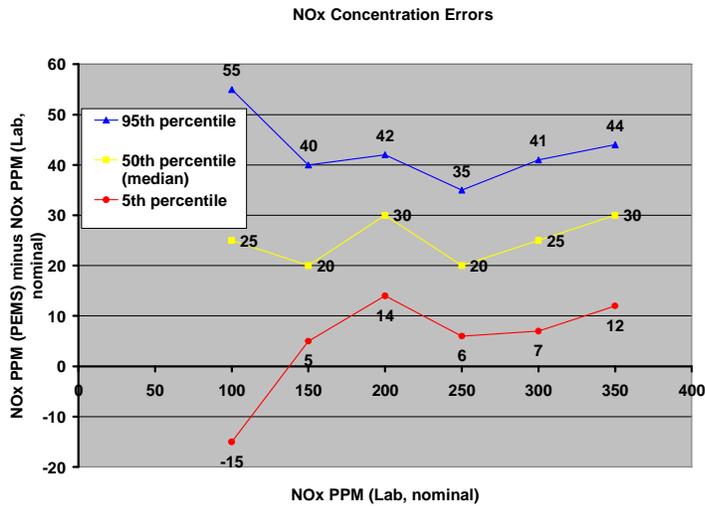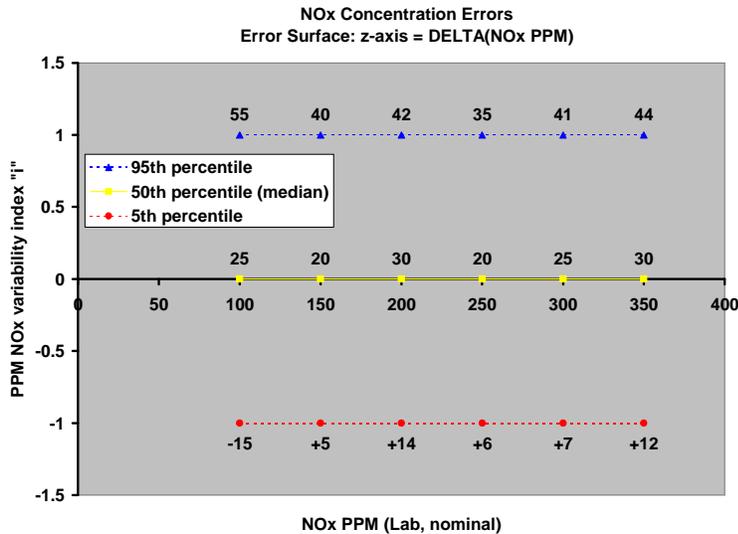
Fig 2.4-a

Fig 2.4-b

Fig 2.4-c

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determined by the number of operating conditions actually run in the test. Section 3.2 for example will select 10 operating conditions from an initial number of 40 operating conditions. Thus the actual plot for section 3.2 will have 10 discrete concentration levels.

Fig 2.4-b: (PEMS minus NOMINAL) vs. NOMINAL level
This plot basically shows the "additive error band" measured during testing. The plot is created by subtracting the "nominal" values from the "PEMS" measured values displayed in Fig 4.2-a. Notice that the 95% percentiles are equivalent between the two plots

Fig 2.4-c: Error Surface
This step normalizes the previous plot using what is called a "variability index (i_c)", which represents the "dice to be rolled" 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 a "probability density function (PDF)" assigned to i_c. In the case of the example given, i_c will be assumed to vary according to a Gaussian 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. Environmental error modules may use flat (random) probability density functions for their respective variability index. Notice that the 5th and 95th percentiles are equivalent between the three plots

Error surfaces such as the one presented in Fig 4.2-c are the input modules that the Monte Carlo simulation program will use during calculations of brake-specific emissions. For example, for a given NTE calculation the dice will be rolled once per valid NTE event. Let us assume that the dice were rolled (by the computer program) the first time and i_c = 0.5. Let us also assume that during this valid NTE event, the nominal NOx concentration error measured at a given step in time is 100ppm. In this case:

$$\Delta(PPM)_1 = (25+55)/2 = 40ppm \text{ (from Fig 4.2-c, for } i_c = 0.5, \text{ Lab NOx }=100)$$

For that step in the calculation, the Monte Carlo approach will add this "delta" to the nominal concentration value of 100ppm (100ppm+40ppm = 140ppm) due to errors in steady state bias and precision for i_c = 0.5, and NOx_nom = 100ppm. If during the same NTE event, a nominal concentration at 200ppm is measured,

$$\Delta(PPM)_1 = (30+42)/2 = 36ppm \text{ (from Fig 4.2-c)}$$

Note that the dice are rolled once per valid NTE event.

Now let us assume that the error in NOx concentration is composed of only 3 modules: $\Delta(PPM)_1$, $\Delta(PPM)_2$, and $\Delta(PPM)_3$. And let us assume that for a given valid NTE event, during a certain step, and after a given roll of dice…
the nominal value of NOx-ppm = 300ppm ; and:

$$\Delta(PPM)_1 = 36ppm, \quad \Delta(PPM)_2 = -20ppm, \quad \Delta(PPM)_3 = -2ppm.$$

Then, when the Monte Carlo model runs, it will use a NOx value of:

$$NOx\_PPM = 300 + 36 - 20 - 2 = 314 \text{ ppm}$$

The calculation continues during the entire NTE event without having to "roll the dice" again. In other words, i_c will not change. However, as the NOx concentration values change during the NTE event, $\Delta(PPM)_1$, $\Delta(PPM)_2$, and $\Delta(PPM)_3$ will take different

values, depending on the nominal value of NOx-ppm at each step. For nominal values that are in between measured nominal values, utilize two-dimensional linear interpolation using the four measured errors that circumscribe the smallest rectangle around the point. The steering committee has provided a spreadsheet of the interpolation algorithm that is to be used for this purpose. Send the contractor EPA's Part 1065 t and F test spreadsheet.

This same approach would be used for other error modules (ambient temp, ambient pressure, shock and vibration, etc.), and other error types (e.g., BSFC, torque, exhaust flow rate, etc, etc.)

3 Engine Dynamometer Laboratory Tests

Utilize engine dynamometer laboratory testing to establish the difference between PEMS emissions analyzers and flow-meters against lab grade instruments. Also establish how exhaust flow meter installation affects performance, and establish how well ECM parameters can be used to estimate torque and BSFC.

First, however, audit all the PEMS and the lab equipment to ensure that they are operating properly, according to 40 CFR Part 1065 Subpart D. Next, conduct steady-state engine dynamometer testing to establish PEMS bias and precision relative to the lab. Then, conduct transient engine dynamometer testing to determine PEMS precision by repeating transient NTE events. Afterward, investigate the effects of exhaust flow meter installation. 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 allowances 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.

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 to provide the contractor with guidance regarding which specific sections of Part 1065 Subpart D are required and which are optional.

3.1.3 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. Do not allow recalibrations based on a comparison between lab audit results and PEMS audit results. 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.

3.1.4 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.

3.2 Bias and Precision Errors under steady state engine operation

3.2.1 Objective

Evaluate the bias and precision of measuring 10 different steady-states NTE over a 30-minute cycle. Determine the Δ_{SS} surface plot for the error model.

a) Obtain data for torque mapping and test matrix selection (40 data points)
b) Quantify bias and precision errors of gaseous emissions concentration measurements (ppm raw and fuel-specific dilute), under standard laboratory conditions.
c) Quantify bias and precision errors in exhaust flow measurement measurements using PEMS' portable flow-meters, under standard laboratory conditions.
d) Quantify bias and precision errors in gaseous emissions flow rate measurements (e.g. g/hr NOx).

3.2.2 Background

Testing will be conducted to capture bias and precision errors in PEMS' emissions analyzers and flow meters, versus lab grade instruments. The tests will be steady-state only. In essence, testing under this section will use a methodology consistent with that currently used and tolerated by engine manufacturers during certification and compliance with respect to the supplemental emissions test (SET).

Note: Section 3.3 (next section) will evaluate precision errors (not bias) due to the dynamic response of the PEMS instrumentation, with respect to those of lab grade analyzers. 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.

3.2.3 Methods and Materials

Use the following systems:
a) Three (3) heavy duty diesel engines (1 HHDE, 1 MHDE, 1 LHDE)
b) Six (6) PEMS analyzers (3 Sensors Semtech-D models, and 3 Horiba OBS-2200 models)
c) Six (6) PEMS exhaust flow-meters (3 from Sensors, and 3 from Horiba)
d) Oversized passive DPF (diesel particulate filters) for each engine.

You will need to select DPF's to be attached to the exhaust of each engine. You will also need to establish a procedure to ensure that the DPF's are cleaned at the beginning of each test, and remain clean in order to make their impact on emissions variability negligible.

PEMS manufacturer equipment must pass red-face test with respect to being consistent with acceptable practices for in-use testing. For example, use of large gas bottles that can not be utilized by the EPA/ARB/EMA HDIU enforceable program is unacceptable.

Also, PEMS systems cannot be "prototype" systems, nor can their software be beta versions. What is tested in this program is what the measurement allowances will be based on. Once the program starts, PEMS manufacturers will not be allowed to introduce "improvements" or "fixes" to their systems.

Each PEMS manufacturer must supply the contractor with PEMS software that calculates NTE events. This software may be built into the PEMS on-board software, or the software may be a spreadsheet with "macros" built-in to post-process and analyze NTE events to determine brake-specific results. PEMS manufacturers may train the contractor on how to use their software prior to the start of testing. Neither the contractor nor a PEMS manufacturer may change any of the software once testing has started, unless agreed-upon by the steering committee.

Use the following overall guidelines:
e) Measure raw as well as CVS-dilute emissions
f) Measure engine inlet airflow through use of LFE or equivalent
g) Measure instantaneous fuel consumption and torque
h) Ensure purging of the DPF system as often as needed in order to ensure negligible impact on emissions variability
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 PM. Just measure AVL smoke
k) Stabilization time = 120 seconds. Data acquisition = 30 seconds, after stabilization. Dwell time between points = 30 seconds (total time per point = 180 sec. = 3 min)
l) Zero and span PEMS at beginning of day following manufacturer's guidelines. Do not re-span PEMS analyzers again during the day, unless PEMS manufacturer provides a way to do this automatically, so it is realistic with real-life in-use testing practices. Re-zeroing should be allowed if and only if done automatically by the PEMS for the same reasons.
m) Zero and spanning of the instrument lab analyzer can be repeated as often as laboratory common practices.
n) Perform carbon balance checks on CVS emissions data to ensure data quality
o) Always power off PEMS equipment at end of each day. Re-start start-up process every day.

40 point selection testing:

p) Map each engine lug curve according to the variable speed engine sweep map test procedures in Part 1065 Subpart F and follow the applicable calculations in Part 1065 Subpart G.

q) Measure 40 points spanning the NTE zone. These points are listed in Table 3.2.3-a (no repeats). Denormalize the points in this table according to Part 1065 Subpart G.

r) Verify that none of these test points have triggered emissions deficiencies (this will have to be accomplished with assistance from the respective engine manufacturer)

s) Stop testing, analyze 40 points of emissions and examine data for overwhelming biases. For example: i) One of three PEMS is very different than the other two from a given PEMS manufacturer; ii) Lab raw vs. lab dilute is very different from one another (i.e. questionable reference); iii) One flow meter seems very different than all others; iv) All PEMS from all manufacturers seem very different than all lab measurements; etc.

t) Spend minimum amount of time to determine source of bias, correct if possible via adjustments to the experimental setup, Part 1065 calibration specifications, PEMS manufacturer-specified calibrations, lab system manufacturer specifications, contractor QA/QC procedures. Under no circumstances will PEMS be calibrated to lab instruments or vice versa. However, torque/BSFC tables will be created (i.e. calibrated) based on mapped data.

u) During the 40 point selection testing, all PEMS analyzers and flow meters can be connected at the same time (daisy chain fashion) if PEMS manufacturers agree. This would allow evaluation of interactions between PEMS. Testing in the next portion of testing will not allow daisy chaining of PEMS however.

10 point cycle repeat-testing → evaluate bias and precision errors:

v) Down select 10 operating conditions from 40 points, to be used during repeat testing. Select these points to appropriately span the range of expected emissions concentrations and exhaust flow rates obtained during 40 point test set. The points should also represent the highest degree of bias errors with respect to the lab measurements.

w) Create a test cycle consisting of the 10 selected points, using the criteria described above (l). As this cycle is tested a second time however, the order in which each operating condition is entered into the cycle needs to be changed randomly. Keep randomizing the order of the operating conditions during all subsequent cycle tests.

x) Repeat each cycle a total of 20 times.

y) Each test will use one PEMS manufacturer at a time, to measure emissions concentration and exhaust flow rate (unless otherwise agreed to by PEMS manufacturer)

z) Expected test duration: 10 points x 3 minutes x 20 repeats = 600 minutes (10 hrs). This assumes that the DPF will not need to be purged during testing.

aa) Each engine will have to be run on 6 different days to obtain data from all 6 PEMS

Table 3.2.3-a: Steady State Operating Conditions for 40 point matrix					
NTE Event	[1]Speed % Range	[2]Torque % Range	NTE Event	[1]Speed % Range	[2]Torque % Range
NTE$_1$	17%	[3]32%	NTE$_{21}$	72%	32%

NTE$_2$	17%	49%	NTE$_{22}$	72%	49%
NTE$_3$	17%	66%	NTE$_{23}$	72%	66%
NTE$_4$	17%	83%	NTE$_{24}$	72%	83%
NTE$_5$	17%	100%	NTE$_{25}$	72%	100%
NTE$_6$	31%	32%	NTE$_{26}$	86%	32%
NTE$_7$	31%	49%	NTE$_{27}$	86%	49%
NTE$_8$	31%	66%	NTE$_{28}$	86%	66%
NTE$_9$	31%	83%	NTE$_{29}$	86%	83%
NTE$_{10}$	31%	100%	NTE$_{30}$	86%	100%
NTE$_{11}$	45%	32%	NTE$_{31}$	100%	32%
NTE$_{12}$	45%	49%	NTE$_{32}$	100%	49%
NTE$_{13}$	45%	66%	NTE$_{33}$	100%	66%
NTE$_{14}$	45%	83%	NTE$_{34}$	100%	83%
NTE$_{15}$	45%	100%	**NTE$_{35}$**	100%	100%
NTE$_{16}$	59%	32%	**NTE$_{36}$**	Governor line	32%
NTE$_{17}$	59%	49%	NTE$_{37}$	Governor line	49%
NTE$_{18}$	59%	66%	**NTE$_{38}$**	Governor line	66%
NTE$_{19}$	59%	83%	NTE$_{39}$	Governor line	83%
NTE$_{20}$	59%	100%	NTE$_{40}$	50%	50%

[1] Speed (rpm) = Curb Idle + (Speed % * (MTS - Curb Idle)
[2] Torque (lbf-ft) = Torque % * Maximum Torque At Speed (i.e. lug curve torque at speed)
[3] Torque (lbf-ft) = Maximum of (32 % * peak torque) and the torque at speed that produces (32 % * peak power)
[4] MTS = Maximum Test Speed, as defined per part 1065, subpart F
Note: NTE events in marked in bold above will also be tested in section 3.3 (dynamic response testing)

3.2.4 Data Analysis

Use the acquired data to create the "error surfaces" to be used by the Monte Carlo simulation. Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference, create the error surfaces for steady state bias and precision errors using the parameters indicated in Table 3.2.4-a. Note that this table lists NOx emissions only, but the same methodology applies to NMHC and CO emissions:

Table 3.2.4-a: Steady State Error Surfaces (Refer to section 2.4)

Error Surface for NOx Concentration	
Fig 2.4-a	
x-axis	NOx ppm (lab,nom)
y-axis	NOx ppm (pems)
Fig 2.4-b	
x-axis	NOx ppm (lab,nom)
y-axis	NOx ppm (pems) - NOx ppm (lab,nom)
Fig 2.4-c	
x-axis	NOx ppm (lab,nom)
y-axis	$i_{c\_SS\_NOx}$
z-axis = $\Delta_{SS\_NOx\_ppm}$	NOx ppm (pems) - NOx ppm (lab,nom)
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

Error Surface for NOx Flowrate	
Fig 2.4-a	
x-axis	NOx g/min (lab,nom)
y-axis	NOx g/min (pems)
Fig 2.4-b	
x-axis	NOx g/min (lab,nom)
y-axis	NOx g/min (pems) - NOx g/min (lab,nom)
Fig 2.4-c	
x-axis	NOx g/min (lab,nom)
y-axis	$i_{c\_SS\_NOx}$
z-axis = $\Delta_{SS\_NOx\_flow}$	NOx g/min (pems) - NOx g/min (lab,nom)
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

Error Surface for Exhaust volumetric flowrate	
Fig 2.4-a	
x-axis	SCFM (lab,nom) / SCFM_max -[%]
y-axis	SCFM (pems) / SCFM_max -[%]
Fig 2.4-b	
x-axis	SCFM (lab,nom) / SCFM_max -[%]
y-axis	[SCFM (pems) - SCFM(lab,nom)] / SCFM_max -[%]
Fig 2.4-c	
x-axis	SCFM (lab,nom) / SCFM_max -[%]
y-axis	$i_{c\_SS\_flow}$
z-axis = Δ_{SS_scfm}	[SCFM (pems) - SCFM(lab,nom)] / SCFM_max -[%]
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

Note: SCFM_max = PEMS flowmeter maximum SCFM

Error Surface for Exhaust Mass Flowrate	
Fig 2.4-a	
x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	exh_flow (pems) / exh_flow_max -[%]
Fig 2.4-b	
x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	[exh_flow (pems) - exh_flow(lab,nom)] / exh_flow_max -[%]
Fig 2.4-c	
x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	$i_{c\_SS\_flow}$
z-axis = $\Delta_{SS\_exh-flow}$	[exh_flow (pems) - exh_flow(lab,nom)] / exh_flow_max -[%]
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

Note: exh_flow_max = PEMS flowmeter maximum exhaust flowrate (@ max density)

3.3 Precision Errors under transient engine operation (dynamic response)

3.3.1 Objective

Evaluate the precision of measuring 30 different 32-second NTE events in different orders over a 20-minute cycle. Determine the Δ_{Trans} surface plot for the error model. Carry out this evaluation both for engine emissions and exhaust flow rate.

3.3.2 Background

PEMS are expected to operate in a repeatable manner over NTE events as short as 30 seconds. It is hypothesized that two sources of PEMS repeatability error may be PEMS' dynamic response to rapidly changing signals and its 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 that are combined on a second-by-second basis; 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 gaseous 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 randomly rearranged. 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. Random rearrangement of the NTE events and inter-NTE events will maximize the sensitivity of this test to dynamic response and history effects.

3.3.3 Methods and Materials

a) Use a transient engine dynamometer emissions laboratory.
b) Use a laboratory that can accommodate at least six PEMS, their power supplies, the PEMS flow meters, cables and lines.
c) Use same 3 engines from steady state testing, section 3.2
d) Use same overall guidelines described in section 3.2, but applied to transient engine testing.
e) Ensure that PEMS systems are not spanned more than once per day, and re-zeroed unless PEMS software allows this to be done automatically.

Challenge PEMS to 30 different 32-second NTE events over a 20 minute test cycle (see Table 3.3.3-a). Repeat the test cycle 20 times for a total of 600 measured NTE events. Repeat the test cycle 4 to 5 times per day and over 4 to 5 different days. Create unique

cycles for each repeat by first randomly sampling the order of NTE events from the NTE event table. Separate each NTE event with a randomly sampled inter-NTE event from the inter-NTE event table (Table 3.3.3-b). Regardless of the descriptions in the summary table (Table 3.3.3-b), use the provided spreadsheet (author: Matt Spears, EPA) with the engine maps generated in 3.2.3 to create 20 unique second-by-second de-normalized test cycles, and use one unique cycle for each repeat of this test. 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.

Table 3.3.3-a: Dynamic Response NTE Events			
NTE Event	**[1]Speed % Range**	**[2]Torque % Range**	**Description**
NTE$_1$	17%	[3]32%	Steady speed and torque; lower left of NTE
NTE$_2$	59%	[3]32%	Steady speed and torque; lower center of NTE
NTE$_3$	Governor line	[3]32%	Steady speed and torque; lower right of NTE
NTE$_4$	17%	66%	Steady speed and torque; middle left of NTE
NTE$_5$	59%	66%	Steady speed and torque; middle center of NTE
NTE$_6$	Governor line	66%	Steady speed and torque; middle right of NTE
NTE$_7$	17%	100%	Steady speed and torque; upper left of NTE
NTE$_8$	59%	100%	Steady speed and torque; upper center of NTE
NTE$_9$	100%	100%	Steady speed and torque; upper right of NTE
NTE$_{10}$	Lower third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE$_{11}$	Upper third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE$_{12}$	Middle third	[3]32% - 100%	Highly transient torque; moderate transient speed
NTE$_{13}$	17% - governed	Lower third	Highly transient speed; moderate transient torque
NTE$_{14}$	17% - governed	Upper third	Highly transient speed; moderate transient torque
NTE$_{15}$	17% - governed	Middle third	Highly transient speed; moderate transient torque
NTE$_{16}$	Lower right diagonal		Transient; speed increases as torque increases
NTE$_{17}$	Upper left diagonal		Transient; speed increases as torque increases
NTE$_{18}$	Full diagonal; lower left to upper right		Transient; speed increases as torque increases
NTE$_{19}$	Lower left diagonal		Transient; speed decreases as torque increases
NTE$_{20}$	Upper right diagonal		Transient; speed decreases as torque increases
NTE$_{21}$	Full diagonal; lower right to upper left		Transient; speed decreases as torque increases
NTE$_{22}$	Third light—heavy-duty NTE event from International, Inc. data set		Sample from LHDE
NTE$_{23}$	Cruise; ~ 50 mph		Sample from HDDE
NTE$_{24}$	Cruise; ~ 75 mph		Sample from HDDE
NTE$_{25}$	Small bulldozer		Sample from NRDE
NTE$_{26}$	Large bulldozer		Sample from NRDE
NTE$_{27}$	Second of three NTE events in FTP		Seconds used from FTP: 714-725, 729-743, 751-755
NTE$_{28}$	Third light—heavy-duty NTE event from International, Inc. data set		Sample from LHDE
NTE$_{29}$	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%
NTE$_{30}$	First of two NTE events in NRTC		Seconds used from NRTC: 627-629, 657-664, 685-696, 714-722
[1] Speed (rpm) = Curb Idle + (Speed % * (MTS - Curb Idle) [2] Torque (lbf-ft) = Torque % * Maximum Torque At Speed (i.e. lug curve torque at speed) [3] Torque (lbf-ft) = Maximum of (32 % * peak torque) and the torque at speed that produces (32 % * peak power)			

Table 3.3.3-b: Dynamic Response Inter-NTE Events			
INT Event[1]	Duration (s)	Frequency	Description
INT_1	10	1	Initiation of cycle; INT_1 is always first
INT_{2-6}	2	5	Shortest and most frequent inter-NTE events
INT_{7-10}	3	4	Short and frequent inter-NTE events
INT_{11-14}	4	4	Short and frequent inter-NTE events
INT_{15-18}	5	4	Short and frequent inter-NTE events
INT_{19-21}	6	3	Short and frequent inter-NTE events
INT_{22}	7	1	Medium inter-NTE event
INT_{23}	8	1	Medium inter-NTE event
INT_{24}	9	1	Medium inter-NTE event
INT_{25}	11	1	Medium inter-NTE event
INT_{26}	13	1	Long inter-NTE event
INT_{27}	17	1	Long inter-NTE event
INT_{28}	22	1	Long inter-NTE event
INT_{29}	27	1	Long inter-NTE event
INT_{30}	35	1	Longest inter-NTE event
INT_{31}	5	1	Termination of cycle; INT_{31*} 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 3.3.3-a: Example of Transient Test Cycle
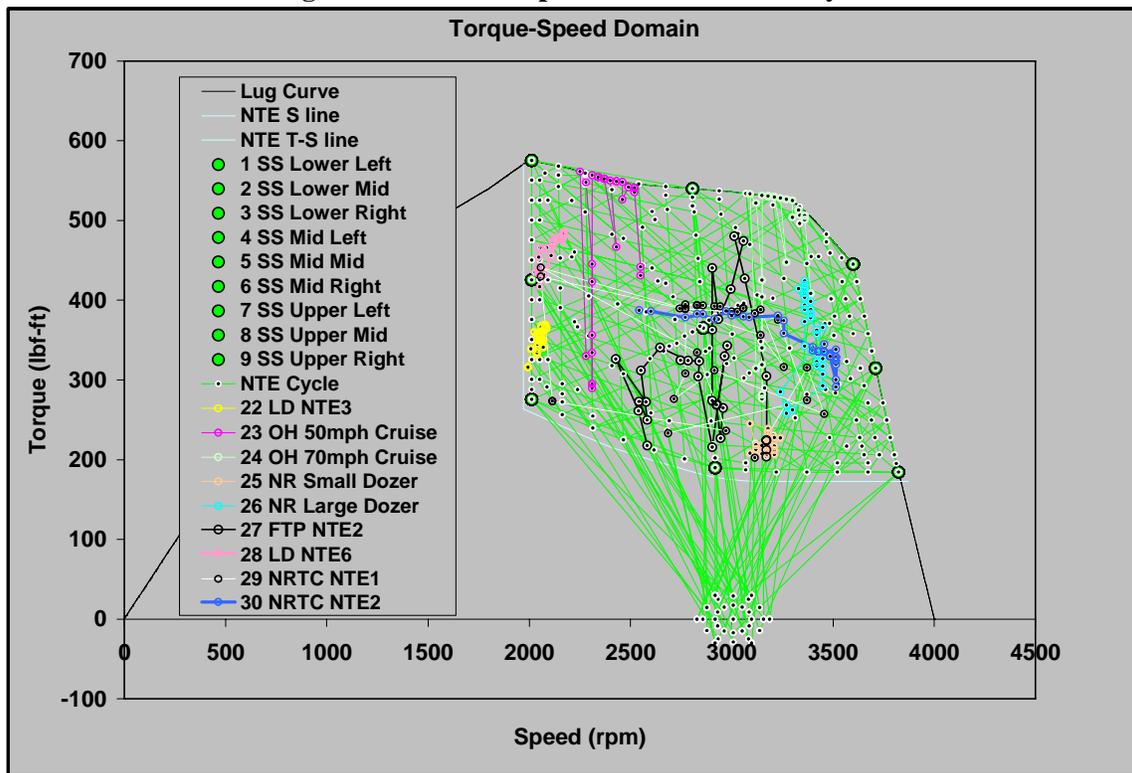
Prior to executing the first repeat, setup each PEMS and stabilize engine operation at the first inter-NTE operating point. Setup the PEMS according to 40 CFR Part 1065 and PEMS manufacturer instructions, including any warm-up time, zero-spans of the analyzers and the setup of all accessories including 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. For each NTE event, calculate brake-specific means for NOx, NMHC, and CO using the three different work calculation methods defined in 1065 Subpart G. For convenience the equations are also shown in Figure 3.3.4-(a), and the abbreviations associated are included as Appendix 7.2. For each NTE event, calculate brake-specific means for NOx, NMHC, and CO using the three different work calculation methods given in Figure 3.3.4-(a). The three different methods are referred in this document as i) Torque-Speed Method, ii) BSFC method, and iii) Fuel Specific method respectively. Note that NOx is used here as an example and that the symbol notation is described in 40 CFR Part 1065 Subpart K:

a) For each of the 30 events (repeated 20 times) and 3 calculation methods, calculate the variance.
b) Next adjust each variance by subtracting from it its corresponding steady-state variance, generated by a surface of respective steady-state precision data collected in the previous section.
c) For any adjusted variance less than zero, set that variance equal to zero. Note that such a result is possible if there was no increase in precision error due to PEMS dynamic response during transient NTE events.
d) Create a precision surface using all of the adjusted variances (including any 0 variances). Randomly sample a new value from this surface once per NTE event and assign Δ_{Trans} the value of that sample. Note that the Environmental Tests Data Analysis spreadsheet illustrates how to decrease the variance of a data set.

e)

Table 3.3.4-a: Methods for Calculation of Brake Specific Emissions

Torque-Speed:	e_{NO_x} (g/ hp-hr) $= \dfrac{M_{NO_2} \displaystyle\sum_{i=1}^{N} x_i \dot{n}_i \Delta t}{\displaystyle\sum_{i=1}^{N} f_{ni}\, \tau_i\, \Delta t}$
BSFC:	e_{NO_x} (g/ hp-hr) $= \dfrac{M_{NO_2} \displaystyle\sum_{i=1}^{N} x_i \dot{n}_i \Delta t}{\dfrac{M_C}{w_{fuel}} \displaystyle\sum_{i=1}^{N} \dfrac{x_{Cproddryi}}{1 + x_{H2Oi}}\dfrac{\dot{n}_i}{e_{fueli}}\Delta t}$
Fuel Specific:	e_{NO_x} (g/ hp-hr) $= \dfrac{\dfrac{M_{NO_2}\, w_{fuel}}{M_C} \displaystyle\sum_{i=1}^{N} x_i \dfrac{\dot{m}_{fueli}(1 + x_{H2Oi})}{x_{Cproddryi}}\Delta t}{\displaystyle\sum_{i=1}^{N} f_{ni}\, \tau_i\, \Delta t}$
	$\Delta t = \dfrac{1}{f_{record}}$

f) Using Figure 2.4-(c) as reference, create the error surfaces for steady state bias and precision errors using the parameters indicated in Table 3.3.4-b. Note that this table lists NOx emissions only, but the same methodology applies to NMHC and CO emissions:

Table 3.3.4-b: Dynamic response (Transient) Error Surfaces

Error Surface for NOx Concentration		Error Surface for NOx Flowrate	
Fig 2.4-a		**Fig 2.4-a**	
x-axis	NOx ppm (lab,nom)	x-axis	NOx g/min (lab,nom)
y-axis	NOx ppm variance (pems)	y-axis	NOx g/min variance (pems)
Fig 2.4-b		**Fig 2.4-b**	
x-axis	NOx ppm (lab,nom)	x-axis	NOx g/min (lab,nom)
y-axis	NOx ppm var. (pems) - **NOx ppm var. SS** (pems)	y-axis	NOx g/min var. (pems) - **NOx g/min var. SS** (pems)
Fig 2.4-c		**Fig 2.4-c**	
x-axis	NOx ppm (lab,nom)	x-axis	NOx g/min (lab,nom)
y-axis	$i_{c\_TR\_NOx}$	y-axis	$i_{c\_TR\_NOx}$
z-axis = $\Delta_{TR\_NOx\_ppm}$	NOx ppm var. (pems) - **NOx ppm var. SS** (pems)	z-axis = $\Delta_{TR\_NOx\_flow}$	NOx g/min var. (pems) - **NOx g/min var. SS** (pems)
i_c sample frequency	once per NTE event	i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)	i_c sample distribution	Gaussian (normal distribution)

Error Surface for Exhaust volumetric flowrate		Error Surface for Exhaust Mass Flowrate	
Fig 2.4-a		**Fig 2.4-a**	
x-axis	SCFM (lab,nom) / SCFM_max -[%]	x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	SCFM variance (pems) / SCFM_max -[%]	y-axis	exh_flow cariance (pems) / exh_flow_max -[%]
Fig 2.4-b		**Fig 2.4-b**	
x-axis	SCFM (lab,nom) / SCFM_max -[%]	x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	[SCFM var. (pems) - **SCFM var SS** (pems)] / SCFM_max -[%]	y-axis	[exhflow var. (pems) - **exhflow var SS** (pems)] / SCFM_max -[%]
Fig 2.4-c		**Fig 2.4-c**	
x-axis	SCFM (lab,nom) / SCFM_max -[%]	x-axis	exh_flow (lab,nom) / exh_flow_max -[%]
y-axis	$i_{c\_TR\_flow}$	y-axis	$i_{c\_TR\_flow}$
z-axis = Δ_{TR_scfm}	[SCFM var. (pems) - **SCFM var SS** (pems)] / SCFM_max -[%]	z-axis = $\Delta_{TR\_exh\text{-}flow}$	[exhflow var. (pems) - **exhflow var SS** (pems)] / SCFM_max -[%]
i_c sample frequency	once per NTE event	i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)	i_c sample distribution	Gaussian (normal distribution)

Note: SCFM_max = PEMS flowmeter maximum SCFM

Note: exh_flow_max = PEMS flowmeter maximum exhaust flowrate (@ max density)

3.4 Exhaust Flow Meter Installation

3.4.1 Objective

Evaluate potential bias errors of PEMS exhaust flow sensor due to exhaust system installation related factors; measuring 10 different steady-state NTE over a 30-minute cycle, and under different installation configurations. Determine the Δ_{cfg_pulse} and Δ_{cfg_swirl} surface plots for the error model.

This part of the test program extends the exhaust flow senor evaluation conducted in Section 3.2, which assessed the bias and precision characteristics of the exhaust flow sensor.

3.4.2 Background

The PEMS exhaust flow sensors rely upon stable uniform exhaust velocity profiles near the flow sensor in order to provide the best opportunity for accurate flow measurements. When applying PEMS exhaust flow metering systems to actual in-use vehicles, a wide variety of exhaust system designs will likely be encountered, which could expose the flow sensor to exhaust plumes that are not fully established or altered from the case in which the flow sensor was calibrated. In such situations, a decrease in the accuracy or precision of the exhaust flow metering would result.

In order to evaluate the sensitivity of the exhaust flow sensors to installation effects, the PEMS exhaust flow sensor will be installed in test set-ups where the sensor will be exposed to factors intended to alter the exhaust velocity profiles approaching the sensor to see if the reported flow rate changes from baseline data. The installation factors to be assessed are i) pulsating exhaust flow, ii) non-uniform velocity profile (swirl), and iii) wind effect on the exhaust tailpipe exit.

3.4.3 Methods and Materials

The following items apply to each of the test set-up phases of this program. The only difference between each test phase is the configuration of the exhaust system near the PEMS exhaust flow sensor.

a) Perform the flow sensor evaluation on only one (1) of the test program engines. Engine selection will be based upon project schedule efficiency, but the HHDE engine is desired due to its higher exhaust flow range.
b) Use two PEMS for this testing (one Sensors Semtech-D, and one Horiba OBS-2000). Test each PEMS individually to eliminate the chance of one flow sensor influencing the other.
c) Do not connect the exhaust (after the PEMS flow meter) to a CVS tunnel. It is desired to discharge the exhaust flow to the cell ambient. As in section 3.2.3, it is imperative to measure engine inlet air flow and fuel flow rate in order to calculate exhaust flow rate using lab-grade instrumentation.
d) Follow the same testing guidelines of Section 3.2.3 for determining engine stability time, logging duration, test mode dwell time, and engine test conditions (inlet temperatures, restrictions, etc)

e) Use the same 10 NTE zone test points selected in Section 3.2.3. These test points are the final reduced set test point matrix derived from the initial 40 point test point map. NOTE: the 10 NTE test points are nominal engine speed/load targets. It is important to fine adjust the engine speed and/or load to achieve the same Laboratory exhaust flow rates observed for the 10 NTE zone test points selected in Section 3.2.3.

f) Repeat the test matrix 5 times for each test set-up. For each repeat of the test matrix, alter (randomize) the sequence of the engine operation test points. If after 3 repeats of the test point matrix the data suggests no significant difference between the PEMS flow rate data observed in this section and the PEMS flow rate data reported in Section 3.2.3, halt further testing of the specific test set-up.

g) At minimum record the following data:
   1. Laboratory exhaust mass and volume flow rate (kg/hr)
   2. PEMS indicated exhaust mass and volume flow rate (kg/hr)
   3. Engine speed (rpm) and engine torque (N-m)
   4. Engine intake air mass flow rate (kg/hr)
   5. Engine fuel consumption mass rate (kg/hr)

h) Do not record raw PEMS gaseous emissions unless the PEMS requires these measurements in order to report the exhaust flow rate.

i) Expected test matrix time duration:
   3 min/point x 10 points x 5 repeats = 150 min (or 2.5 hrs) per test configuration
   3 Test configurations = 3 x 2.5 hrs = 7.5 hrs per PEMS
   2 PEMS evaluations = 2 x 7.5 hrs = 15 hrs = total engine running time.

Allocate additional time for fabrication of needed test set-up components, installation of the PEMS exhaust flow sensors, and pre-test instrumentation check-out.

3.4.3.1 Pulsation Test

Utilizing the exhaust configuration used in Section 3.2.3 (sensor bias and precision evaluation), remove the aftertreatment device and replace it with an unobstructed full flow exhaust pipe of the same diameter as the entrance and exit of the aftertreatment device. The intent of this set-up is to expose the exhaust flow sensor to higher pulsations than found in typical exhaust systems by eliminating the pulse attenuating characteristics of the aftertreatment device.
Conduct the testing following the provisions of Section 3.4.3 items (g-n).

3.4.3.2 Non-Uniform Velocity Test (swirl)

Utilizing the same exhaust configuration used in Section 3.2.3, (including the aftertreatment device), install two 90º elbows connected in series, in non-parallel planes, immediately upstream of the exhaust flow metering device supplied by the PEMS manufacturer. Connect the two elbows together in a manner such that their axial planes are 90º to each another. The intent of this set-up is to induce swirl into the exhaust flow stream to produce non-uniform flow velocity profiles across the exhaust pipe prior to the PEMS flow metering system.
Conduct the testing following the provisions of Section 3.4.3 items (g-n).

3.4.3.3   Tailpipe Wind Test

a) For this test set-up utilize an exhaust system set-up in which the exhaust can freely exit the PEMS flow metering device and form a typical exhaust plume. Utilize the same exhaust configuration utilized in Section 3.2.3., including the aftertreatment device.
b) Operate the engine at the exhaust flow rates established in Section 3.4.3 item d (10 NTE test points). For each of these test points, use a common leaf blower, or perhaps a carpet dryer blower (or other high velocity/high volume air source) to blow air across the tailpipe exit in an attempt to see if the PEMS indicated exhaust flow rate shows any noticeable change.
c) Set the test-points by directing the high velocity air at the tailpipe exit from a wide variety of angles, perpendicular and non-perpendicular to the exhaust axial flow.
d) Adapt to the blower exit and connect a flexible hose, of at least 5 in. dia. Attach to the flexible hose a short section of solid thin-wall tubing (material of steel, aluminum, or plastic), that will provide the ability to be portable and direct the air flow at the exhaust plume from various directions. The outlet of the blower, at the point the air is directed at the exhaust plume, should be at least 5 in. diameter.
e) Ensure that the air velocity directed on the exhaust plume is in the range of 60-65 mph (88 ft/sec – 95 ft/sec). A second PEMS exhaust flow sensor may be useful in determining the blower air velocity.
f) At each test point, obtain two 30 sec. average data logs of the PEMS indicated flow rate. Obtain one average log without the blower air impinging on the exhaust plume, and obtain a second log with the blower air impinging on the exhaust plume.

Notes:
g) The intent of this effort is to detect any significant change in the exhaust flow rate reported by the PEMS due to the air being blown across the tailpipe. If initial efforts do not show significant changes, this phase of the test program is to be terminated.
h) However, should the PEMS exhaust flow sensor show sensitivity to air currents moving across the tailpipe exit, this information is to be noted and communicated to the project director in a timely manner. In such a case, request discussions with the steering team to determine if more extensive and quantitative testing is warranted.

3.4.4 Data Analysis

3.4.4.1   Pulsation and Swirl Effects -- Data Analysis

a) For each test matrix data point, calculate the difference between the PEMS reported exhaust flow rate and the flow rate reported by the baseline PEMS data reported for Section 3.2.3. This will be an indication of potential biases due to exhaust flow-meter configuration
b) Also calculate the difference between the PEMS reported exhaust flow rate and the Laboratory reported exhaust flow rate. If the magnitude of these differences are similar to those measured under section 3.2, then the effect of these configuration factors is negligible.

c) Use the data in (a) above to create the "error surfaces" to be used by the Monte Carlo simulation. Refer to section 2.4 for the description and an example of an error surface. Using Figure 2.4-(c) as reference, create the error surfaces for exhaust flow configuration bias errors using the parameters indicated in the table below (Table 3.4.4.1-a). Note that examples are given only for exhaust mass flow, but the same could be used for volumetric flow rate if needed:

Table 3.4.4.1-a: Exhaust Flow Configuration Error Surfaces (Refer to section 2.4)

Error Surface for Pulasation effects on Exhaust Mass Flowrate

Fig 2.4-a

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	exh_flow (pems,pulse) / exh_flow_max -[%]

Fig 2.4-b

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	[exh_flow (pems,pulse) - exh_flow(pems,ss)] / exh_flow_max -[%]

Fig 2.4-c

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	$i_{c\_cfg\_pulse}$
z-axis = Δ_{cfg_pulse}	[exh_flow (pems,pulse) - exh_flow(pems,ss)] / exh_flow_max -[%]
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance to roll any number between -1 to +1)

Note: exh_flow_max = PEMS flowmeter maximum exhaust flowrate (@ max density)

Error Surface for Swirl effects on Exhaust Mass Flowrate

Fig 2.4-a

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	exh_flow (pems,swirl) / exh_flow_max -[%]

Fig 2.4-b

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	[exh_flow (pems,swirl) - exh_flow(pems,ss)] / exh_flow_max -[%]

Fig 2.4-c

x-axis	exh_flow (pems,ss) / exh_flow_max -[%]
y-axis	$i_{c\_cfg\_swirl}$
z-axis = Δ_{cfg_swirl}	[exh_flow (pems,swirl) - exh_flow(pems,ss)] / exh_flow_max -[%]
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance to roll any number between -1 to +1)

Note: exh_flow_max = PEMS flowmeter maximum exhaust flowrate (@ max density)

3.4.4.2 Tailpipe Wind Velocity Effects – Data Analysis

Create a table showing the following information:

Test Point Number	Blower Orientation Description	PEMS Flow No Wind kg/hr	PEMS Flow with Wind kg/hr	Difference w/wind – no wind $\Delta_{cfgwind}$
1	90º to axial flow | horizontal to exhaust pipe			
2	45º to axial flow | horizontal to exhaust pipe			
3,4,5,…8,9				
10				

If the differences are of a magnitude equal to or greater than 1%, call a meeting with the in-use testing steering team, to decide how to proceed in the creation of an error surface for tailpipe wind velocity effects.

3.5 ECM Torque and BSFC

3.5.1 Objective

Evaluate the performance of engine torque and BSFC through ECM-based parameters (speed, fuel commanded).
Evaluate bias and precision errors from ECM-broadcast Torque and BSFC. Determine the Δ_{cfg_pulse} and Δ_{cfg_swirl} surface plots for the error model.

This part of the test program relies on data acquired from section 3.2 for Torque and BSFC mapping.

3.5.2 Background

Data for this section will come from two sources: contractor engine dynamometer testing and the engine manufacturers themselves. Additional errors not evaluated at the contractor's will be evaluated at engine manufacturer labs (involving testing that would be considered confidential for each engine manufacturer). Examples of such errors include, among others, non-deficiency AECD strategies that are not captured in the contractor's evaluation, and others, as listed in Task 3.5.2.5. Note that the accuracy of the torque/BSFC maps is only relevant to in-use emissions testing when under the NTE zone, and in operating conditions not declared as deficiencies. Also, it is not the intent of this task to "minimize" torque/BSFC mapping errors by developing more sophisticated mapping techniques as that would impose new demands in normal engine development processes, for every engine rating.

During this section, five different tasks will be used to evaluate the impact of various parameters on the accuracy of ECM-broadcast torque and BSFC (maps). The first four will be performed at a contractor's facility. The first task will evaluate parameters that are likely to interact with each other, and thus a Design of Experiments (DOE) approach will be used. The second task will evaluate temperature-related parameters that cannot be independently controlled, using an engine warm-up test. The third task will evaluate parameters that are not likely to have strong interactions, using a sensitivity analysis. The fourth task will evaluate the effect of interpolating torque and BSFC from discrete data sets of (speed, fuel, torque) and (speed, fuel, BSFC). The fifth task is open-ended in that manufacturers have the option to submit additional data for consideration for an additional Δ in the error model. The parameters to be used in the investigation of their corresponding effects on torque/BSFC map accuracy are listed below:

Task 1: (1) Intake air restriction; (2) Exhaust gas restriction; (3) Barometric pressure (altitude); (4) Charge air cooler out temperature
Task 2: (1) Oil viscosity (weight); (2) Fuel temperature; (3) Oil temperature; (4) Coolant temperature
Task 3: (1) Intake air humidity; (2) Fuel properties (cetane number, viscosity, API density, etc.)
Task 4: (1) Estimation of engine torque/BSFC through ECM-based parameters

Task 5: (1) Non-deficiency AECD strategies that are not captured by the contractor's evaluation; (2) Effect of multi-torque engine software on torque/BSFC maps; (3) Effect of production variability on torque/BSFC; (4) Effect of engine deterioration on torque/BSFC; (5) Any parameters not covered under 3rd party lab testing that are deemed important by any engine manufacturer.

Note 1:   All measurements uncertainties associated with Task 5 are the burden of the engine manufacturers only. If engine manufacturers fail to provide this data 1 month before the beginning of the validation testing tasks (section 5), a zero contribution to the torque/BSFC error will be assessed under this task.

3.5.2.1   Interacting parameters - DOE

The DOE will evaluate the effect of the following parameters on torque/BSFC map errors:
(1) intake air restriction; (2) exhaust gas restriction; (3) barometric pressure (altitude); (4) Charge air cooler out temperature.   Only operating conditions not declared as deficiencies will be evaluated.

3.5.2.2   Interacting parameters – Warm-up

The warm-up test will evaluate the effect of the following parameters on torque/BSFC map errors:
(1) oil viscosity (weight); (2) fuel temperature; (3) oil temperature; (4) coolant temperature

3.5.2.3   Independent parameters

The sensitivity test will evaluate the effect of the following parameters on torque/BSFC map errors:
 (1) intake air humidity; (2) fuel properties (cetane number, viscosity, API density, etc.)

3.5.2.4   Interpolation

The HDIU testing program will not require ECMs to be programmed to transmit torque and BSFC values, which are needed for the work calculation as well as the calculation of brake-specific emissions. It was determined that this requirement would place an unnecessary burden on the engine manufacturers, who are only required to test a relatively small number of engines each year for this program (25% of an engine manufacturer's families, with a maximum of 20 vehicles tested per family). Instead, torque and BSFC will be mapped as a function of speed and fuel commanded with the engine installed in a dyno prior to any in-use testing of the same engine family and rating. Data for the mapping exercise is actually acquired as part of section 3.2. Since the mapping process is time consuming and is required for each engine family and rating tested in the HDIU testing program, it would be advantageous to reduce the number of points required for a torque/BSFC map to a minimum, striking a balance between mapping effort and limiting errors due to linearly interpolating torque and BSFC on a coarser grid. Map interpolation errors will be quantified in this task.

3.5.2.5   Other parameters

As stated above, each engine manufacturer will be responsible for this task, and thus the structure of testing and reporting will be communicated as CBI (confidential business information) to the EPA.

A list of anticipated parameters (not all inclusive) envisioned being a part of this task is shown below:
Non-deficiency AECD strategies that are not captured by tasks 1-4 above
Effect of multi-torque engine software on torque/BSFC maps
Effect of production variability on torque/BSFC
Effect of engine deterioration on torque/BSFC
Any parameters not covered under 3rd party lab testing

The methods and materials for evaluating these "other parameters" are left up to the individual manufacturers to determine.

EPA and CARB will accept manufacturer–supplied information for an additional allowance according to the terms agreed upon in the Memorandum of Agreement.

3.5.3 Methods and Materials

Use the following systems:
a) Two (2) heavy duty diesel engines (1 HHDE, 1 LHDE) for Subtask 3.5.2.1.
b) Three (3) heavy duty diesel engines (1 HHDE, 1 MHDE, 1 LHDE) for Subtask 3.5.2.2.
c) One (1) heavy duty diesel engine (1 MHDE) for Subtask 3.5.2.3.
d) Three (3) heavy duty diesel engines (1 HHDE, 1 MHDE, 1 LHDE) for Subtask 3.5.2.4.
e) Each engine will be mapped as per section 3.2 It is likely that these data points will be down sampled to 20 points to create the map for each engine.

3.5.3.1   Interacting Parameters Test - DOE

a) Evaluate torque/BSFC map errors due to intake air restriction, exhaust gas restriction, barometric pressure, and charge air cooler out temperature using a Design of Experiments (DOE) test matrix (half factorial), with resolution IV, 4 factors, and 1 center point (9 pts).
b) Evaluate each parameter two conditions (min and max) plus a center point, to investigate nominal conditions.
c) Evaluate accuracy of the Torque and BSFC map under five (5) steady-state engine operating conditions, as shown in Table 3.5.3.1-a (which are a subset of the 40-point map evaluated in Task 3.2)
d) For each operating condition, use closed loop control on engine speed and load cell torque.
e) At each condition, measure torque, fuel flow rate, and BSFC. Also, record ECM speed and fuel commanded (in order to infer broadcast torque and BSFC).

f) This will result in a total number of points of 9 x 5 = 45 / engine. No repeats of this test are needed, unless necessary to establish that the precision error is less that the variability for the above task.
g) Use the parameter settings given in Table 3.5.3.1-b for the DOE matrix
h) Note that this test must be performed in an altitude cell so that barometric effects may be studied. For example, hook up a CVS tunnel to simulate the barometric pressures at engine inlet and exhaust.

Table 3.5.3.1-a: DOE Engine Operating Conditions (%speed, and %torque respectively)				
17%, 32%	100%, 100%	59%, 49%	100%, 32%	100%, 100%

Table 3.5.3.1-b: DOE Parameter Set Points		
Parameter	Minimum	Maximum
Intake air restriction	Minimum capable[*]	Max. allowed by manufacturer[*]
Exhaust gas restriction	Minimum capable[*]	Max. allowed by manufacturer[*]
Barometric pressure	82.7 kPa	105 kPa
Charge air cooler out temperature	Minimum per manufacturer specifications and ambient conditions[**]	Maximum per manufacturer specifications and ambient conditions[**]

[*]Consider removing aftertreatment to extend range of restrictions
[**]Assume that a 1 deg. change in ambient temperature corresponds to a 1 deg. change in charge air cooler out temperature

3.5.3.2   Interacting Parameters Test - Warm-up

a) Evaluate torque/BSFC map errors due to oil viscosity (weight), fuel temperature, oil temperature and coolant temperature.
b) Since these parameters cannot easily be independently controlled, they will be evaluated during an engine warm-up cycle.
c) Install the Caterpillar (non-EGR) engine in cell capable of controlling ambient temperature, preferably at 0 deg C [this may be not feasible]. Warm up the engine until the coolant temperature reaches above 212 deg. F.
d) Install the International and DDC engines will be installed in a standard test cell at ambient temperature, and perform the same type of warm up test.
e) You will receive the speed/torque schedule to be used during the warm-up cycle from the CSTF in-use testing steering team.
f) Sample engine torque at 5 Hz and fuel flow at 1 Hz (per Part 1065 recommendations)
g) Record fuel temperature, oil temperature, and coolant temperature, along with the ECM channels of speed and fuel commanded.
h) Resample and/or bin data as deemed appropriate.

i) Record data throughout the engine warm-up, but use only data obtained when the engine's operating conditions meet the criteria for a valid NTE event, for the measurement allowance.

j) Warm up all three engines in the same manner, which is to be established by the contractor and agreed on by the engine manufacturers. This test does not need to be repeated, unless it becomes necessary to establish that the precision error is less that the variability for the above task.

3.5.3.3 Independent Parameters Test

a) Evaluate torque/BSFC map errors due to intake air humidity and fuel properties (cetane number, viscosity, API density, etc.) using a sensitivity analysis with 5 total points.

b) Evaluate each parameter at two or three conditions (min, mid and max, or 1 and 2).

c) Set engine to three (3) steady state operating conditions which are a subset of those tested in Task 3.5.3.1. and given in Table 3.5.3.3-a.

d) For each operating condition, use closed loop control on engine speed and load cell torque.

e) At each condition, measure torque, fuel flow rate, and BSFC. Also, record ECM speed and fuel commanded (in order to infer broadcast torque and BSFC).

f) This will result in a total number of points of 5 x 3 = 15 data pts/ engine.

g) Use parameter settings specified in Table 3.5.3.3-b.

h) Perform only minimal repeat testing to establish that the precision error is less than the variability observed in the above subtasks, as explained in Note 3.

i) Note: One or two additional sensitivity parameters may be added to Table 3.5.3.3-b. In that case you will be asked to test those conditions also. The steering committee will finalize any additional sensitivity parameters prior to signature of the Memorandum of Agreement. If no additional parameters are added prior to Memorandum of Agreement signature, additional parameters may be added by written mutual agreement of all parties.

Table 3.5.3.3-a: Sensitivity Engine Operating Conditions (%speed, and %torque respectively)		
17%, 32%	59%, 49%	100%, 100%

Table 3.5.3.3-b: Sensitivity Parameter Set Points			
Parameter	Minimum (#1)	Mid. (#2)	Maximum (#3)
Intake air humidity	Minimum possible (@30 deg. C); 0 grains/lb dry air	50% RH (@30 deg. C); 95 grains/lb dry air	95% RH (@30 deg. C)[*]; 180 grains/lb dry air
Fuel properties	Fuel used in program	Fuel selection #2	California ULSD

[*]Run charge air cooler water inlet temperature of 30 deg. C

3.5.3.4 Interpolation Test

a) Evaluate torque/BSFC errors due to interpolating map values.

b) To quantify interpolation errors, down-sample the 40 steady-state points taken in Task 3.2 to 20 points (used to create the torque/BSFC maps)

c) Quantify interpolation errors by subtracting the subset of the 40 points that were NOT used to create the 20-point map.

Note 3: the methodology used in the preceding tasks does not separate bias and precision errors. Both types of errors will be coupled together. In order to better assess precision errors, repeat testing would be necessary. However, it is expected that the variability in ECM mapped torque and mapped BSFC will be greater than the precision interval on a repeated test for the above Subtasks . It is also expected that the precision error (as percent of point) in Subtask 3.5.2.3 will be less than the variability interval (as percent of point) of Subtask 3.5.2.1.

If this does not hold, a modification to the test plan may be needed, which may include repeated testing.

3.5.4 Data Analysis

Use the acquired data to create the "error surfaces" to be used by the Monte Carlo simulation. Refer to section 2.4 for description and example of an error surface.

Assume the errors to be independent and additive unless determined otherwise. The following sub-sections will describe the error surfaces for ECM-based torque. Construct BSFC models in a similar fashion, based on BSFC data.

Determine mean of the ten steady-state torque variances, where each of the ten variances is calculated from the 20 repeats of each of the points in the 10-point steady-state matrix in 3.2.3. Subtract this mean torque variance from each of the respective ECM deltas.

3.5.4.1 Interacting Parameters Analysis DOE

Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference, create the error surface Δ_{Torque_DOE} using the parameters indicated in Table 3.5.4.1-a.

Tables 3.5.4.1 through 3.5.4.6: Torque Error Surfaces

Table 3.5.4.1-a: Error Surface for Torque (interacting parameters - DOE)	
Fig 2.4-a	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map)
Fig 2.4-b	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	% Peak Torque (load cell)
y-axis	$i_{c\_Torque\_DOE}$
z-axis = $\Delta_{\%Torque\_DOE}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance for i_c: -1 to +1)
Data:	All parameters sampled in DOE matrix

Table 3.5.4.2-a: Error Surface for Torque (interacting parameters - warm up)	
Fig 2.4-a	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map)
Fig 2.4-b	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	% Peak Torque (load cell)
y-axis	$i_{c\_Torque\_warm-up}$
z-axis = $\Delta_{\%Torque\_warmup}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance for i_c: -1 to +1)
Data:	warm-up cycle. Discretize data at different torque levels

Table 3.5.4.3-a: Error Surface for Torque (independent parameters - humidity)	
Fig 2.4-a	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map)
Fig 2.4-b	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	% Peak Torque (load cell)
y-axis	$i_{c\_Torque\_hum}$ [Discrete Range: 1,or 2, or 3]
z-axis = $\Delta_{\%Torque\_hum}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance for i_c: 1, or 2, or 3)
Data:	3 different humidity levels will need to be pooled at each of the 3 torque levels

Table 3.5.4.3-b: Error Surface for Torque (independent parameters - fuel type)	
Fig 2.4-a	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map)
Fig 2.4-b	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	% Peak Torque (load cell)
y-axis	$i_{c\_Torque\_fuel}$ [Discrete Range: 1,or 2, or 3]
z-axis = $\Delta_{\%Torque\_fuel}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance for i_c: 1, or 2, or 3)
Data:	3 different fuel types will need to be pooled at each of the 3 torque levels

Table 3.5.4.4-a: Error Surface for Torque (interpolation effects)	
Fig 2.4-a	
x-axis	single point
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-b	
x-axis	single point
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	single point
y-axis	$i_{c\_Torque\_intp}$
z-axis = $\Delta_{\%Torque\_intp}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	once per NTE event
i_c sample distribution	random (same chance for i_c: -1 to +1)
Data:	results from all 20 points will be pooled under a single point in the x-axis (unless data shows clear trend with

Table 3.5.4.5-a: Error Surface for Torque (engine manufacturer data)	
Fig 2.4-a	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map)
Fig 2.4-b	
x-axis	% Peak Torque (load cell)
y-axis	% Peak Torque (ECM map) - % Peak Torque (load cell)
Fig 2.4-c	
x-axis	% Peak Torque (load cell)
y-axis	$i_{c\_Torque\_eng-man}$
z-axis = $\Delta_{\%Torque\_eng-man}$	% Peak Torque (ECM map) - % Peak Torque (load cell)
i_c sample frequency	to be specified by engine manufacturer
i_c sample distribution	to be specified by engine manufacturer
Data:	to be specified by engine manufacturer

3.5.4.2   Interacting Parameters Analysis – Warm-up

Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference, create the error surface Δ_{Torque_warmup} using the parameters indicated in Table 3.5.4.2-a.

3.5.4.3   Independent Parameters Analysis

Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference:

a)   create the error surface Δ_{Torque_hum} using the parameters indicated in Table 3.5.4.3-a

b) create the error surface Δ_{Torque_fuel} using the parameters indicated in Table 3.5.4.3-b

3.5.4.4   Interpolation Analysis

Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference, create the error surface Δ_{Torque_intp} using the parameters indicated in Table 3.5.4.4-a.

3.5.4.5   Analysis for Torque/BSFC errors provided by engine manufacturers

Refer to section 2.4 for description and example of an error surface. Using Figure 2.4-(c) as reference, engine manufacturers can create the various error surfaces $\Delta_{Torque\_eng-man}$ using the parameters indicated in Table 3.5.4.5-a.

It must be emphasized that these error surfaces will not be determined by the contractor. Engine manufacturers can supply as many error surfaces as deemed appropriate, so long as they back up their claims with data and/or engineering judgment. This data and error surfaces must be supplied by the engine manufacturers to the contractor on or before one month prior to the beginning of the validation test work (section 5)

4 Environmental Chamber Tests

The environmental chamber tests challenge PEMS to a variety of environmental disturbances, namely electromagnetic interference, atmospheric pressure, ambient temperature, vibration, and ambient hydrocarbons. During each of the tests, plus a baseline test, PEMS will sample a series of reference gases, and errors quantifying the reference values will be calculated. Each test is designed to mimic real-world environmental disturbances with the magnitude and frequency of the disturbance adjusted to real-world conditions. Because of this, error from these tests can be sampled randomly, 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.

All of the testing will be done with reference gases during application of the ambient conditions. All tests will use the same gases, except for the ambient hydrocarbons test. The following tables list the gases:

Table 4-a: Gas Cylinder Contents for 5 of 6 Environmental Tests	
Gas	Number of AL size cylinders[1]
1. purified air	5, +1 spare
2. quad-blend span: CO2, CO, NO, C3H8, balance N2	5, +1 spare
3. CH4 span, balance N2	5, +1 spare
4. NO2 span, balance N2	5, +1 spare
5. quad-blend audit: CO2, CO, NO, C3H8, balance N2	5, +1 spare
6. CH4 audit, balance N2	5, +1 spare
7. NO2 audit, balance N2	5, +1 spare
[1]AL size compressed gas cylinders are high pressure (2000 psi full) and hold 29.5 liters of water. Considering the compressibility (Z) of certain gases, a safe approximate supply from one full AL cylinder is 4,000 liters at atmospheric conditions. Assuming 6 PEMS consuming 40 lpm total for a given test, times 8 hr 20 min equals 20000 liters per day or 5 cylinders per day. Because a minimum of 7 cylinders are used each day (one for each of 7 mixtures), only 1 of each cylinder is needed per day—as long as full cylinders are used each day.	

N2 is not in the gas cylinder matrix as a zero quantity since N2 would be just like the CH4 or NO2 cylinders for the other gases, and the quad-blends are just like N2 for CH4 and NO2. Gas cylinder concentrations will be selected so that the audit values are near the flow-weighted average concentration of emissions in the raw exhaust at the NTE standards, span values will be about twice the audit values, NO2 will be at half the concentration of NO, and CH4 will be at half the concentration of C3H8. The gas cylinders purity and accuracy do not have to meet 1065 Subpart H specifications because PEMS outputs will only be used for relative differences.

Table 4-b: Gas Cylinder Contents for Ambient Hydrocarbons	
Gas	Number of AL size cylinders[1]
1. purified air	2, +1 spare
2. C6H14 span, balance N2	2, +1 spare
3. CH4 span, balance N2	2, +1 spare
[1]AL size compressed gas cylinders are high pressure (2000 psi full) and hold 29.5 liters of water. Considering the compressibility (Z) of certain gases, a safe approximate supply from one full AL cylinder is 4,000 liters at atmospheric conditions. Assuming 6 PEMS consuming 40 lpm total for a given test, times 8 hr 20 min equals 20000 liters per day or 5 cylinders per day. Because a minimum of 3 cylinders are used each day (one for each of 3 mixtures), 2 of each cylinder are needed to complete the test day.	

Cylinder concentrations of the ambient hydrocarbons will be selected to allow adjustment to the concentrations specified in the ambient hydrocarbons test cycle.

4.1 Data Analysis for all Environmental Tests

Refer to the spreadsheet prepared for performing this data analysis. The spreadsheet describes the schedule to be used with the various gas bottles, during the 8hr (480min) tests. Reduce data by first calculating means for each 30-second period of stabilized measurements. Subtract from each mean the respective reference concentration. The results are errors or "deltas". Group the errors by the categories of zero errors, mid-span errors, and span errors. Correct each of these three error distributions by removing their respective baseline biases and variances, which were determined in section 4.1. To remove the baseline bias from each distribution, subtract the respective median baseline error from each of the errors in each respective distribution. This shifts each error distribution to null out any respective baseline zero, mid-span, or span bias. Next 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, set all error values of the distribution to the corrected bias value 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 bias and variance.

Sample the errors by randomly selecting a number between 1 and 480, which represent the minutes of the actual test. For the selected minute, record the most recent past set of baseline corrected errors for each emission. Wrap backwards to the end of the data set (i.e. 480) if a complete set of recent errors are not available. Do this by going backward from minute 1.

For each nominal NTE event, randomly sample one minute's error. Then, second-by-second use the nominal second-by-second concentrations to linearly interpolate between the respective zero, mid-span, and span error values for each emission as a function of concentration to find the error associated with that second's nominal concentration.

Apply this error as a "delta" to the nominal concentration for that second. Calculate the brake-specific NTE event once all errors are applied.

Next calculate whether or not a periodic drift check would have invalidated the NTE event. Simulate drift check results by subtracting from each of the zero, mid-span, and span error values a single delta that would result in the zero error value being zero. Then subtract from the span error a value that would result in the span error being zero. Divide that value by the span reference value, multiply it by the mid-span reference value and subtract the result from the mid-span error. The results are three values for zero, mid-span, and span error, where zero and span errors are zero. The mid-span may have a positive or negative value, which would indicate a non-linearity that was not checked by the pre-test 0-span maneuver. Use the three values to recalculate the NTE event, but use all of the other original flow and torque errors. If the NTE result with all of the errors applied is more than ±4% different than the NTE event with the errors decreased, discard the results. Then calculate the NTE result with all errors, including torque and flow errors set to zero. This is the true value. Then for each of the validated results, subtract the true NTE value and record this difference in one of the eighteen measurement allowance distributions: three emissions (NOx, CO, NMHC) times three calculation methods (torque-speed, fuel-specific * BSFC, ECM fuel flow) times two PEMS manufacturers. Then proceed to the next NTE event in the nominal data set. Repeat the entire nominal data set over and over until all 18 measurement allowance distributions converge. Follow the data reduction steps set out in Section 2 to select the final measurement allowances.

4.2 Baseline

4.2.1 Objective

Evaluate the baseline repeatability and bias of PEMS with ambient conditions held constant. Determine the medians and variances for each baseline error for each emission. Use the medians and variances to correct all other environmental test results according to Section 4.1, Data Analysis for All Environmental Tests.

4.2.2 Background

All of the other environmental tests inherently incorporate the baseline bias and 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 bias and variance of PEMS to the model too many times. In order to compensate for this in the model, the baseline bias and variance of PEMS is determined and subtracted from each of the environmental tests' results.

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

4.2.3 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 all 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.

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, zero-span-audits of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc. Then supply the PEMS' overflow sample ports with the sequence of gases from the seven gas cylinders described at the beginning of Section 4.

Flow each cylinder 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 1 minute per cylinder (30 seconds to stabilize + 30 seconds to record stable readings), or 7 minutes to cycle through all 7 cylinders. Repeat this 7-minute cycle over the 8-hr test cycle. Note that this results in about 68 repeats per cylinder.

Perform this test once for each of the six PEMS with as many PEMS tested at once. Test at least one PEMS from each PEMS manufacturer simultaneously so at most repeat this test three times to test each of the three pairs of PEMS once.

Zero and span PEMS at beginning of day following manufacturer's guidelines. Do not re-span PEMS analyzers again during the day, unless PEMS manufacturer provides a way to do this automatically, so it is realistic with real-life in-use testing practices. Re-zeroing should be allowed if and only if done automatically by the PEMS for the same reasons.

4.2.4 Data Analysis

Reduce data by first calculating means for each 30-second period of stabilized measurements. Subtract from each mean the respective reference concentration. The results are errors or "deltas". Group the errors by the categories of zero errors, mid-span errors, and span errors for each emission. Calculate each error distribution's median and variance and use these values in the data reduction of the remaining environmental tests.

4.3 Electromagnetic Radiation

4.3.1 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. Determine Δ_{EMI}.

4.3.2 Background

The performance of the PEMS could be affected by being in a vehicle which is traveling on the roadway and is subject to interferences from surrounding EMI/RFI signals – from the vehicle itself and from items external to the vehicle.

There were many EMI/RFI tests considered for this program. They include the following list

1. Radiated Immunity – This test method is used to verify the ability of the PEMS and associated cabling to withstand electric fields
2. Radiated Emissions – This test method is used to verify that the electric field emissions from the PEMS and its associated cabling do not exceed specified requirements
3. Conducted Immunity – This test method is used to verify the ability of the PEMS to withstand signals coupled onto input power leads
4. Conducted Emissions – This test method is used to verify that electromagnetic emissions from the PEMS do not exceed the specified requirements for power input leads, including returns
5. Electrostatic Discharge – This test method is used to verify the ability of the PEMS to withstand electrostatic discharge from the human body
6. Conducted Transient Immunity – This test method is used to verify the ability of the PEMS to withstand electrical transients
7. Electrical fast transients – This test method is used to verify the ability of the PEMS and associated cabling to withstand short transients
8. Surge Immunity – This test method is used to verify the ability of the PEMS and associated cabling to withstand surges caused by switching and lightning transients
9. Alternator Noise – This test method is used to verify the ability of the PEMS to withstand transients where voltage differences are developed across different current return paths through the chassis
10. Magnetic field immunity – This test method is used to verify the ability of the PEMS and associated cabling to withstand magnetic fields resulting from nearby wiring carrying high current.

After consulting with an expert at The contractor facility, four tests were selected based on SAE standards. Those tests are listed below along with a time estimate for each test.

Standard	Description	Calibration Time	Test time
J1113-4	Bulk Current Injection	0.5 day	1 day
J1113-11	Conducted Transients		0.5 day
J1113-13	Electrostatic Discharge		0.5 day
J1113-21	Radiated Immunity	1 day	1 day

4.3.3 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.

Because of the length of these tests, test only one PEMS from each of the two manufacturers. Normally these tests are run separately on each unit under test. Under this scenario, it will take 4.5 days for each PEMS for a total of 9 days.   This does not include PEMS set up time. Test multiple PEMS simultaneously on the -4 and -21 tests if the EMI facility can accommodate multiple PEMS. If both PEMS can be tested together on the -4 and -21 tests, then the estimated test time for both PEMS drops to 5.5 days. Since the PEMS output is not expected to deteriorate with prolonged exposure to EMI tests, the test times for any of the four tests may be reduced to the time it takes to collect at least 30 samples of each of the seven gas cylinders. This is only appropriate for EMI tests that have either steady inputs or repetitive input cycles 30 seconds or shorter.   If it takes 7 minutes to sample all 7 cylinders, then the test time for each test needs to be at least 210 minutes (3.5 hrs). For EMI tests that sweep the input, run the full test time. There is no requirement to synchronize the sweeping of EMI inputs with the sampling of gases.   Suspend the PEMS data logging whenever the EMI inputs are suspended to adjust parameter or conditions such as antennas.

Where the standard includes various severity levels, choose the one most appropriate for the purpose of this program, which is to subject the unit under test to typical levels for normal operation (normally the lowest severity level).

For each EMI test, setup the PEMS according to 40CFR1065, Subpart J and the PEMS manufacturer instructions, including any warm-up time, and zero-spans of the analyzers. Begin the data logging functions, then begin the EMI inputs, then supply the PEMS' overflow sample ports with the sequence of gases from seven gas cylinders described in the beginning of section 4. Flow each cylinder long enough so that at least 30 seconds of stabilized readings are recorded for the slowest responding analyzer. Target to sample about 1 minute from each cylinder (30 seconds to stabilize and 30 seconds to record stable readings), or 7 minutes to cycle through all 7 cylinders. Repeat this 7-minute cycle over the duration of each test.

4.3.4 Data Analysis

Subtract baseline variances according to Section 4.1. Also, when subtracting the baseline biases and variances at zero, mid and span levels, use the baseline data from the same PEMS under test. Treat each set of EMI test results as part of a single environmental test. In other words, after calculating baseline adjusted deltas for zero, audit and span, pool all zero, audit, and span deltas, respectively. Then use the same error surface generation technique that was used in Section 3 for the engine dynamometer tests, where the error is ranked from 5th to 95th percentile and centered with the truncated normal PDF at the 50th percentile error.

Table 4.3.4-a: EMI / RFI Pooled Error Surface

Error Surface for EMI/RFI effect on NOx concentration (Repeat for CO and NMHC)	
Fig 2.4-a	
x-axis	NOx ppm (pems, nom)
y-axis	NOx ppm (pems,EMI)
Fig 2.4-b	
x-axis	NOx ppm (pems, nom)
y-axis	NOx ppm (pems,EMI) - NOx ppm (pems,baseline)
Fig 2.4-c	
x-axis	NOx ppm (pems, nom)
y-axis	$i_{c\_EMI\_pooled\_NOx}$ [Range: $t_{initial}$ through t_{final}]
z-axis = $\Delta_{EMI\_pooled\_NOx}$	NOx ppm (pems,EMI) - NOx ppm (pems,baseline)
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

4.4 Atmospheric Pressure

4.4.1 Objective

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

a) Determine Δ_{P_NOx}, Δ_{P_NMHC}, and Δ_{P_CO}, as a function of test time and concentration for use in the error model.

b) Also determine $\Delta_{P\_exhflow}$ as a function of test time only. This error only needs to be quantified if the flow meter zero flow reading during these tests change due to various atmospheric pressures.

4.4.2 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. The following table depicts the NEI data distribution (based on 3149 data points) and the test cycle pressure distribution.
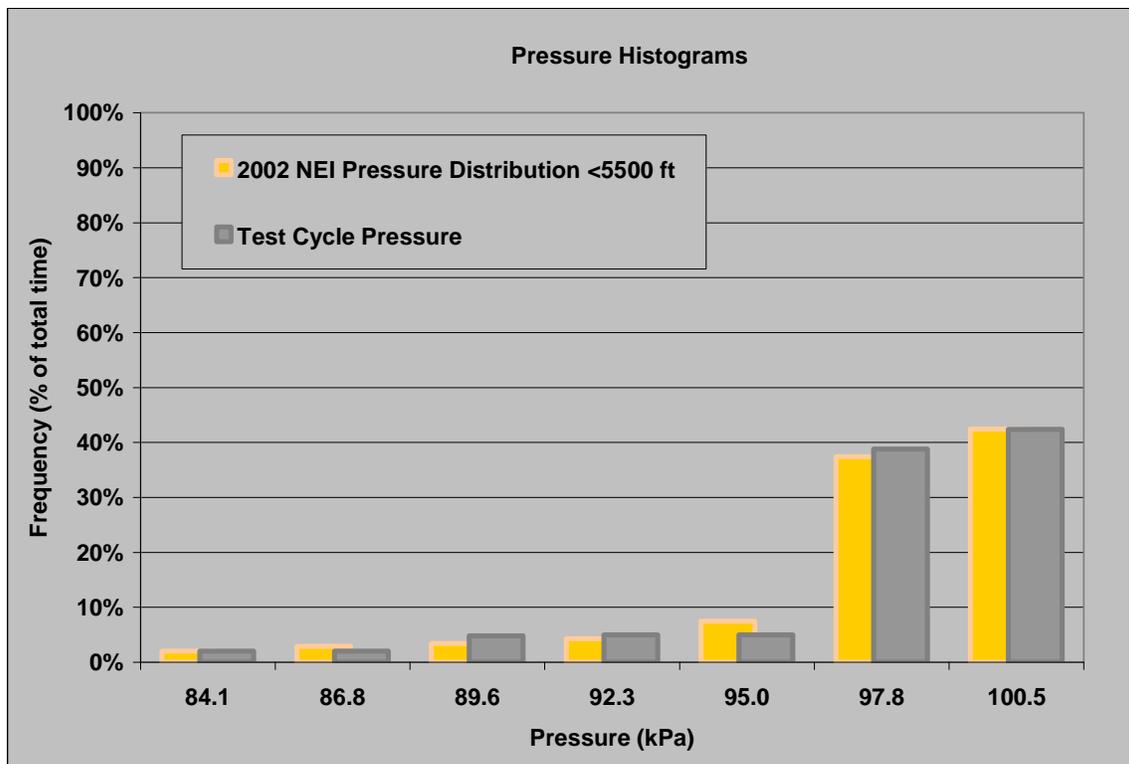
4.4.3 Methods and Materials

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 two PEMS at a time, one of each PEMS manufacturer, 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 pressure, then ramp the pressure to a new pressure, soak the PEMS at that new pressure, and then ramp to another pressure. Use the following sequence of pressures and times 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>
<tr><th colspan="6">Atmospheric Pressure Test Sequence</th></tr>
<tr><td rowspan="2">Phase</td><td colspan="2">Pressure</td><td>Time</td><td>Rate</td><td rowspan="2">Comments</td></tr>
<tr><td>kPa</td><td>Alt. ft.</td><td>min</td><td>ft/min</td></tr>
<tr><td>1   Soak</td><td>101</td><td>89</td><td>10</td><td>0</td><td>Flat near sea-level</td></tr>
<tr><td>2   Ramp</td><td>101-97</td><td>89-1203</td><td>20</td><td>56</td><td>Moderate hill climb from sea level</td></tr>
<tr><td>3   Soak</td><td>97</td><td>1203</td><td>20</td><td>0</td><td>Flat at moderate elevation</td></tr>
<tr><td>4   Ramp</td><td>97-101.87</td><td>1203- -148</td><td>60</td><td>-23</td><td>Moderate descent to below sea level</td></tr>
<tr><td>5   Soak</td><td>101.87</td><td>-148</td><td>20</td><td>0</td><td>Flat at extreme low elevation</td></tr>
<tr><td>6   Ramp</td><td>101.87-101</td><td>-148-89</td><td>20</td><td>12</td><td>Moderate hill climb to near sea level</td></tr>
<tr><td>7   Soak</td><td>101</td><td>89</td><td>20</td><td>0</td><td>Flat near sea level</td></tr>
<tr><td>8   Ramp</td><td>101-97</td><td>89-1203</td><td>20</td><td>56</td><td>Moderate hill climb from sea level</td></tr>
<tr><td>9   Soak</td><td>97</td><td>1203</td><td>25</td><td>0</td><td>Flat at moderate elevation</td></tr>
<tr><td>10 Ramp</td><td>97-96.6</td><td>1203-1316</td><td>20</td><td>6</td><td>Slow climb from moderate elevation</td></tr>
<tr><td>11 Soak</td><td>96.6</td><td>1316</td><td>20</td><td>0</td><td>Flat at moderate elevation</td></tr>
<tr><td>12 Ramp</td><td>96.6-82.74</td><td>1316-5501</td><td>20</td><td>209</td><td>Rapid climb to NTE limit</td></tr>
<tr><td>13 Soak</td><td>82.74</td><td>5501</td><td>20</td><td>0</td><td>Flat at NTE limit</td></tr>
<tr><td>14 Ramp</td><td>82.74-96.8</td><td>5501-1259</td><td>30</td><td>-141</td><td>Rapid descent from NTE limit</td></tr>
<tr><td>15 Soak</td><td>96.8</td><td>1259</td><td>20</td><td>0</td><td>Flat at moderate elevation</td></tr>
<tr><td>16 Ramp</td><td>96.8-90</td><td>1259-3244</td><td>15</td><td>132</td><td>Rapid hill climb to mid elevation</td></tr>
<tr><td>17 Soak</td><td>90</td><td>3244</td><td>10</td><td>0</td><td>Flat at mid elevation</td></tr>
<tr><td>18 Ramp</td><td>90-96.8</td><td>3244-1259</td><td>20</td><td>-99</td><td>Rapid descent within middle of NTE</td></tr>
<tr><td>19 Soak</td><td>96.8</td><td>1259</td><td>20</td><td>0</td><td>Flat at moderate elevation</td></tr>
<tr><td>20 Ramp</td><td>96.8-99.2</td><td>1259-586</td><td>20</td><td>-34</td><td>Moderate descent to lower elevation</td></tr>
<tr><td>21 Soak</td><td>99.2</td><td>586</td><td>20</td><td>0</td><td>Flat at lower elevation</td></tr>
<tr><td>22 Ramp</td><td>99.2-101</td><td>586-89</td><td>10</td><td>-50</td><td>Moderate decent to near sea-level</td></tr>
<tr><td>23 Soak</td><td>101</td><td>89</td><td>20</td><td>0</td><td>Flat near sea-level</td></tr>
</table>

Time Series Chart of Atmospheric Pressure Test

Pressure-Time Environmental Test Cycle
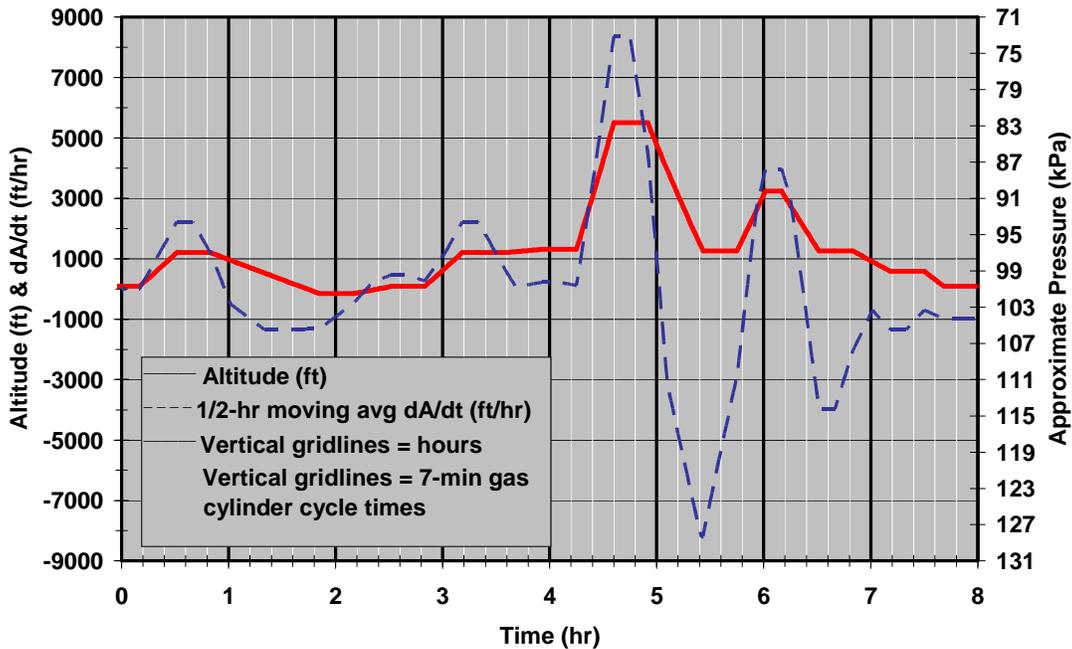
Prior to executing this pressure sequence, setup each PEMS and stabilize the PEMS in the chamber's first pressure. Perform PEMS setup according to 40 CFR Part 1065 Subpart J and PEMS manufacturer instructions, including any warm-up time, zero-span-audits of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc. Then supply the PEMS' overflow sample ports with the sequence of gases from the seven gas cylinders described at the beginning of Section 4.

Flow each cylinder 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 1 minute per cylinder (30 seconds to stabilize + 30 seconds to record stable readings), or 7 minutes to cycle through all 7 cylinders. Repeat this 7-minute cycle over the 8-hr test cycle. Note that this results in about 68 repeats per cylinder or about 480 minutes of data points per day per concentration output recorded.

Perform this test once for each of the six PEMS with as many PEMS tested at once. Test at least one PEMS from each PEMS manufacturer simultaneously so at most repeat this test three times to test each of the three pairs of PEMS once.

4.4.4 Data Analysis

Perform data analysis according to Section 4.1.

4.5 Ambient Temperature

4.5.1 Objective

Evaluate the effects of ambient temperature on PEMS gas concentration outputs.

a) Determine Δ_{T_NOx}, Δ_{T_NMHC}, and Δ_{T_CO}, as a function of test time and concentration for use in the error model.

b) Also determine $\Delta_{T\_exhflow}$ as a function of test time only. This error only needs to be quantified if the flow meter zero flow reading during these tests change due to various ambient temperatures.

4.5.2 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. The following table depicts the NEI data distribution (based on over 900,000 temperatures and over 270 trillion vehicle miles) and the test cycle temperature distribution.
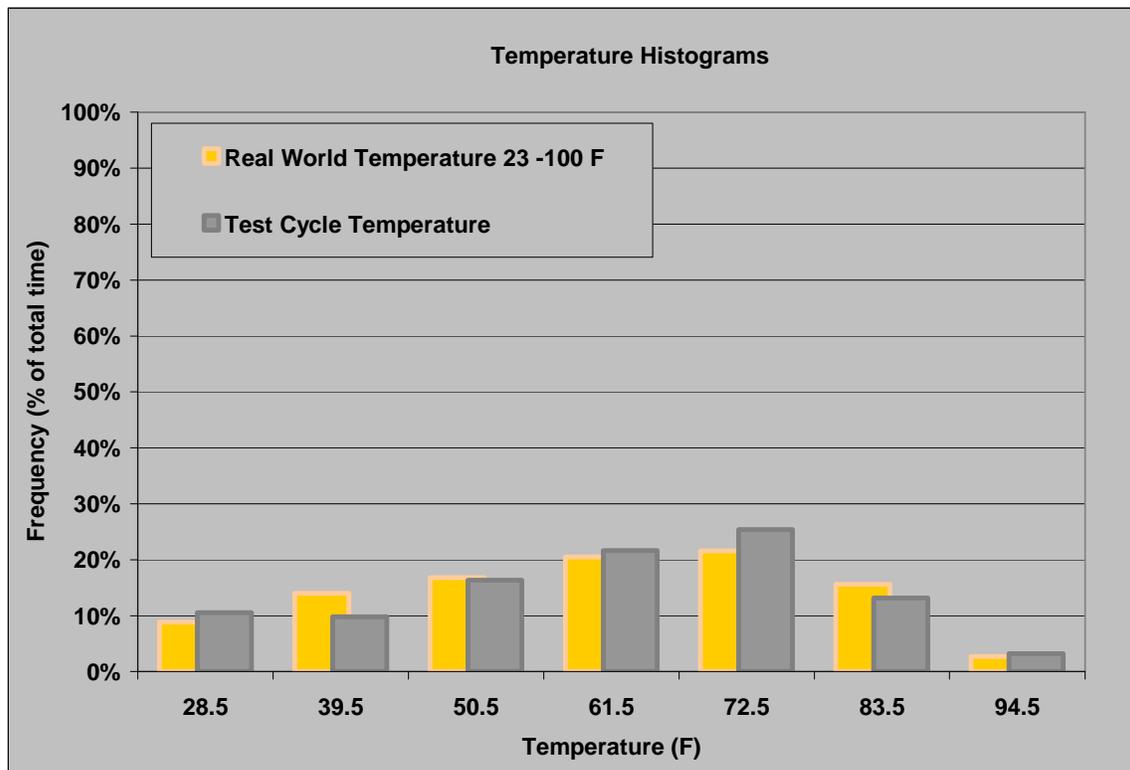
4.5.3 Methods and Materials

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

	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

Time Series Chart of Ambient Temperature Test

Temperature-Time Environmental Test Cycle
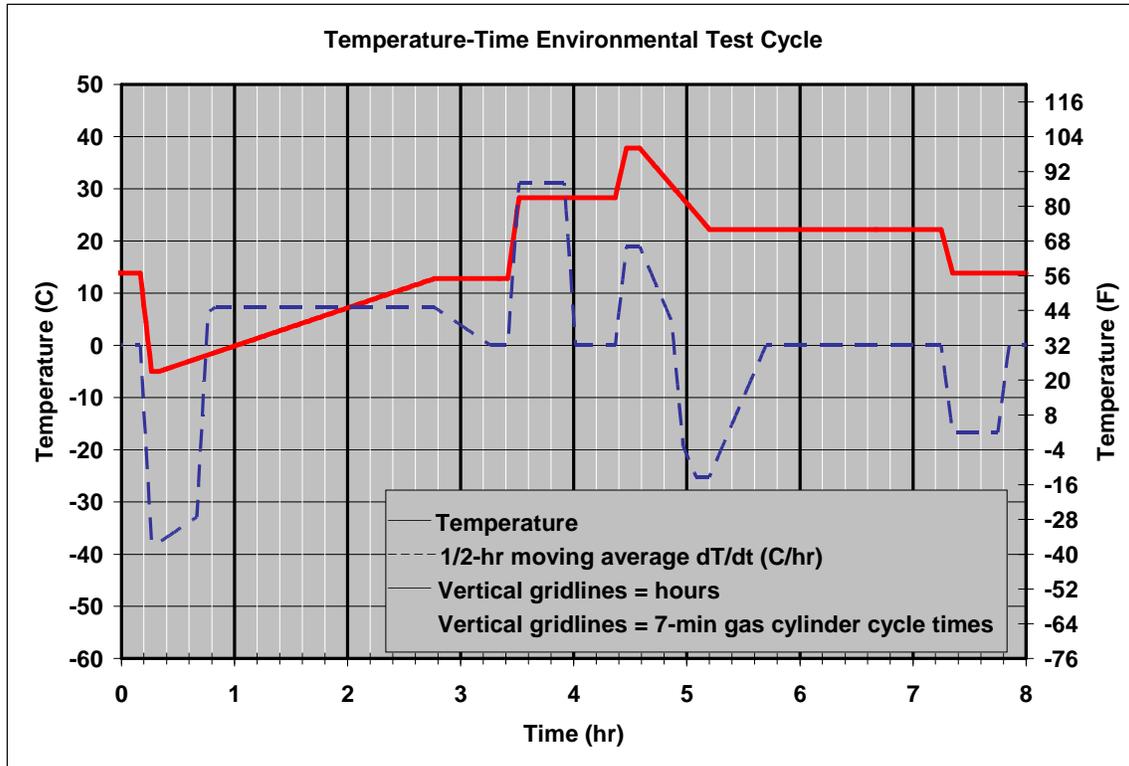
Prior to executing this temperature sequence, setup each PEMS and stabilize the PEMS in the chamber's first temperature. Perform PEMS setup according to 40 CFR Part 1065 Subpart J and PEMS manufacturer instructions, including any warm-up time, zero-span-audits of the analyzers and the setup of all accessories including flow meters, ECM interpreters, etc. Then supply the PEMS' overflow sample ports with the sequence of gases from the seven gas cylinders described at the beginning of Section 4.

Flow each cylinder 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 1 minute per cylinder (30 seconds to stabilize + 30 seconds to record stable readings), or 7 minutes to cycle through all 7 cylinders. Repeat this 7-minute cycle over the 8-hr test cycle. Note that this results in about 68 repeats per cylinder or about 480 minutes of data points per day per concentration output recorded.

Perform this test once for each of the six PEMS with as many PEMS tested at once. Test at least one PEMS from each PEMS manufacturer simultaneously so at most repeat this test three times to test each of the three pairs of PEMS once.

4.5.4 Data Analysis
Perform data analysis according to Section 4.1.

## 4.6 Orientation, Shock, and Vibration

4.6.1 Objective

Evaluate the effect of vehicle vibration on the performance of the PEMS and determine error factors for the PEMS due to these effects.

a) Determine $\Delta_{Vib\_pooled\_NOx}$, $\Delta_{Vib\_pooled\_NMHC}$, and $\Delta_{Vib\_pooled\_CO}$.

b) Also determine $\Delta_{Vib\_pooled\_exhflow}$ as a function of test time only. This error only needs to be quantified if the flow meter zero flow reading during these tests change due to vibration level.

4.6.2 Background

The performance of the PEMS could be affected by being in a vehicle which is traveling on the roadway and is subject to roadway irregularities resulting in the transmission of shock and vibration to the PEMS. The location/orientation of the PEMS in the vehicle could also be a factor.

Several vibration tests were considered, including random vibration, sine sweep, and resonate dwell tests. Experts in this field recommended the random vibration test as the most appropriate vibration test for this program. This kind of testing is run with electrodynamic shakers with controllers that can input a broad range of frequencies of varying amplitudes. These controllers are generally programmed with the desired Power Spectral Density (g^2/Hz versus Hz).

Three different approaches were considered for identifying appropriate Power Spectral Density - 1) use a proprietary PSD's or proprietary vehicle accelerometer data from either an EMA member or a vehicle manufacturer; 2) collect vehicle accelerometer data and reduce it down to a PSD; and 3) use a standard. Although some limited vehicle accelerometer data was available, experts at The contractor and Cummins Inc. agreed that the Mil Standard 810, method 514.5, appendix C, p 514.5c-8, US Highway Truck Vibration Exposure was a representative vibration profile based on a larger data set and has been widely used. It is also more cost effective and less ambiguous to use an existing vibration profile from a standard than to develop a custom profile from limited vehicle accelerometer data. The PSD from the Mil Standard includes vibration PSD in three axes – vertical, longitudinal and transverse. These three PSD's are run one at a time, i.e. vibration is applied to the unit under test one axis at a time.

Shock is short term, high level pulses that are generally unusual events. With the adsorbing action of vehicle suspensions, shock testing was deemed to not be applicable for the purposes of this test plan. The PSD of the Mil Standard was judged to adequately cover the normal range of vibrations.

Orientation of the PEMS vertical axis with respect to gravity was also deemed to be adequately covered in the vibration test. Since PEMS are typically mounted top up (one PEMS manufacture even requires this), the angle of the PEMS vertical axis with respect to gravity will be limited to road grades. This angle would create small static side loads,

but these were judged to be too small to include in the test plan. The transverse and longitudinal axis vibration profiles will be applied and are expected to provide adequate testing of dynamic side loads that were of more concern. Since the PEMS can be rotated to any position around its vertical axis when it is mounted in the vehicle, differences in the transverse and longitudinal axis PSD are not appropriate. Rather than test both horizontal axis of the PEMS with both PSD's, use a single PSD for both horizontal axes that contains the PSD of both the longitudinal and transverse PSD's in the Mil Standard.

Two locations on the vehicle was also considered – in-cab and on the frame rails for an outside installation. In-cab installations are not possible on many vehicles and operators often object to the in-cab installations. So a special PSD for the in-cab location was not pursued. The PSD of the Mil Standard was judged to be adequately representative of the frame rail location.

4.6.3 Methods and Materials

Use a shaker test facility capable of running the Mil Standard 810, version F, method 514.5, appendix C, p 514.5C-8, US Highway Truck Vibration Exposure. A total of four test days are allocated for this test. This does not include set up time. Test multiple PEMS simultaneously if the shaker table can accommodate multiple PEMS. If not, test a minimum of two PEMS – one from each manufacture. Run the vertical axis test for a minimum of 6, and preferably 8 hours. Run each of the transverse and longitudinal axes of the PEMS for a minimum of 3, and preferable 4 hours.

Take appropriate measures to shield the PEMS from EMI from the shaker table. Fabricate the fixture to mount the PEMS to the shaker table. Use any isolation/mounting device recommended by the PEMS manufacturer for the frame rail.

Setup the PEMS according to 40CFR1065, Subpart J and the PEMS manufacturer instructions, including any warm-up time, and zero-spans of the analyzers. Begin the data logging functions, then begin the vibration inputs, then supply the PEMS' overflow sample ports with the sequence of gases from seven gas cylinders described in the beginning of section 4. Flow each cylinder long enough so that at least 30 seconds of stabilized readings are recorded for the slowest responding analyzer. Target to sample about 1 minute from each cylinder (30 seconds to stabilize and 30 seconds to record stable readings), or 7 minutes to cycle through all 7 cylinders. Repeat this 7-minute cycle over the duration of each test. Suspend the PEMS data logging whenever the vibration inputs are suspended to adjust the test rig such as switching axes.

4.6.4 Data Analysis

Subtract baseline variances according to Section 4.1. Also, when subtracting the baseline biases and variances at zero, mid and span levels, use the baseline data from the same PEMS under test. Treat each set of EMI test results as part of a single environmental test. In other words, after calculating baseline adjusted deltas for zero, audit and span, pool all zero, audit, and span deltas, respectively. Then use the same error surface generation technique that was used in Section 3 for the engine dynamometer tests, where the error is

ranked from 5th to 95th percentile and centered with the truncated normal PDF at the 50th percentile error.

Table 4.6.4-a: Shock and Vibration Pooled Error Surface

Error Surface for Vibration effect on NOx concentration	
(Repeat for CO and NMHC)	
Fig 2.4-a	
x-axis	NOx ppm (pems, nom)
y-axis	NOx ppm (pems,vibration)
Fig 2.4-b	
x-axis	NOx ppm (pems, nom)
y-axis	NOx ppm (pems,vibration) - NOx ppm (pems,baseline)
Fig 2.4-c	
x-axis	NOx ppm (pems, nom)
y-axis	$i_{c\_vibration\_pooled\_NOx}$ [Range: $t_{initial}$ through t_{final}]
z-axis = $\Delta_{Vib\_pooled\_NOx}$	NOx ppm (pems,Vibration) - NOx ppm (pems,baseline)
i_c sample frequency	once per NTE event
i_c sample distribution	Gaussian (normal distribution)

4.7 Ambient Hydrocarbons

4.7.1 Objective
Evaluate the effects of ambient hydrocarbons on PEMS FID zero error, and establish error as a function of time. Determine Δ_{HC} for use in the error model.

4.7.2 Background
PEMS are expected to operate over ranges of ambient hydrocarbons. It is hypothesized that zero error of the PEMS FID outputs may be a function of ambient hydrocarbons. Therefore, this experiment will change the ambient hydrocarbons surrounding PEMS to evaluate its effects on PEMS FID zero error.

There are two reasons why a FID might be affected by ambient hydrocarbons:
1. The FID uses ambient air as FID burner air. This introduces hydrocarbons into the detector chamber from a source other than raw engine exhaust. Because a FID uses

burner air continuously, ambient air hydrocarbons from the burner air will also be present in the reaction chamber.

2. The FID may use ambient air as zero air during over-the-road periodic zeroing. This introduces into the detector a second source of ambient hydrocarbons during a FID zeroing procedure, in addition to the burner air ambient hydrocarbons.

Furthermore, these effects become more complicated when one considers that EPA regulations set HDDE standards on a non-methane hydrocarbons (NMHC) basis. Because there is no real-time instrument that directly measures NMHC, NMHC is determined by subtracting a real-time methane measurement from a real-time total hydrocarbons (THC) measurement.

This means two things:

1. Ambient hydrocarbons will have different effects on the net results, depending upon what fraction of the total ambient hydrocarbons is methane.

2. A PEMS will have to quantify exhaust NMHC, which by regulation can be done in real-time by using two FIDs; one with a non-methane hydrocarbon catalytic cutter that measures only methane (CH_4), and one without a cutter so that it measures total hydrocarbons (THC). EPA specifies that NMHC shall be reported as the lower of NMHC=THC-CH4 or NMHC=0.98*THC. This provision will be incorporated into the model.

4.7.3 Methods and Materials

Use a well ventilated temperature-controlled room at nearly constant pressure. Use a room that is able to house two PEMS (one from each manufacturer), their power supplies, the PEMS flow meters, cables and lines, plus different zero, audit, and span gas cylinders, and two gas dividers.

Follow burner air hydrocarbons changes in a pattern of stabilizing the PEMS FIDs' burner air to one of nine hydrocarbon combinations output to an ambient pressure overflow. After stabilizing each burner air hydrocarbon concentration, set zero for the THC and CH4 FIDs using a zero gas cylinder. Operate the PEMS to quantify zero air from a gas cylinder at each of ten (9, plus repeat of 1st) different burner air hydrocarbon combinations. Record at least 30 seconds of values at each combination. Then switch to the next of the nine ambient hydrocarbons combinations. Reset zero with the new burner air hydrocarbons concentration overflowing to the burner air port.

Repeat the entire zero quantification sequence after zeroing with the latest ambient hydrocarbons concentration. Continue this series of sequences until all combinations have been quantified and recorded (see table 4.7.3-a below)

Table 4.7.3-a: Ambient Hydrocarbon Error Test Sequence

Phase	Burner air hydrocarbons during Hexane, ppm	Burner air hydrocarbons during Methane, ppm	Burner air hydrocarbons during Hexane, ppm	Burner air hydrocarbons during Methane, ppm
1	0	0	0	0
2			2	2
3			8	8
4			0	2
5			2	8
6			8	0
7			0	8
8			2	0
9			8	2
10			0	0
11	2	2	2	2
12			8	8
13			0	0
14			2	8
15			8	0
16			0	2
17			2	0
18			8	2
19			0	8
20			2	2
21	8	8	8	8
22			2	2
23			0	0
24			8	2
25			2	0
26			0	8
27			8	0
28			2	8
29			0	2
30			8	8
31	0	2	0	0
32			2	2
33			8	8
34			0	2
35			2	8
36			8	0
37			0	8
38			2	0
39			8	2
40			0	0
41	2	8	2	2
42			8	8
43			0	0
44			2	8
45			8	0
46			0	2
47			2	0
48			8	2
49			0	8
50			2	2

Phase	Burner air hydrocarbons during Hexane, ppm	Burner air hydrocarbons during Methane, ppm	Burner air hydrocarbons during Hexane, ppm	Burner air hydrocarbons during Methane, ppm
51	8	0	8	8
52			0	0
53			2	2
54			8	0
55			0	2
56			2	8
57			8	2
58			0	8
59			2	0
60			8	8
61	0	8	0	0
62			2	2
63			8	8
64			0	2
65			2	8
66			8	0
67			0	8
68			2	0
69			8	2
70			0	0
71	2	2	2	2
72			8	8
73			0	0
74			2	8
75			8	0
76			0	2
77			2	0
78			8	2
79			0	8
80			2	2
81	8	0	8	8
82			0	0
83			2	2
84			8	0
85			0	2
86			2	8
87			8	2
88			0	8
89			2	0
90			8	8

Prior to executing this ambient hydrocarbons sequence, setup each PEMS and stabilize the PEMS at the zero methane, zero hexane FID burner air condition. 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 PEMS' overflow sample ports with the sequence of gases from the seven gas cylinders described at the beginning of Section 4.

Flow each cylinder 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 1 minute per cylinder (30 seconds to stabilize + 30 seconds to record stable readings). Expect that this test cycle will take about 5 hours to complete, which should be completed in one day:

9 separate zero setting procedures at 4 minutes each (9 x 4 =~1/2 hr)

90 phases where hydrocarbons are switched and zero air must be stabilized and quantified; 3 minutes each (90x3=4.5 hr).

Ambient hydrocarbons concentrations will be controlled by a gas divider to the values specified in table 4.7.3-a. Unless new information about the range of ambient hydrocarbons dictates a change in the test matrix's values. Such information could come from the UCR CE-Cert results of CE-Cert trailer continuous CVS background measurements.

This test should be replicated only once.

4.7.4 Data Analysis

Perform data analysis according to Section 4.1, noting that only the zero error will be determined. This means that there will be no "surface" to sample. There will be just a line to sample. Use this error for all second-by-second concentrations

5 Model Validation and Measurement Allowance Determination

5.1 Model validation

5.1.1 Objective

Validate the Monte Carlo model by
a) Testing the PEMS in parallel with the CE-CERT trailer, and
b) Replaying tests in a laboratory.

5.1.2 Background

5.1.2.1 Validation with CE-CERT Trailer

Previous tests are designed to evaluate the effect of various potential noise parameters on PEMS units. These effects have are then incorporated into a Monte Carlo model (section 2). The testing in this section is designed to verify the model by comparing the in-use differences between the PEMS system and the CE-CERT trailer in relation to model predicted differences. Test routes will be designed to meet the limits reasonable expected to be found in use testing, and to appropriately cover NTE operation.

Several weeks worth of testing are necessary to validate the Monte Carlo Model. The 1065 audit of the CE-CERT trailer may take several weeks in itself. The NTE cycle test will consist of a 20-minute cycle repeated 20 times on one engine, a total of approximately 2 test days. For the on-road portion of the testing, it is likely that Route 1 will take a complete test day and that Routes 2 and Route 3 can be completed in one test day. This requires 2 test days per PEMS, per mounting location, plus 2 days of on-road CE-CERT validation testing, for a total of 10 test days of on-road CE-CERT trailer operation. If more then one PEMS is available, several systems could be tested in parallel. While two flow meters in the exhaust could affect results, it is likely that this measurement already experiences reduced ambient effects because the CE-CERT trailer captures the exhaust and that any further deviation from the true operating conditions is immaterial.

5.1.2.2 Validation in dyno test cell

Additional testing will be conducted in a laboratory, where selected tests will be "replayed," while the PEMS is maintained at laboratory conditions.

The engine will be operated as close as possible to previously recorded tests from the on-road portion of the validation testing. Controlled conditions will include engine speed/load, ambient conditions, and any other condition that can be repeated with a reasonable level confidence. For each PEMS, two test days will be replayed, for a total of 4 test days.

5.1.3 Methods and Materials

5.1.3.1   CE_CERT Trailer validation

a) Use two PEMS units, one Sensors and one Horiba, in parallel with the CE-CERT emissions trailer.
b) Ensure that the trailer is able to measure regulated emissions and CO2, ambient hydrocarbons (methane and NMHC), humidity, temperature, and pressure and have adequate data acquisition capabilities to capture the additional measurements discussed herein.
c) Acquire ECM data to allow "re-play" of engine conditions during section 5.1.3.2 (Dyno cell validation). Work with engine manufacturer to ensure enough data is capture, using proprietary tools if needed for subsequent re-play of conditions.
d) Test the trailer at Contractor facility to insure that a reasonable level of confidence can be placed on the reported NTE results. As part of these tests include a 1065 audit.
e) In addition, validate the trailer by testing over the conditions present during the over-the-road test by measuring zero, span, and audit gases while traveling over the designated routes. Ensure that the CE-CERT trailer emissions measurements are insensitive to these over-the-road changing conditions

f) Install and calibrate the PEMS as specified by the manufacturer in a Class 8 truck.
g) Install temperature sensors inside the protective enclosure housing PEMS analyzers, near exhaust flow meter, and in the ambient air stream.
h) Use a Rohde & Schwarz Spectrum Analyzer FSH3 or similar unit to measure electromagnetic spectrum and power.
i) Use Two 3-axis vibration/shock transducers to measure vibration/shock for the PEMS analyzer unit and the flow meter. Note: The accelerometers and the spectrum analyzer should have previously been used during section 4.6 of this test plan.

j) Mount the PEMS in two locations: inside the cab and behind the cab, in order to maximize environmental differences.
k) Drive the vehicle over 3 routes, each design to test particular limits that are expected to simulate conditions imposed the environmental tests of sections 4.3-4.7

Use the following Routes:

l) Route 1--Route starts in the morning in room temperature garage. Vehicle is driven into cold ambient conditions of less than 32 deg F. Vehicle is operated throughout day in a warm location where temperatures exceed 100 deg F. Vehicle returns to cooler ambient temperatures.
m) Route 2--Vehicle travels from sea level to a high altitude exceeding 6000 ft and returns to sea level.
n) Route 3--Vehicle is operated in locations were following conditions are known to exist: high ambient HC, high EMI/RFI, and rough road surface.

Table 5.1.3-a: CE-CERT Model Validation Test Sequence		
CE-CERT Validation		Test Day
Contractor CE-CERT Validation	1065 Audit	xx
	NTE Cycle	xx
On-Road CE-CERT Validation	Route 1	xx+1
	Route 2, Route 3	xx+2
On-Road CE-CERT Tests		Test Day
Sensors/ Behind Cab	Route 1	xx+3
	Route 2, Route 3	xx+4
Sensors/ In Cab	Route 1	xx+5
	Route 2, Route 3	xx+6
Horiba/ Behind Cab	Route 1	xx+7
	Route 2, Route 3	xx+8
Horiba/ In Cab	Route 1	xx+9
	Route 2, Route 3	xx+10
Laboratory Replay		Test Day
Sensors	Simulate Route 1	xx+11
	Simulate Routes 2 & 3	xx+12
Horiba	Simulate Route 1	xx+13
	Simulate Routes 2 & 3	xx+14

5.1.3.2 Dyno test cell validation

a) Remove engine from chassis and install in dyno test cell
b) Select portions of the CE-CERT tests that are deemed appropriate for "re-play" in a dyno test cell. These portions of test should be limited to about 30-60 minutes in duration
c) Operated engine as close as possible to previously recorded conditions
d) Control engine boundary conditions (charge cooler outlet temperature, intake/exhaust restrictions, ambient pressure, etc.) tests from the on-road portion of the validation testing.
e) Control engine operating conditions (torque, speed, AECD's if active, etc,) to mimic operating conditions that can be repeated with a reasonable level of confidence.
f) For each PEMS, perform testing during two days, for a total of 4 test days.
g) Record emissions data with PEMS and lab-grade analyzers, and compare the two.

5.1.4 Data Analysis

5.1.4.1 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. Data on ambient conditions must be analyzed to insure that the model was fully exercised. Special consideration will be paid to conditions where the PEMS was found to be sensitive to its environment. If it

was found that the PEMS did not see conditions that are likely to occur in the field that are known to increase erroneous reporting, then more testing is required.

To validate the Monte Carlo Model data must be run through the model and the model's results must predict the actual test results. To run data forwards through model, raw concentration must be known. This requires the CE-CERT trailer to either measure raw exhaust concentration or determine dilution ratio accurately enough to calculate the raw concentration. If concentration can be established with a reasonable level of confidence, then the model can be validated as follows by comparing data in brake specific units (using the work recorded by the PEMS for both the CE-CERT and PEMS data) or in fuel specific units. Raw exhaust concentration, ambient conditions, and exhaust flow are fed to the model. Since ambient effects are incorporated as a distribution of error, the model must be run many times for each NTE event. The model then produces a likely distribution of error expected from the PEMS. If 95% (or maybe 90%-99%) of the PEMS recorded NTE events fit within the model predicted NTE distribution then the model can be considered validated. Data from 20 pseudo NTE events are plotted below in the graph titled "Brake Specific NTE Events." The "model" predicted a likely error distribution from the CE-CERT measured data and ambient conditions. The PEMS data is compared to the error distribution, and if enough NTE events are within the range the model is deemed validated.
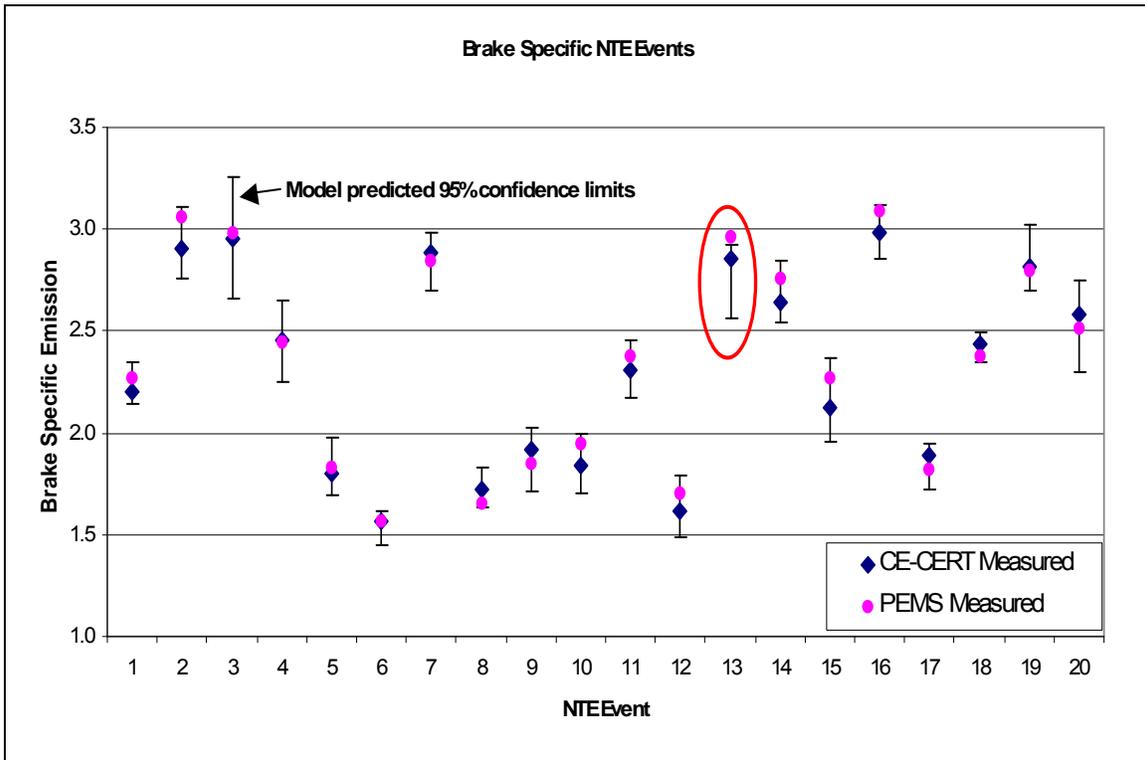

Chart of Model Validation NTE Events

If it is determined that the CE-CERT trailer is unable to accurately determine raw exhaust concentration then the model cannot be run forward. Instead the PEMS recorded data can be run through the model as if it were absolutely correct. Then the model will predict a distribution of error that is likely to occur. This error distribution should overlap with CE-CERT recorded data as long as the error is random. If there is a bias, then the PEMS will record the bias and the model will predict a further bias in the same direction, misrepresenting the comparison—not ideal.

One could also compare the NTE events recorded by the PEMS and the CE-CERT trailer. Below is a graph that shows PEMS NTE events minus the Accuracy Margin versus the CE-CERT trailer results. If 95% (or maybe 90%-99%) of the PEMS values are less than the CE-CERT NTE events, then the margin seems to be correct. Unfortunately this does not incorporate the model directly, but it gives evidence that the model's end result, the Accuracy Margin, is suitable. This test fails to test the intricacies of the model and may be too broad for comfort.
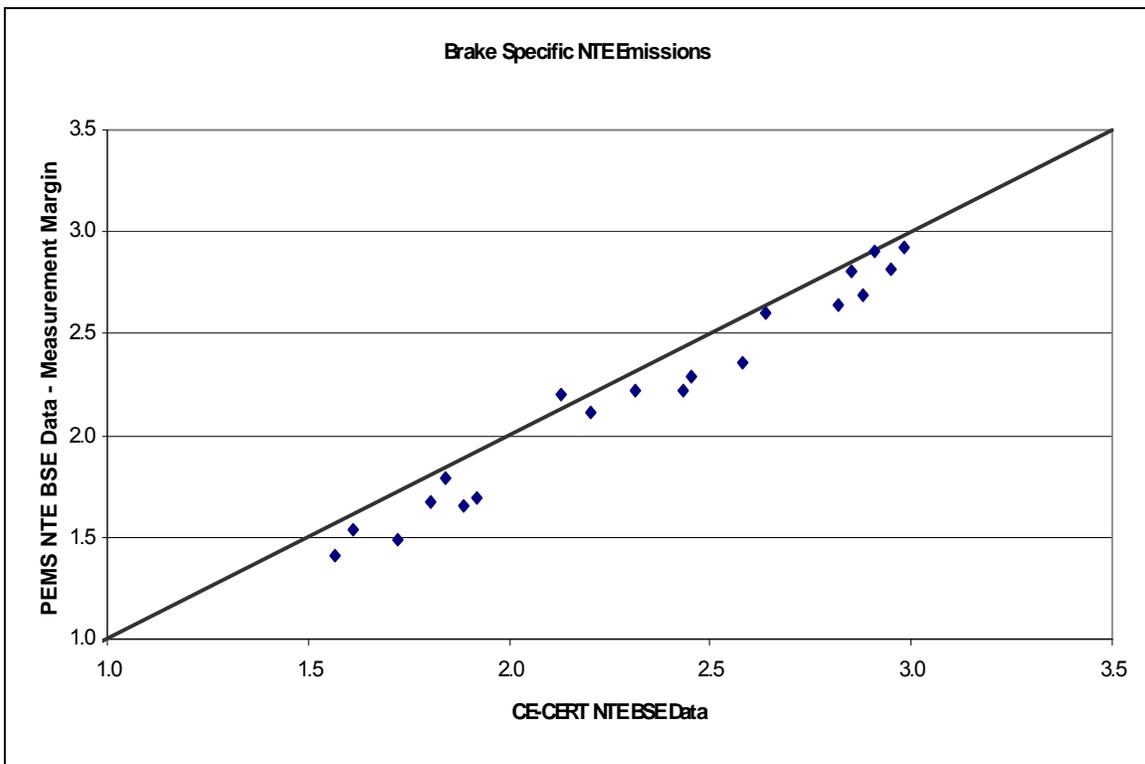

Chart of PEMS vs. Tow-along lab Results

5.1.4.2 Dyno Test Cell Validation

Compare brake specific emissions from each valid NTE event between the PEMS and lab-grade analyzers. Confirm that differences fall within the expected ranges as predicted by the Monte Carlo simulation. If they do not, conduct further investigation to try to understand and resolve the discrepancies.

5.2 Measurement Allowance Determination

5.2.1 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 allowances for all regulated emissions, at 2007 emissions standards

5.2.2 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 allowances for BSNOx, BSNMHC, and BSCO.

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

5.2.4 Data Analysis
Use the methodology explained in section 2.2, and Table 2.2-a to arrive at the final measurement allowance.

6 Time and Cost

Budget

Contractor to provide independent estimate.

Timeline

Contractor to provide independent estimate.

Timeline			
	Weeks	Date	Year
Model creation			
Lab Audit			
PEMS audits			
Engine setup			
PEMS setup			
Steady-state testing			
Steady-state data reduction			
Transient testing			
Transient data reduction			
Exhaust flow meter test setup			
Exhaust flow meter testing			
Exhaust flow meter data reduction			
ECM torque bsfc setup			
ECM torque bsfc testing			
ECM torque bsfc data reduction			
Baseline environmental test setup			
Baseline environmental testing			
Baseline environmental data reduction			
Pressure environmental test setup			
Pressure environmental testing			
Pressure environmental data reduction			
Temperature environmental test setup			
Temperature environmental testing			
Temperature environmental data reduction			
EMI/RFI environmental test setup			
EMI/RFI environmental testing			
EMI/RFI environmental data reduction			
Vibration environmental test setup			
Vibration environmental testing			
Vibration environmental data reduction			
Ambient HCs environmental test setup			
Ambient HCs environmental testing			
Ambient HCs environmental data reduction			
Model Validation			
Final Report preparation and publication			
Submission of Final Report to EPA/EMA/ARB			

7 Appendices

These appendices provide additional detailed information and descriptions of spreadsheets and other sources of information.

7.1 Description of Spreadsheet provided by Matt Spears

To use the spreadsheet, here's a description of the various worksheets:

1. Input lug curve: paste any speed-torque lug curve up to 5000 data points long into this worksheet. Make sure the lug curves last data point is where the governor line intersects exactly 0 torque. Tweak your lug curve so that this is the case.

2. Interpolated lug curve: don't do anything here.

3. Cycles: here is where the data for the On-highway, Non-road, condensed on-highway+non-road, and dynamic response NTE cycles are. The SET RMC is also here. The upper part of the spreadsheet has NTE and SET calculations. I think the column headings for the cycles are self-explanatory. I haven't created the random cycle generator for the "NTE cycle", which is for the dynamic response test. The cycle just currently sequences the events and inter-NTE events in the order that I'm building them. Note that only 12 of the 30 events are complete in this spreadsheet.

4. 32 s Events: here is where I'm building the dynamic response NTE events. The first 9 are steady-state. The next three (10-12) are "vertical" NTEs in the lower, mid, and upper third of the zone. For NTEs 13-15 I plan to do the same horizontally, and then 16-18 will be diagonal from low speed & torque to high speed and torque. 19-21 will be diagonal from high speed & low torque to low speed and high torque. 22-24 will be 32 second samples from HDDE PEMS testing, 25-27 will be from LHDDE, and 28-30 will be 3 from non-road operation. Note I made these 32 seconds long to account for 1-second ECM under-sampling on the entry and exit of each event. That way even if the ECM is 1-second off the wrong way on the entry and exit, PEMS will still ID an NTE event. If the ECM is worse, then we'll see that.

5. INT events: here are the inter-NTE events on a second-by-second basis. Note that I took Bill Trestrail's suggestion to scramble up the origin a little. This scrambling is easily tweaked and/or eliminated, but it's easier to build the NTE cycles when the cycle traces (in the charts) don't overlap.

6. NTE event finder: I cut and paste the last column of this spreadsheet "as values" into the first column of each cycle in "Cycles" to ID the NTE events. I have to tweak the second column each time I name the NTE events in different cycles.

7. Histogram data: supplies data to the speed, torque, and power histograms. Nothing to do here.

8. dHistogram data: work in progress, I plan to repeat the histograms as first derivatives:
dspeed, dtorque, dpower to visualize how the different cycles compare.
9. Speed, torque, and power histograms: self explanatory. Note that because the "NTE
Cycle" is only 1/3 complete, the histograms are skewed because they are counting
unfinished NTE events. They're counted at the lowest bins in torque and power.

10. T-S domain & P-S domain: good visualization of all the cycles.

11. dT-dS domain: visualization of "transientness" of cycles. Note that currently the
"NTE Cycle" is the most severe. I hope the engine/dyno can do this. If not the NTEs can
be tweaked.

12. All the cycles vs time: self explanatory. You can see that the "NTE Cycle" is not
complete.]

7.2 Abbreviations used in Brake Specific Equations (Table 3.3.4-a)

Method 1:

e_{Nox} = brake-specific emission, NO_x (g/hp-hr)
M_{NO2} = Molecular weight, NO_2 (~46 g/mol)
N = total number (of time intervals) in series
x = amount of substance fraction (mol NO_x/mol exhaust; note that 1μmol (emission constituent)/mol (exhaust) = 1ppm (part per million)

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

e_{Nox} = brake-specific emission, NO_x (g/hp-hr)
M_{NO2} = Molecular weight, NO_2 (~46 g/mol)
N = total number (of time intervals) in series
x = amount of substance fraction (mol NO_x/mol exhaust; note that 1μmol (emission constituent)/mol (exhaust) = 1ppm (part per million)

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

e_{Nox} = brake-specific emission, NO_x (g/hp-hr)
M_{NO2} = Molecular weight, NO_2 (~46 g/mol)
w_{fuel} = g (carbon)/g (fuel); Note fuel is roughly 86% carbon by mass
M_C = Atomic weight of carbon (~12 g/mol)
N = total number (of time intervals) in series

x = amount of substance fraction (mol NO_x/mol exhaust; note that 1μmol (emission constituent)/mol (exhaust) = 1ppm (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
Δt = time interval (sec)
f_n = rotational frequency (shaft), rev/min
T = torque (N-m)
Δt = 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)