

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

Part 2 – Statistical Modeling and Simulation Approach

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ABSTRACT

Beginning in 2007, heavy-duty engine manufacturers in the U.S. have been responsible for verifying the compliance of in-use vehicles with Not-to-Exceed (NTE) standards under the Heavy-Duty In-Use Testing Program (HDIUT). This in-use testing is conducted using Portable Emission Measurement Systems (PEMS) which are installed on the vehicles to measure emissions during field operation. A key component of the HDIUT program is the generation of measurement allowances which account for the relative accuracy of PEMS as compared to conventional laboratory-based measurement techniques. A program to determine these measurement allowances for gaseous emissions was jointly funded by the U.S. Environmental Protection Agency (EPA), the California Air Resources Board (CARB), and various member companies of the Engine Manufacturer's Association (EMA). The gaseous pollutants examined in the program were carbon monoxide (CO), non-methane hydrocarbons (NMHC), and oxides of nitrogen (NO_x). As part of a three-paper series, this paper summarizes the part of this program that involved the development of the Monte Carlo simulation model and describes the methodology used in determining the additive emission measurement allowances for in-use testing. It also describes the

validation phase of this project, including a summary of the comparisons of the simulation model outcomes to the PEMS results obtained 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]. CE-CERT is the Center for Environmental Research & Technology at the University of California-Riverside which operates the Mobile Emissions Laboratory. 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. The first paper in this series gives an overview of the program, and provides details regarding the individual experiments that were run to investigate various sources of PEMS measurement error [10]. This second paper describes the statistical methodology used during the program, and the model simulation that was developed. The third paper focuses on the model results, validation exercises, and analysis [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].

INITIAL CONSIDERATIONS

A logical approach for generating PEMS measurement allowances could have been to test PEMS against some kind of mobile laboratory reference on a large number of vehicles and quantify the resulting errors directly. However, such an approach would have been prohibitively expensive in terms of both time and funding. This type of testing would also have required manipulation of external parameters that are difficult to control in the real-world (e.g., radio frequency interference, ambient levels of hydrocarbons). In addition, the desired laboratory reference point for error comparison was certification testing, which is normally conducted in a dynamometer laboratory facility. Therefore, a simulation approach was chosen in order to generate the measurement allowances. All the expected sources of PEMS measurement errors were identified so that they could be quantified using a series of controlled laboratory experiments, each designed to isolate errors related to a single source [16]. The outcome of each experiment would be an empirical model of a given source of measurement referred to as an error surface. Each error surface would represent an

incremental error of PEMS measurement as compared to an associated laboratory reference measurement.

The error surfaces were programmed into a computer model using Microsoft® Excel and Crystal Ball® forecasting and simulation software which employed Monte Carlo random sampling methods to simulate the combined effects of all of these sources of error on the final measured brake-specific (BS) emissions value. These included BSNO_x, BSCO and BSNMHC measured in g/kW-hr.

The components of this study that are addressed in this paper include (1) the description of the simulation methodology including the emissions calculation methods, (2) the distribution assumptions of the various errors measured during the dynamometer engine testing and environmental chamber testing, (3) the sampling method and interpolation approach in modeling the 37 different error surfaces, and (4) the time alignment and periodic drift check procedures for the brake-specific emissions. Issues related to the Monte Carlo simulation convergence criteria, run-time checks, and statistical simulation options are discussed. In addition, statistical methods for computing the measurement error allowances from the simulation results for BSNMHC, BSCO and BSNO_x are presented.

A summary of the statistical regression techniques for comparing the simulated and on-road data are provided in addition to an evaluation of the sensitivity of the various emissions measurement errors to the final simulated error differences.

DESCRIPTION OF MODEL AND SIMULATION PROCEDURE

The simulation model generated data for computing the brake-specific NMHC, CO and NO_x measurement error allowances by three different calculation methods in accordance with methods outlined in the Code of Federal Regulations 40 Part 1065 Subparts G and J. 40CFR Part 1065 allows for the use of any of three different calculation methods in order to determine brake-specific emission values from in-use test data.

EMISSIONS CALCULATION METHODS

The three calculation methods vary somewhat in the approach used to determine either the flowrate component or the work component of this calculation. Because each method relies on different inputs, it is possible that each method of calculation will react differently to various measurement errors. Therefore, measurement allowances must be examined independently for each method. The three calculation methods are referred to as Method 1 (Torque-Speed Method), Method 2 (BSFC Method) and Method 3 (ECM Fuel Specific Method). Formulas for each calculation

method are given in the equations below and described in more detail in Reference 16.

Equation (1):

$$Method\ 1 = \frac{\sum g}{\sum Work} = \frac{\sum (concentration \times exhaustflow)}{\sum (speed \times torque)}$$

Equation (2):

$$Method\ 2 = \frac{\sum g}{\sum \left[\frac{CB\ fuel}{BSFC} \right]} = \frac{\sum (concentration \times exhaustflow)}{\sum \left(\frac{exhaustflow \times concentration_{carbon} (HC + CO + CO_2)}{BSFC} \right)}$$

Equation (3):

$$Method\ 3 = \frac{\sum \left[g \times \frac{ECM\ fuel}{CB\ fuel} \right]}{\sum Work} = \frac{\sum \left(\frac{concentration \times fuelflow}{concentration_{carbon} (HC + CO + CO_2)} \right)}{\sum (speed \times torque)}$$

Method 1 is referred to as the “Torque-Speed” method and is similar to the method used to calculate laboratory emission results in that flow and work are calculated directly from measured or, in the case of torque, predicted quantities. Method 1 depends on accurate exhaust flow measurement.

Method 2 is referred to as the “BSFC” method. This method flow weights individual data points against the total measured exhaust flow for a given NTE event, and uses a carbon balance method and a predicted brake-specific fuel consumption (BSFC) to transform measured values to brake-specific results. As a result of the flow weighting, Method 2 depends on the exhaust flow measurement to be linear, but not necessarily accurate.

Method 3 is referred to as the “ECM Fuel Specific” method. This method does not involve direct measurement of exhaust flow. Instead, it relies on the engine control module (ECM) broadcast fuel rate and carbon balance to produce mass emission rates, and on ECM broadcast torque and speed for work. As a result this method is wholly dependent on the accuracy of ECM broadcast signals, but is not subject to exhaust flow measurement errors. It should be noted that the use of this method in the HDIUT program would require prior approval by EPA.

NTE THRESHOLDS FOR SCALING OF RESULTS

Throughout the measurement allowance program were a number of key parameters designed to be scaled to a set of compliance threshold values. For this program, a single set of NTE threshold values was determined by the Steering Committee. The threshold values were determined based on the 2007 heavy-duty diesel standards, and incorporated the relevant NTE multiplier and initial “placeholder” measurement allowance value.

The NTE threshold values used for the program are given in Table 1.

Table 1. NTE Threshold Values Used During the Measurement Allowance Program (based on 2007 HDDE Standards)

Pollutant	NTE Threshold	
	g/hp-hr	g/kW-hr
BSNMHC	0.21	0.2816
BSNO _x	2.00	2.6820
BSCO	19.40	26.0200

FLOWCHART OF MONTE CARLO PROCEDURE

The process of simulating the BS emissions differences involved the following steps: (1) select the emissions and operating data from a reference NTE event, (2) randomly select errors from the appropriate error surfaces, (3) apply the errors to the BS emissions from the reference NTE event, (4) apply a time alignment adjustment as a source of error in the PEMS data, and (5) calculate the final BS emissions differences between the emissions “with errors” and the “ideal” emissions (e.g., calculated level for the given reference NTE event with no errors applied). Steps (2) through (5) were repeated up to 30,000 trials for each reference NTE event simulation. The 95th percentile of the BS emissions differences from the trials was selected as a simulation of the reference NTE events. This process was repeated for all 195 reference NTE events simulated in this study. Figure 1 is a graphical representation of the simulation process for BSNO_x differences. The symbols in the figure are explained in more detail below.

SELECTION AND USE OF REFERENCE NTE EVENTS

In order to provide a realistic simulation of engine operating conditions a collection of NTE event reference data was compiled representing real-world PEMS data sets. These reference NTE events were gathered from various sources: the transient lab experiments on each of the three engines tested at SwRI, pre-pilot CE-CERT data, and five engine manufacturers. CE-CERT is the Center for Environmental Research & Technology at the University of California-Riverside which operates the Mobile Emissions Laboratory (MEL). Data were collected with the MEL during on-road testing. In some cases the NTE events were adjusted to cover a larger range of the emissions. This was done to help insure that the NTE events being simulated covered a credible representation of actual emissions values. Table 2 summarizes some descriptive statistics for the 195 reference NTE events simulated in this study.

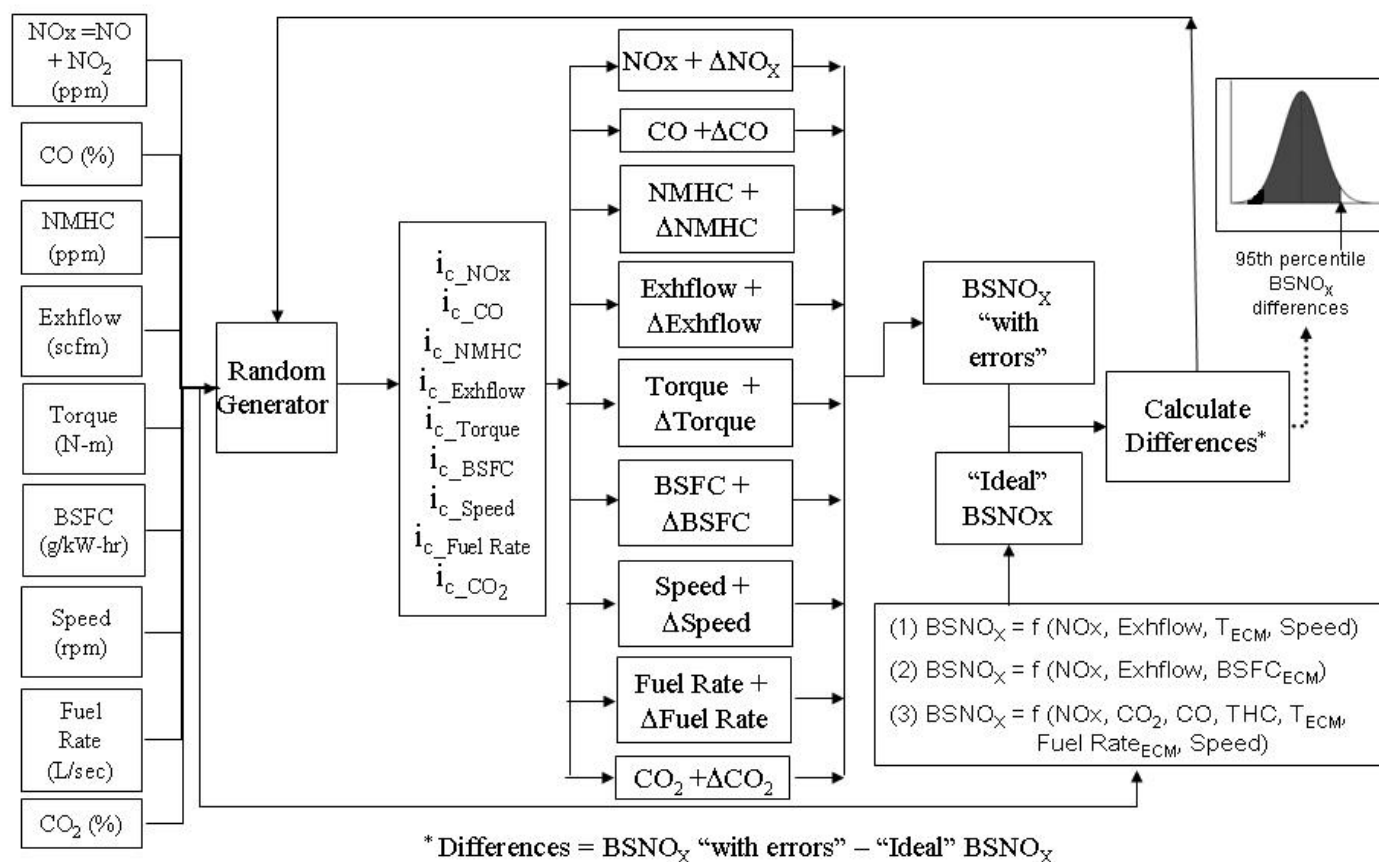
Figure 1. Overview of Monte Carlo Simulation for BSNO_x

Table 2. Descriptive Statistics for BS Emissions for 195 Reference NTE Events

Descriptive Statistic	BSNO _x g/kW-hr	BSCO g/kW-hr	BSNMHC g/kW-hr
Minimum	0.0249	0.0000	0.0000
Maximum	7.1927	5.9949	0.4258
Mean	3.0071	0.5936	0.0287
Median	2.6033	0.3836	0.0021
Standard Deviation	1.4807	0.7129	0.0591

Underlying statistical distributions and assumed parameters

Multiple data collected at a given laboratory "nominal" value were used to represent the distribution of (PEMS minus Laboratory) "delta errors". Since there was neither an underlying assumption on the type of distribution the deltas possessed, nor an engineering reason for a particular distribution, the repeat measurements at a specific operating condition were used to identify the nonparametric 5th, 50th and 95th percentiles. This eliminated endpoints when at least 20 repeat measurements were made.

An example of the error surface created for the steady-state (SS) NO_x delta error, including the "error band" measured during testing, is illustrated in Figure 2. This plot was created by first subtracting the individual "lab nominal" NO_x value from the corresponding individual PEMS NO_x measurement for each test run. This difference was defined as the "delta" error. Second, these "PEMS minus Laboratory" delta errors were pooled at each average lab nominal NO_x value to obtain the 5th, 50th, and 95th percentile values displayed in Figure 2. The resulting plot represents the average NO_x lab nominal at 30 discrete concentration levels versus

PURPOSE OF ERROR SURFACES

Thirty-seven error surfaces were created to represent incremental errors of each PEMS measurement, as compared to an associated laboratory reference measurement. Data for these error surfaces were derived from laboratory experiments on three selected engines, environmental experiments, or from historical data provided by the engine manufacturers [16].