

Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program

Part 1 – Project Overview and PEMS Evaluation Procedures

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ABSTRACT

Under the U.S. Environmental Protection Agency's (EPA's) Heavy-Duty In-Use Testing (HDIUT) program, emission of non-methane hydrocarbons (NMHC), carbon monoxide (CO), and oxides of nitrogen (NO_x) have been regulated using Portable Emissions Measurement Systems (PEMS) during in-use field operation for heavy-duty on-highway diesel engines with 2007 or later model year designations. As directed by the EPA, the Engine Manufacturers Association (EMA), and the California Air Resources Board (CARB), additive emission measurement accuracy margins (measurement allowances) were experimentally determined for HDIUT to account for the measurement differences between laboratory testing with laboratory grade equipment and in-use testing with PEMS.

As part of a three-paper series, this paper summarizes the HDIUT measurement allowance program while focusing on the laboratory evaluations of the Sensors Inc. SEMTECH-DS PEMS. The objective of the project was to quantify PEMS measurement errors as compared to concurrent measurements from a 40 CFR Part 1065 compliant dynamometer test cell. PEMS measurement errors were also evaluated when subjected to various environmental disturbances. The error data recorded

during laboratory testing were used to populate a Monte Carlo statistical model. The model was iterated to randomly combine the various sources of PEMS measurement errors, the results of which were used to determine the additive measurement allowances for in-use testing. Model validation exercises were conducted by comparing PEMS emission results with the Center for Environmental Research & Technology (CE-CERT) Mobile Emissions Laboratory during on-road testing.

INTRODUCTION

BACKGROUND – Based on a Settlement Agreement dated June 3, 2003, EPA and EMA agreed to a regulatory proposal for a manufacturer run Heavy-Duty In-Use Testing program. As stated in a subsequent EPA Regulatory Announcement dated June 2004, "Under this in-use testing program, manufacturers will measure gaseous and particulate exhaust emissions from diesel engines using portable onboard emission measurement systems. This cooperative effort represents a significant advance in helping to ensure that the benefits of more stringent emission standards are realized under real-world driving conditions" [1], [2], [3]. The final rule for the HDIUT program was announced in June 2005 [4], [5].

A Memorandum of Agreement (MOA) dated May 2005 defined a cooperative effort between EPA, EMA, and CARB “with regard to developing data-driven emission measurement accuracy margins for gaseous and PM emissions to be applied to the results of PEMS in-use in field testing under the forthcoming HDIUT regulations” [6]. Furthermore, a Test Plan dated May 20, 2005 was developed by EPA, EMA, and CARB to define procedures and methodologies used to determine the gaseous measurement allowances [7].

This effort was guided in part by experiences gained during an earlier “pre-pilot” program which was run at CE-CERT comparing laboratory reference and PEMS measurements [8]. Evaluation of PEMS versus laboratory equipment has also been carried out on a light-duty chassis dynamometer [9].

OBJECTIVE – The HDIUT gaseous measurement allowance program was performed to experimentally determine additive measurement accuracy margins for in-use compliance testing using PEMS. This paper provides a summary of the measurement allowance program while focusing on the laboratory evaluations of the PEMS. Paper number two of this series pertains to the program’s statistical modeling and simulation [10], while paper number three summarizes the model results, validation, and determination of the final gaseous measurement allowances [11]. Comprehensive final reports were prepared for EPA that contain details of the program [12], [13], while the measurement allowances generated during the program were issued in a direct final rule in February 2008 [14], [15].

Laboratory evaluation of the PEMS included audits based on 40 CFR Part 1065, comparative engine testing in a 1065 compliant dynamometer test cell, and environmental chamber testing. Dynamometer engine testing was performed to quantify PEMS emission concentration and exhaust flow rate measurement errors, as well as engine control module (ECM) broadcast torque and BSFC (derived from ECM speed, torque, and fuel rate) errors, when compared to the laboratory standard. Engine evaluations included steady-state and transient testing, flow meter testing, and various experiments to determine ECM broadcast torque and BSFC errors. Environmental chamber testing was conducted to examine PEMS measurement errors when subjected to environmental perturbations including temperature, pressure, electromagnetic radiation, vibration, and ambient hydrocarbon levels.

PROJECT OVERVIEW

STEERING COMMITTEE – In addition to cooperatively developing the gaseous program Test Plan, the HDIUT Measurement Allowance Steering Committee was responsible for directing the program. The Steering Committee was composed of representatives of EPA,

CARB, EMA, and various individual EMA member companies. This group reviewed all results generated during the program and was responsible for developing and approving changes to the Test Plan.

STATISTICAL MODEL SIMULATION - During Test Plan development, it was understood that direct quantification of the measurement allowances would not be feasible. This was due to the large number of potential PEMS measurement error sources and the inability to experimentally test the unlimited combination of these measurement errors. Therefore, the Steering Committee chose a methodology which involved the construction of a statistical Model of PEMS measurement error. The Model incorporated Monte Carlo (random sampling) techniques and was iterated to randomly combine the various sources of PEMS measurement errors; the results of which were used to determine the additive measurement allowances for in-use testing.

The Model incorporated a variety of error components, each of which represented potential measurement differences between laboratory testing with laboratory grade equipment and in-use testing with PEMS. Each potential error source was associated with a laboratory experiment designed to quantify the effect of the error source. The result of each experiment was an empirical model, often visualized as a three-dimensional surface (error surface), which linked the chosen test conditions to the error between the laboratory reference and the PEMS measurement. Thirty-seven error surfaces were incorporated into the Model, the majority of which were based on gaseous emission concentration measurement errors, exhaust flow rate measurement errors, and ECM broadcast torque and BSFC errors. A detailed description of the Monte Carlo error Model and simulation technique can be found in part two of this three-paper series.

PEMS LABORATORY EVALUATIONS – An audit of the PEMS and dynamometer laboratory was performed according to the procedures in 40 CFR Part 1065 Subpart D. The audit results were approved by the Steering Committee prior to laboratory testing.

A number of potential error sources were investigated during the program. The laboratory evaluations can be grouped into two categories, engine dynamometer testing and environmental chamber testing. Steady-state and transient engine testing was performed on three different heavy-duty diesel engines to quantify PEMS emission concentration and exhaust flow rate measurement errors when compared to the reference laboratory. Three unique PEMS were collocated and operate simultaneously during each engine test. Their data were subsequently pooled to account for PEMS-to-PEMS variability. Additional engine experiments were designed to evaluate ECM broadcast torque and BSFC errors as well as exhaust flow rate errors. Error surfaces

were also incorporated into the Model to account for PEMS data time alignment errors as well as ECM broadcast torque and BSFC errors due to engine production variability.

Environmental chamber testing was conducted to examine PEMS emission concentration and exhaust flow rate measurement errors when subjected to environmental perturbations including temperature, pressure, electromagnetic radiation, vibration, and ambient hydrocarbon levels.

MODEL RESULTS AND VALIDATION - The results of the Model simulation were validated using on-road NTE test data generated by CE-CERT [16]. A SEMTECH-DS PEMS unit was tested in parallel with CE-CERT's Mobile Emissions Laboratory (MEL) during several days of on-road NTE testing. Having successfully completed a correlation exercise with the laboratory reference dynamometer test cell used during the PEMS evaluation, the NTE results generated by the CE-CERT MEL were used as the reference during the on-road validation testing.

The PEMS NTE measurement errors observed during in-use testing were compared to the results of the error Model simulation to determine the validity of the calculated measurement allowances. Additional validation testing was performed in the laboratory dynamometer test cell to evaluate ECM broadcast torque and BSFC errors when NTE events from the on-road validation were replayed in the laboratory. Although not all of the Model results validated, the Steering Committee reached an agreement to set the in-use measurement allowances based on validated results.

Due to the lack of validation of some of the Model results, EPA funded additional work to investigate the cause of the validation failure and to rerun the Model. This additional effort resulted in revised and validated measurement allowances for 2010 and later model year engines. Detailed Model and validation results can be found in part three of this three paper series [11] as well as the measurement allowance final reports [12], [13].

1065 PEMS AND LABORATORY AUDIT

An initial task of the program was to audit the PEMS and dynamometer laboratory according to 40 CFR Part 1065 Subpart D. The audit procedures were performed to insure the equipment used for the In-Use Measurement Allowance Program met the minimum performance requirements as regulated by the EPA. Table 1 lists the 1065 verification procedures performed during the program as selected by the Steering Committee.

Table 1. 1065 Audits Required for the Measurement Allowance Program

Description	CFR Reference	Lab Raw	Lab Dilute	PEMS
Linearity	1065.307	x ¹	x ¹	x ²
Torque Meter	1065.310	x	x	
Fuel Flow	1065.320	x		
Intake Flow	1065.325	x		
Exhaust Flow	1065.330			x
CVS Verification	1065.341		x	
H ₂ O Interference on CO ₂	1065.350	x	x	x
H ₂ O and CO ₂ Interference on CO	1065.355	x	x	x
FID Optimization	1065.360	x ³	x ³	x ³
Non-stoichiometric raw FID O ₂ Interference	1065.362	x		x
Nonmethane cutter penetration fractions	1065.365	x	x	
CLD H ₂ O and CO ₂ quench	1065.370	x	x	
NDUV HC and H ₂ O Interference	1065.372			x
Chiller NO ₂ penetration	1065.376			x
NO ₂ -to-NO converter check	1065.378	x	x	
¹ Linearity for lab on gas analyzers, flow meters, torque meter, pressures, temperatures ² Linearity for PEMS on gas analyzers, exhaust flow meters ³ Verify methane response factors only, THC instruments				

The reference laboratory passed all of the performance verifications listed in Table 1, therefore, the Steering Committee approved the laboratory audit results for both the raw and dilute sampling systems. Audits were performed on each of the seven unique SEMTECH-DS units used during the program. In addition to the initial analyzer verification procedures, a number of additional audits were required as a result of maintenance or repairs performed on several of the PEMS units over the course of the program. In general, the PEMS passed the requirements in 40 CFR Part 1065, but there were exceptions.

ANALYZER LINEARITY – Mono-blend span gases were used with a STEC Inc. Model SGD-710C 10-step gas divider to perform the PEMS analyzer linearity verification. Numerous gas analyzers on various PEMS units failed to meet the 1065 Subpart D linearity criteria. Nearly all of these failures were in the regression line intercept criteria outlined in 1065.307 Table 1, which specify an intercept tolerance of 0.5 percent of the maximum value expected during testing. Because the maximum test concentrations were not known at the time of the audits, these values were interpreted as the span gas concentrations used for the instruments. This interpretation of the verification resulted in the most liberal linearity criteria.

Sensors Inc. initially re-calibrated one unit as a result of an analyzer linearity failure. However, other units that failed the linearity criteria were deemed by Sensors Inc. to be operating correctly, and not in need of recalibration. Furthermore, Sensors Inc. indicated that they were concerned with the linearity criteria as written in 40 CFR Part 1065. Due to the difficulty in continually recalibrating the PEMS, and comments from Sensors Inc. regarding the linearity criteria, the Steering Committee elected to continue testing with PEMS that failed the 1065 linearity verification. Even though the Part 1065 intercept criteria has been updated to apply at the minimum value expected, rather than at zero, the 0.5 percent of maximum threshold could remain an issue, where manufacturers will be legally bound to use equipment that meets all 1065 specifications.

CHILLER NO₂ PENETRATION – Initially, all of the PEMS failed the NO₂ penetration check in 1065.376, with chiller NO₂ penetration levels at approximately 90 percent with humidified 280 ppm NO₂ span gas. Due to the relatively high tailpipe NO₂ fractions, the low NO₂ penetration levels resulted in a low PEMS NO_x concentration bias during initial steady-state engine testing. As a result, the Steering Committee asked Sensors Inc. to modify the test equipment to resolve the NO_x measurement discrepancy.

Sensors Inc. developed a remedial upgrade to estimate the chiller NO₂ loss and numerically correct the NO₂ measurement. The upgrade package included a drain manifold relative humidity sensor and software upgrade and is now commercially available on all new SEMTECH-DS units and as a retrofit for existing SEMTECH-DS systems. After Sensors Inc. implemented the upgrade for the SEMTECH-DS, all units passed the NO₂ penetration check. All of the data used in the Monte Carlo Model reflect the use of this retrofit. Figure 1 shows the PEMS NO_x concentration error during steady-state engine testing before and after the system upgrade. The negative bias of the original data set was replaced with pooled errors showing a slight positive bias.

EXHAUST FLOW METER LINEARITY – The Sensors Inc. electronic flow meters (EFMs) were checked for flow linearity using a flow calibration stand. The flow stand used NIST traceable reference laminar flow elements (LFEs) with positive displacement blower to pull air through the reference LFE and EFM. Two 12.7-cm diameter flow meters passed the linearity verification, while one 12.7-cm unit failed the check. The noncompliant 12.7-cm EFM was recalibrated at Sensors Inc., after which it passed the linearity verification at the measurement allowance test lab.

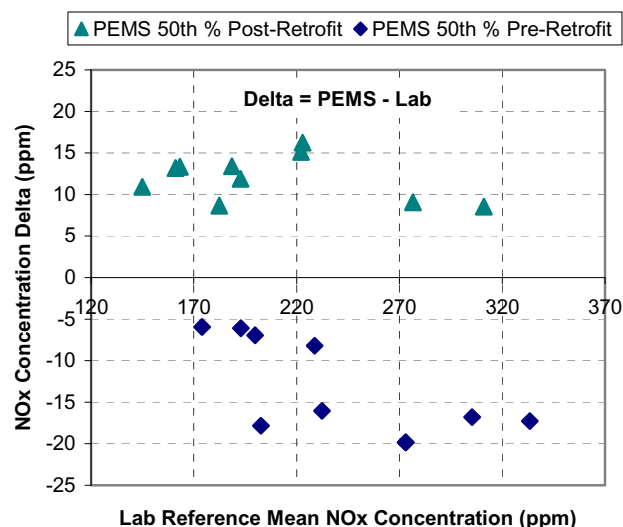


Figure 1. PEMS NO_x Concentration Pooled Delta Data from Engine 1 Steady-State Repeat Testing Before and After Chiller NO₂ Penetration Retrofit Installation

However, the initial linearity checks with the 7.6 and 10.2-cm EFMs resulted in linearity failures, therefore the smaller diameter meters were sent to Sensors Inc. for re-calibration. Linearity verifications on the newly calibrated meters also failed at the test lab, with low slopes for the 10.2-cm flow meters, and even lower on average for the 7.6-cm flow meters.

Considerable effort was directed into determining the root cause for the 7.6 and 10.2-cm flow meter linearity failures. Sensors Inc. used a similar LFE-based flow stand to calibrate their electronic flow meters. However, the Sensors Inc. flow stand used a blower to push air through the reference and test flow meters. Therefore, the flow meters calibrated at Sensors Inc. were under slight positive pressure, but were under slight negative pressure during the linearity testing for the measurement allowance program. The pressure discrepancy between the flow stands at the test lab and Sensors Inc. may have been a factor contributing to linearity failures of the 7.6 and 10.2-cm flow meters.

Presented with the linearity data, the Steering Committee decided to authorize recalibration of the Sensors Inc. flow meters using the test lab linearity data. The average slope adjustment was on the order of a four percent positive offset for the 7.6 and 10.2-cm flow meters. As discussed in the steady-state testing section of this paper, the recalibration of the 7.6 and 10.2-cm EFMs resulted in increased PEMS exhaust flow rate measurement errors during steady-state testing.

ENGINE DYNAMOMETER TESTING

Engine testing was performed to characterize bias and precision errors for the SEMTECH-DS instruments versus laboratory grade emission measurement

equipment. Analyzer and exhaust flow rate measurements were compared over both steady-state and transient engine operation. Several engine laboratory tests were designed to evaluate errors associated with ECM-broadcast channels and subsequent interpolation errors of torque and BSFC. Finally, tests were conducted to assess the exhaust flow measurement errors due to installation related factors.

Engine dynamometer tests were conducted using three model year 2005 and 2006 test engines. Engine one was a Detroit Diesel Corporation Series 60 Heavy Heavy-Duty (HHD) engine, engine two was a Caterpillar C9 Medium Heavy-Duty (MHD) engine, and engine three was an International VT 365 Light Heavy-Duty (LHD) engine. These engines were contributed to the program by the engine manufacturers, along with all support needed to insure successful engine operation. In order to simulate 2007 HDDE exhaust composition, several diesel particulate filters (DPFs) were installed in the exhaust systems of the various engines during testing. The filters were designed to regenerate primarily via passive regeneration, as active regeneration systems were not available at the time of this program.

The engine laboratory reference measurements used for this program were made using a transient capable engine dynamometer test cell, with full-flow CVS dilution tunnel. The test cell was capable of simulating a wide variety of ambient conditions in order to facilitate several torque and BSFC error experiments. All PEMS concentration measurement errors used in the Model were generated using the dilute laboratory measurements as the reference value. However, raw exhaust laboratory measurements were also conducted during the program for quality assurance purposes. The laboratory reference measurement techniques are summarized in Table 2. All calculations were performed using methods detailed in 40 CFR Part 1065. Unless otherwise stated, all engine tests were run using U.S. EPA certification grade ultra-low sulfur 2-D diesel fuel.

40-POINT ENGINE MAP GENERATION – An initial task completed during engine dynamometer testing was to generate 40-point engine maps for torque, BSFC, emission concentrations, and exhaust flow rate for the PEMS and reference laboratory. The points were chosen by the Steering Committee, and were distributed over the engine torque versus engine speed domain of the NTE zone. The 40-point maps were used to create interpolation surfaces for the estimation of ECM Torque and ECM BSFC from ECM broadcast speed and fuel rate. The emission results from these points were considered when selecting the 10 test points to be used in subsequent steady-state error surface experiments. The 10 points were selected to evenly span NO_x concentration, exhaust flow rate, and NO_x mass flow rate observed during 40-point testing, and to provide adequate distribution over the NTE zone.

Table 2. Laboratory Reference Methods

PEMS Measurement	Laboratory Reference	Reference Method
Gaseous Analyzers	Dilute Emission Analyzers ¹	Raw concentrations calculated from dilute concentrations using laboratory CVS and raw exhaust flow rates
Raw Exhaust Flow	Measured Intake Air Flow and Fuel Flow	Air Flow measured using Laminar Flow Element (LFE) Fuel Flow measured using coriolis type meter
Predicted Torque (from CAN)	Measured Torque	Shaft mounted in-line torque meter
Predicted BSFC (from CAN)	Measured Fuel flow and Power	See above notes
¹ Reference NMHC levels were based on laboratory raw measurements due to low levels.		

Shown in Figure 2, three PEMS devices were tested simultaneously during all engine testing because PEMS exhaust flow rate measurements showed no biases when tested in series. However, due to various equipment failures, the same three PEMS were not used for all three engines.

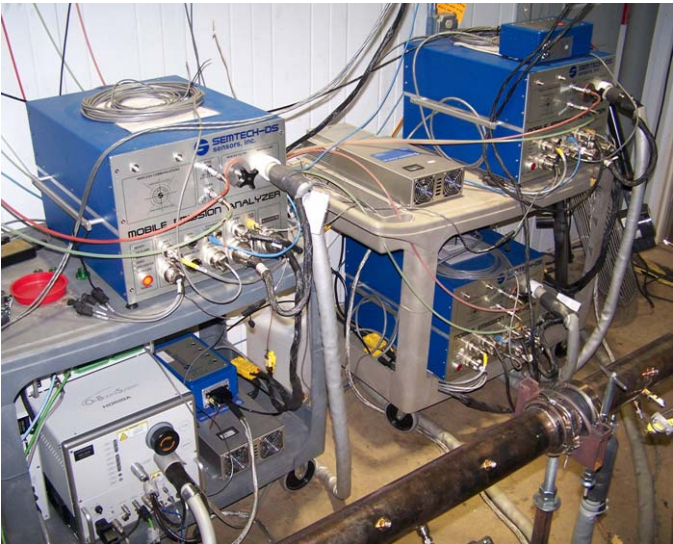


Figure 2. PEMS Instrumentation Setup in the Dynamometer Test Cell

STEADY-STATE TESTING AND ERROR SURFACES - Repeat steady-state engine testing was performed to quantify PEMS bias and precision errors versus laboratory emission measurement equipment. The measurement errors evaluated during steady-state testing included gaseous emission concentration measurements and exhaust flow rate measurements. The 10-mode steady-state cycles were repeated 20 times, with the mode order randomized for each test.

The laboratory reference analyzers were zeroed and spanned before and after each 32-minute cycle, while the PEMS were only spanned at the start of each test day, and were zeroed prior to the start of each test. This was roughly equivalent to zeroing the instrument every hour, which is the recommended schedule for auto-zero maneuvers during field measurements.

The wet-corrected gaseous PEMS concentration data and EFM data were compared to the laboratory reference. Each PEMS measurement was compared individually to the laboratory reference for each repeat of the steady-state cycle. These errors, or deltas, were pooled to generate steady-state error surfaces for each engine. The 5th, 50th, and 95th percentile values of the pooled error terms were plotted against the mean laboratory reference measurement. Figure 3 shows the pooled PEMS NO_x measurement errors for engines one, two, and three.

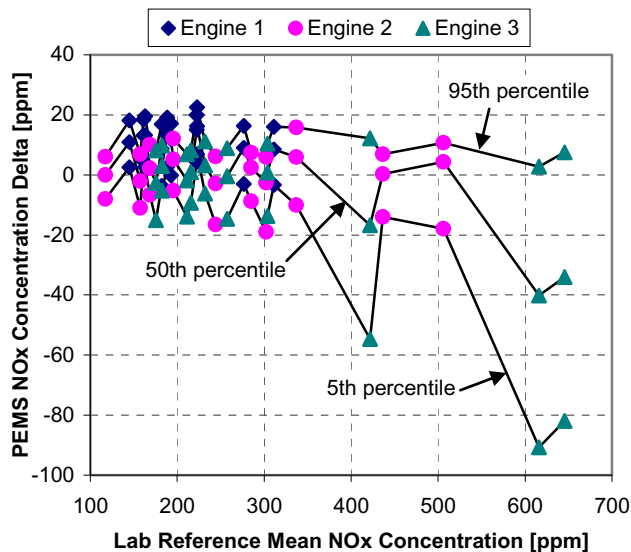


Figure 3. Steady-State NO_x Concentration Error Data for Engine 1, 2, and 3

In general, PEMS NO_x measurement errors were within ± 20 ppm. However, two SEMTECH-DS instruments showed repeated low NO_x measurements above 300 ppm during testing with Engine three. Post-test span checks for all PEMS, conducted using the instrument span port, indicated no problems despite the low bias. Several diagnostic tests were performed immediately after steady-state testing with the PEMS to determine the cause of the bias. Linearity verifications for NO and NO₂ showed no indication of problems with the instruments. As a check, dry span gas was then overflowed to the sample line of the PEMS. At 100 percent of span value, NO read nearly 7 percent below the bottle concentration and NO₂ read over 4 percent low. At 70 percent of span value, NO read approximately 2 percent low while NO₂ read slightly over 1 percent low. At 30 percent of span value, both NO and NO₂ measurements were accurate. This confirmed

the low biases observed during testing, but only when the gas was introduced through the sample line.

After sampling ambient air over the weekend, the sample line inlet overflow checks with dry NO and NO₂ span gas were repeated. Low biases were not observed during the repeated checks. A possible explanation for the performance difference is the drying of accumulated water in the sample handling system. It is not known why two of the PEMS showed a low bias while the third did not during Engine three steady-state testing; however, none of the analyzers failed any of the 1065 performance checks during this time. The Steering Committee elected to accept the biased steady-state data because a specific cause for the low NO_x bias was not evident, and because the PEMS continued to pass all pertinent 1065 audit verifications.

Because NO_x concentration error profiles for the three engines were notably different, the combined final error surface was extremely irregular, displaying sharp transitions in areas where concentration values for the three engines overlapped. The original intent of testing three engines was to generate a broad, uniform, well-distributed final error surface. The underlying assumption with this method was that the three engines would produce similar errors, and the combined error surface would therefore be relatively uniform. Because the steady-state concentration error surfaces were sampled normally, the 5th and 95th percentile deltas were to represent the largest, or worst case, delta values. Following that argument, if all engines would have generated deltas at all x-axis concentration levels, the 5th percentile value would have been generated by the engine having the lowest bias and the 95th percentile would have been generated by the engine reporting the highest bias.

The steering committee elected to reprocess the final error surfaces by linearly interpolating between each engine's error surface data points to populate x-axis values generated by the other engines. For example, the Engine 1 deltas were used to linearly interpolate Engine 2 deltas that would have occurred at the other x-axis concentrations. This method was applied to the 5th, 50th, and 95th percentile values for each engine. For concentration values beyond the range of data actually taken for a given engine, the method for generating delta values depended on the trends observed in the measured data. If no definite trend was observed in the data for a given engine, the nearest x-axis error value was repeated to generate the extrapolated data (i.e., the first or last data point of the data set). If a trend was evident, a regression line was fit through the engine's delta data. The regression line was then used to generate deltas for points requiring extrapolation.

Using the method described above, a 5th, 50th, and 95th percentile delta was generated for all three engines at each of the 30 x-axis mean laboratory reference points.