APPENDIX C

DETERMINATION OF MEASUREMENT ALLOWANCES THROUGH LABORATORY TESTING, COMPUTER MODELING, AND OVER-THE-ROAD TESTING VALIDATION

In 2006, the Air Resources Board (ARB or Board) adopted a new heavy-duty in-use testing (HDIUT) program. This compliance program incorporated temporary measurement allowances when testing for compliance using portable emission measurement systems (PEMS). Measurement allowances are needed to account for measurement error associated with using PEMS in the field during over-the-road vehicle operation, instead of testing the engine in a controlled laboratory environment on an engine dynamometer. Prior to the adoption of this program, an agreement was made between ARB, the United States Environmental Protection Agency (U.S. EPA), and the Engine Manufacturers Association (EMA), along with individual engine manufacturers, to fund a research program that establishes appropriate measurement allowances for each regulated pollutant. A research program was developed through the guidance of a Measurement Allowance Steering Committee (MASC), comprised of members from ARB, U.S. EPA, and the engine manufacturers. Testing, statistical modeling, and model validation of three different measurement allowance methods has been completed by the main contractor, Southwest Research Institute (SwRI), in San Antonio, Texas, with the help of the University of Riverside's Center for Environmental Research and Technology (CE-CERT).

The overall research program was a multi-faceted, complex research program that can be described with the following chronological steps:

1. Statistical model selection for measurement allowance generation

2. Testing for data generation using engine dynamometers and environmental chamber laboratories

3. Model simulation runs for measurement allowance determination

4. Initial model validation of measurement allowances

5. Additional model validation work and revised measurement allowances

1. Statistical Model Selection for Measurement Allowance Generation

A key element of the research program involved the use of a comprehensive and rigorous statistical modeling method to generate measurement allowances. A direct approach could have been to test PEMS against some kind of mobile laboratory reference, on a large number of vehicles, and quantify measurement errors directly. An example of this would be the mobile emissions laboratory used by CE-CERT. However, this approach would have been prohibitively expensive and time consuming. Also, it was felt that the desired laboratory reference point for error comparison was certification testing, normally conducted on an engine dynamometer in a laboratory. Since it was not feasible to conduct enough representative experiments to directly quantify measurement allowances, the MASC recommended a methodology that involved the use of a statistical model for the determination of potential measurement errors. In this approach MASC would define all the sources of PEMS measurement errors, based on existing in-use testing expertise and the understanding of how the PEMS functions. It was then agreed that each of these errors would be quantified using a series of controlled laboratory experiments, each designed to isolate errors related to a single error source.

The heavy-duty diesel engine (HDDE) exhaust emission standard is expressed in terms of grams per brake horsepower-hour (g/bhp-hr). To measure exhaust in terms of g/bhp-hr, three separate inputs are needed. These include pollutant concentration in the exhaust, total engine exhaust flow rate, and the horsepower of the engine. There is the potential for measurement errors when these parameters are measured using PEMS, compared to the same measurements made by laboratory instruments. Because PEMS are exposed to an open and uncontrolled environment, these errors are introduced from variations of temperature, humidity, road vibration, and other factors. Potential errors are also introduced when instantaneous torque or fuel rate information is provided (or "broadcasted") to the PEMS by the engine's on-board computer. Thus, numerous experiments were conducted at SwRI to account for, and quantify, the margin of errors associated with all these variables.

The margin of errors were then programmed into a computer model, called the "Monte Carlo" model that employed statistical random sampling methods to simulate the combined effects of all sources of error on the final measured brake-specific emission value. For further details on the Monte Carlo model development, data simulation, and measurement error determination see SwRI Report, Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated under the Heavy-Duty Diesel Engine In-Use Testing Program, March 2007, (SwRI (2007a)).

2. Testing for Data Generation Using Engine Dynamometers and Environmental Chamber Laboratories

Since manufacturers certify their engines on an engine dynamometer in a laboratory, it was essential to test candidate engines simultaneously with PEMS and an engine dynamometer. Certified 2005 and 2006 model year HDDEs were tested, one engine typically used in a heavy heavy-duty vehicle with a gross vehicle weight rating (GVWR) of over 33,000 pounds, one typically used in a medium heavy-duty vehicle (GVWR between 19,501 to 33,000 pounds), and one typically used in a light heavy-duty vehicle (GVWR between 8,500 to 19,500 pounds). In order to simulate a post-2007 test environment, SwRI procured and installed diesel particulate filters for the three test engines.

The original intention of the program was to examine PEMS from more than one manufacturer. However, at the time of testing only one PEMS manufacturer, Sensors Incorporated, was able to supply commercially available PEMS for the program. Therefore, the measurement allowance values are based solely on PEMS measurements using the Sensors Inc. SEMTECH-DS. Multiple SEMTECH-DS units were used during the program, often in parallel with each other, in order to assess PEMS-to-PEMS variability. Late in the program, several Horiba OBS-2200 PEMS were incorporated into the program as time and resources allowed. However, all measurements made with the OBS-2200 units were used for informational purposes only, and thus were not used for the final measurement allowance determination.

Engine dynamometer laboratory tests were conducted to establish the error between the PEMS emission analyzers and flow-meters against laboratory grade instruments. This required auditing all the PEMS and laboratory equipment in advance to ensure that they were operating properly, according to 40 CFR Part 1065 Subpart D (U.S. EPA (2005 c)). The laboratory tests involved determining the PEMS measurement errors compared to the lab instruments for steady-state and transient Not-to-Exceed (NTE) events. Also quantified was the impact of the engine control module's (ECM) ability to derive torque and brake specific fuel consumption (BSFC) compared to measured values in the laboratory. The ability of the PEMS to measure exhaust flow using different flow meter installations was also observed.

Environmental chamber tests were conducted to expose the PEMS to a variety of environmental factors, namely electromagnetic interferences, atmospheric pressure, temperature, humidity, vibration, and ambient hydrocarbon levels. During these tests, PEMS sampled a series of reference gases, and errors quantifying the reference values were calculated. The tests were designed to mimic real-world environmental factors with magnitude and frequency adjusted to the real-world conditions.

All emission calculations for brake-specific emission values were done using three calculations methods, as per 40 CFR Part 1065 Subparts G and J. The three calculations methods are (1) torque-speed, (2) BSFC, and (3) fuel specific methodologies. All three calculations provide work-based or "brake-specific" mass emissions results in units of g/bhp-hr. The Monte Carlo model was run on a set of 195 pre-determined reference NTE test points.

3. Model Simulation Runs for Measurement Allowance Determination

The determination of a set of brake-specific measurement allowances was the final goal of the research program. The test plan for this program outlined a methodology by which all of the data from the model simulation runs would be collected and analyzed statistically, in order to generate a set of three potential measurement allowances for each pollutant, one for each of the three calculation methods. The test plan outlined a specific method by which the final (i.e., numerically lowest) set of validated allowances for NOx, NMHC, and CO would be chosen.

4. Initial Model Validation of Measurement Allowances

As discussed, the model generated a set (NOx, NMHC, and CO) of measurement allowances for each of the three calculation methods. As a final confirmation, these data sets needed to be validated against a data set generated through actual in-use field testing. This is because the model generated an incremental offset in comparison to a laboratory reference. Thus, a suitable in-use reference measurement was needed. The MASC recommended that the CE-CERT mobile emission laboratory would be an appropriate reference for validation of the model with over-the-road field testing.

In order to insure that the validation was not affected by some inherent bias between the SwRI reference laboratory and the CE-CERT mobile emission laboratory, a correlation exercise was also performed between the two laboratories prior to the start of on-road validation efforts. The mobile emission laboratory was brought to SwRI's laboratory, where side-by-side correlation testing was conducted. During these tests, exhaust from the same test engine was alternately routed to the measurement systems of both SwRI and the mobile emission laboratory. The generated data showed that correlation between the facilities was acceptable.

After the correlation exercise was completed, a test truck was supplied to CE-CERT by a participating engine manufacturer. In addition, one of the PEMS used for testing at SwRI was also delivered to CE-CERT. CE-CERT then conducted a series of on-road test runs over various driving routes in California, which were designed to take the test truck through a wide range of environmental and ambient conditions (altitude, temperature, humidity, etc.). During these tests, simultaneous measurements were made with both the PEMS and the mobile emission laboratory.

Because the mobile emission laboratory is not capable of measuring vehicle torque directly, additional testing was conducted at SwRI to account for potential errors associated with measuring torque and BSFC. This involved removal of the engine from the test truck used by CE-CERT, and installation of that engine in SwRI's dynamometer test cell.

A full description of the validation efforts, including the data analysis methodology and the results of validation for each pollutant by all three calculation methods is given in Section 6 of SwRI's final report (SwRI (2007)). Details of CE-CERT's on-road validation testing are provided in a separate report, titled Measurement Allowance Project-On-Road Validation, March 2007 (CE-CERT (2007)).

As mentioned, a set of measurement allowance values were determined for each calculation method. These are shown in Table 1. The measurement allowance values here are expressed as a percentage of the NTE threshold limits[1] shown in Table 2. In order for a measurement allowance value to be considered valid, measured emissions during over-the-road testing with PEMS were compared to the emissions measured by the mobile emissions laboratory. The differences, or "measurement errors", had to be within the range of measurement predicted by the Monte Carlo model. The results of the model validation are also shown in Table 1; values indicated in white cells were validated successfully, while values shown in gray cells were not validated with the data set initially used in the analysis.

Table 1 Model Results and Validation

Measurement Allowance (%) at Respective NTE Threshold			
Emission	**Method 1 "Torque-Speed"**	**Method 2 "BSFC"**	**Method 3 "ECM Fuel Specific"**
BSNOx	**22.30**	**4.45**	**6.61**
BSNMHC	**10.08**	**8.03**	**8.44**
BSCO	**2.58**	**1.99**	**2.11**
Note: values in white cells were validated successfully, while values shown in gray cells were not validation.			

[1] NTE threshold limits for NOx, NMHC, and CO were agreed upon by the MASC based on expected NTE compliance limits for engines certified to the 2007 model year HDDE emission standards.

Table 2 NTE Thresholds (g/bhp-hr)

NOx	**2.0**
NMHC	**0.21**
CO	**19.4**

As shown in Table 1, the model result for NO_x did not validate for calculation method 2 and 3, while the CO results did not validate for any of the three calculation methods. The model result for NOx was validated only for calculation method 1, while model result for NMHC was validated for all three calculation methods. Note that 2007 model year and newer engines (likely to be evaluated in the HDIUT program) are likely to be several orders of magnitude below the CO NTE threshold, and therefore the lack of validation for CO is not deemed to be a significant issue.

With the validation of CO not considered critical for the purpose of the HDIUT program, only Method 1 contained validated values for the other pollutants. The additive measurement allowance value for NOx, 0.45 g/bhp-hr, is calculated using the NOx NTE threshold value, 2.0g/bhp-hr, multiplied by 0.223, the measurement allowance percentage indicated in Table 1. The same calculation can be used to derive the measurement allowance values for NMHC and CO, as shown below in Table 3. In February 2007, the MASC accepted these candidate measurement allowance values but agreed that they would only be temporary until (and if) additional testing/analysis allowed the validation of more representative measurement allowances using the other methods. As a result, and to provide some stability for the manufacturers, the MASC recommended that method 1 be used (Torque-Speed method) for the measurement allowances through the 2009 model year.

Table 3 Measurement Allowances for 2007 – 2009 Model Year

Pollutant	Measurement Allowance, g/bhp-hr	NTE Threshold, g/bhp-hr
NOx	**0.45**	**2.0**
NMHC	**0.02**	**0.21**
CO	**0.50**	**19.4**

5. Additional Model Validation Work and Revised Measurement Allowances

Additional analyses and modeling runs were performed at SwRI in an effort to validate the other measurement allowances methods (method 2 and 3). Specifically, the MASC agreed to further refine the model with modified assumptions and additional modeling runs.[2] The additional modeling analysis validated all three brake specific emission calculation methods (method 1, 2, and 3), resulting in method 2 (the BSFC method) validating to the lowest and most stringent measurement allowances, presented in Table 4 below.

The MASC agreed that these new measurement allowances should be used when conducting the HDIUT program, starting with 2010 and subsequent model year HDDEs. The MASC also agreed that manufacturers should be allowed to use any of the three measurement calculation methods so long as they use the most stringent measurement allowance values established by method 2. The establishment of new and more stringent measurement allowances was essential for having an effective compliance program, especially the measurement allowance for NOx emissions.

Table 4 Measurement Allowances for 2010 and Subsequent Model Year

Pollutant	Measurement Allowance, g/bhp-hr	NTE Threshold, g/bhp-hr
NOx	0.15	0.45 [1] - 0.65 [2]
NMHC	0.01	0.22
CO	0.25	19.63

1. NOx threshold value is 0.45 g/bhp-hr for 2012 and subsequent MY engines when the "in-use compliance margin" provision in the 2007 HDDE regulation expires.
2 NOx threshold value is 0.55 to 0.65 g/bhp-hr for 2007–2011 model year engines, depending on the vehicle's odometer readings when applying the in-use compliance margin provision established in the 2007 HDDE regulation.

[2] See Presentation on 'Results of HDIUT Modeling Runs Using Revised Error Surfaces,' (SwRI (2007b))