

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

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ABSTRACT

This paper summarizes the Heavy-Duty In-Use Testing (HDUIT) measurement allowance program for Particulate Matter Portable Emissions Measurement Systems (PM-PEMS). The measurement allowance program was designed to determine the incremental error between PM measurements using the laboratory constant volume sampler (CVS) filter method and in-use testing with a PEMS. Two independent PM-PEMS that included the Sensors Portable Particulate Measuring Device (PPMD) and the Horiba Transient Particulate Matter (TRPM) were used in this program. An additional instrument that included the AVL Micro Soot Sensor (MSS) was used in conjunction with the Sensors PPMD to be considered a PM-PEMS. A series of steady state and transient tests were performed in a 40 CFR Part 1065 compliant engine dynamometer test cell using a 2007 on-highway heavy-duty diesel engine to quantify the accuracy and precision of the PEMS in comparison with the CVS filter-based method. Additional tests were performed to investigate the susceptibility of the PEMS to ambient pressure, ambient temperature, electromagnetic/radio frequency interference, and vibration. The experimental data were used as input to 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. This paper focuses on the laboratory efforts conducted to determine the PM-PEMS measurement allowance.

It was discovered that the largest source of error was the ability to accurately measure the PM concentration level during steady state engine testing. The precision of the PEMS under transient operation contributed a much smaller but still significant error while the additional error observed during environmental testing was insignificant. The magnitude of the error surfaces was generally smallest for the AVL and largest for the Sensors PEMS. Validation of the model was performed with a mobile CVS laboratory during on-highway operation. The AVL PEMS validated for one of the three calculation methods, while the Sensors PEMS did not validate. Based upon successful validation of the AVL PEMS, the measurement allowance of 0.006 g/hp-hr, which was generated based on the Sensors PPMD laboratory efforts at an NTE threshold level of 0.02 g/hp-hr, was accepted for the HDUIT enforceable program. This measurement allowance value is added to the in-use threshold limit to take into account errors associated with PM-PEMS during in-use testing.

CITATION: Bougher, T., Khalek, I., Laroo, C. and Bishnu, D., "Determination of the PEMS Measurement Allowance for PM Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program," *SAE Int. J. Engines* 5(3):2012, doi: 10.4271/2012-01-1250.

INTRODUCTION

BACKGROUND

The U.S. Environmental Protection Agency's (EPA's) Heavy-Duty In-Use Testing (HDUIT) regulation of June 2005 mandates the measurement of carbon monoxide (CO), non-methane hydrocarbons (NMHC), oxides of nitrogen (NO_x), and particulate matter (PM) for diesel engines certified for Heavy-Duty On-Highway use. This regulation created a demand for commercially-available PEMS that would satisfy the requirements of 40 CFR Part 1065. The EPA in-use testing program was first announced in June 2004 and began with a two-year pilot program in which only gaseous emissions measurements were required. A program was initiated to experimentally determine the incremental error introduced by using a PEMS instead of a laboratory system to measure emissions. Southwest Research Institute (SwRI) conducted the measurement allowance program with funding from the Engine Manufacturers Association (EMA), the California Air Resources Board (CARB), and the EPA. The enforceable gaseous program began in 2007, after the gaseous measurement allowance program was completed and the additive gaseous measurement allowance values were finalized [1,2]. The measurement allowance program for PM was delayed due to the lack of commercially available PM-PEMS at the time. The separate PM measurement allowance program began in June of 2007 and was completed in June of 2010. The measurement allowance was finalized in a direct final rule in August 2010 [3]. The PM pilot program ended in 2010 with the enforceable program beginning in 2011.

The EPA and the EMA agreed to create a manufacturer-run Heavy-Duty In-Use Testing program with the purpose of ensuring that stringent emission standards were met under real-world driving conditions [1]. The measurement allowance program was designed to develop an experimentally derived emission measurement accuracy margin that properly accounts for the incremental error associated with making a PM measurement with a PEMS on a heavy-duty vehicle on the highway compared with the measurement using an engine dynamometer test cell under controlled conditions. Steady state measurements were used to compare the PEMS with the lab to quantify accuracy. Short transient not-to-exceed (NTE) events were used to compare the PEMS against themselves to quantify precision. A number of different environmental tests were performed to quantify errors associated with pressure, temperature, humidity, radio frequency interference, electromagnetic interference, and vibration. Before testing, comprehensive audits were performed on each of the PEMS as well as the lab to ensure that all relevant equipment was in compliance with the specifications set forth in CFR Part 1065. This paper focuses on the results from the steady-state and transient engine testing since these tests were most directly related to the performance of the PEMS, and most significantly affected the measurement allowance value.

The NTE event forms the basis of heavy-duty in-use compliance testing in the US. Emission regulations are only enforced during a valid NTE event, which is a continuous period of engine operation greater than 30 seconds where the engine is above 30 percent speed, torque, and power based on the engine manufacturers published lug curve. The validity of an NTE event is also subject to a number of exclusions such as cold-start, DPF regeneration, extremely high altitude, high temperature, etc. All engine testing, both steady state and transient, were conducted within the limits of valid NTE events to properly exercise the PEMS under realistic conditions.

The European Union (EU) began a gaseous PEMS study in 2004, and a pilot program that started in 2007. Laboratory testing for the PM-PEMS program was conducted between 2009 and 2010 with the pilot program beginning in 2011[4]. Fully enforceable testing for on-road heavy-duty engines will begin with the introduction of Euro VI emission standards in 2014. The major difference between U.S. and European in-use testing is that the EU program uses a CO₂ or work-based window to measure emissions rather than the NTE event. The CO₂ or work-based window integrates emissions over a moving period of time that produces an equivalent amount of work or CO₂ compared with the laboratory enforcement cycle. The EU has also conducted a laboratory verification of PM-PEMS; the EU program included the same three PEMS tested in this work, as well as three additional PEMS [4]. In 2010 the EU published PEMS In-Service Conformity provisions that apply to Euro V and future Euro VI standards for heavy-duty engines. Currently there are no active enforceable in-use testing programs outside of the US and EU. There are also no light-duty in-use compliance programs, although it is possible that they will be implemented in the future [5]. Discussion and planning for future non-road in-use testing are underway in both the US and EU.

PROJECT OVERVIEW

The purpose of this work was to determine the incremental error between PM measurements using the laboratory constant volume sampler (CVS) filter method and in-use testing with a PEMS. This program was directed and reviewed by the HDUIT steering committee, which was composed of representatives from EPA, CARB, EMA, and EMA member companies. The data being generated were constantly reviewed by the steering committee, and changes to the test plan were made by the steering committee based on deadlines, funding limitations, and testing results. The desire was to generate the Brake-Specific Particulate Matter (BSPM) measurement allowance based on rigorous statistical methods applied to a large body of data. At the same time, it was preferred to exclude outlier data caused by extreme measurement errors which were considered not representative of normal in-use operations. A direct approach could have been to test PEMS against a mobile laboratory reference on a large number of vehicles under a wide range of ambient

conditions, and quantify errors directly. However, such an approach would have been expensive in terms of both time and funding. Given these factors, the steering committee ultimately elected to use a simulation approach in order to generate the BSPM measurement allowance, similar to what was done in the gaseous in-use emissions testing program [2]. In this approach, the steering committee defined all of the expected sources of PEMS measurement errors based on existing in-use testing expertise and understanding of how the PEMS functioned. Each of these errors was quantified using a series of controlled laboratory experiments, each designed to isolate errors related to a single error source. The results of each experiment would essentially be an empirical model of a given source of measurement error. In this report, these error models are referred to as error surfaces. It is important to note that each of these error surfaces represents an incremental error of PEMS measurement, as compared to an associated laboratory reference measurement. The Bourns College of Engineering Center of Environmental Research and Technology (CE-CERT) mobile emissions laboratory (MEL) was used to validate the model in a smaller number of tests during on-highway testing.

The measurement allowance steering committee accepted the following PM-PEMS to be part of the measurement allowance program:

Sensors Particle Proportional Micro Diluter (PPMD) -A PM-PEMS that uses proportional dilution and a series of 8 quartz crystal microbalances to measure total (solid plus volatile) PM. The total PM is measured as a single flow-weighted value for a NTE event. The PPMD has an integrated exhaust flow measurement and receives its broadcast engine data and NTE trigger from the Sensors Semtech DS gaseous PEMS.

Horiba Transient Particulate Matter (TRPM) -A PM-PEMS that uses proportional dilution, a real time electrical aerosol detector, and an integrated filter sample to report total PM. The total PM is measured as a single flow-weighted value for a NTE event. This instrument can report real time total PM, but was not used as such during this program. The TRPM received its exhaust flow measurement and engine broadcast data from the Horiba OBS-2200 gaseous PEMS.

AVL Micro-Soot Sensor (MSS) -An instrument that uses constant dilution and a photo acoustic detector to measure soot or the elemental carbon portion of PM. Soot is measured in real time during an NTE event. Near the conclusion of this program AVL developed a filter sampling module that allowed the MSS to report total PM using an integrated filter measurement similar to the TRPM system. However, this system was not used in any of the testing at SwRI, so all AVL measurements reported in this work are actually elemental carbon (soot) rather than total particulate matter.

The steering committee agreed that only the PPMD by Sensors and TRPM by Horiba will be used for the official determination and validation of the measurement allowance generated because both are designated as complete PEMS and both measure total (solid plus volatile) PM, as required

by US EPA to be valid PM-PEMS. The AVL system was included in the program in case either of the other two PEMS failed to validate. Each PEMS manufacturer was given the option of using a correction factor to account for particle loss in the PEMS sampling system. Sensors and AVL elected to include loss correction in their post processors, which were approved by the steering committee. The loss corrections were typically on the order of ten percent but could be as high as 25 percent in certain situations. Horiba declined to include a loss correction for the TRPM.

There are three methods that can be used to determine in-use NTE brake-specific PM emissions. Full calculations for each method listed here can be found in the [appendix](#):

- Method #1: Exhaust Flow-Torque-Speed Method
- Method #2: Exhaust and Fuel Flow-Torque-Speed Method
- Method #3: Fuel Flow-Torque-Speed Method

All methods require engine control module (ECM) broadcasted torque and speed. In addition, Method 1 requires measured exhaust flow but not fuel flow; Method 2 requires measured exhaust flow, ECM broadcasted fuel flow, and gas-based fuel flow; Method 3 is similar to Method 2, but it does not require exhaust flow. All three calculation methods can be used for an instrument reporting mass concentration in real-time, but only Method 1 and Method 2 can be used for a device reporting a flow-weighted PM concentration. Thus, Method 1 and Method 2 were applied to all three PM-PEMS, but Method 3 was only applied to the AVL MSS.

STATISTICAL MODEL SIMULATION

A brief description of the statistical model is included here so that the reader may have a complete picture of the program. For a more complete description of the statistical work the reader is referred to the final report, listed in reference [6]. The main objective of this portion of the project was to use Monte Carlo techniques (e.g. random sampling) in an error model to simulate the combined effects of all the agreed-upon sources of PEMS error incremental to lab error on the components of the brake-specific (BS) PM emissions. This was accomplished by creating "error surfaces" for the Monte Carlo simulation to sample, based upon the results of a variety of lab experiments. An error surface is an experimentally derived relationship between an ideal measurement and the band of possible error incurred by performing that measurement under non-ideal conditions. Each error surface is a list of ideal measurement values, and percentiles describing the bounds of the error. Concentration deltas were created by subtracting the individual "lab nominal" PM value from the corresponding individual PEMS PM measurement for each test run. The deltas are calculated as follows:

$$\text{Delta}_i = \text{CVS}_i - \text{PEMS}_i$$

where CVS_i and PEMS_i are the PM concentration for the i^{th} data point. The data were pooled into 11 bins, with each



containing between 10 and 13 data points. The bins were created based on CVS measured PM concentration without regard to engine mode. The 50th percentile of the CVS data is the reference PM concentration for that bin. The 50th, 5th, and 95th percentiles of the concentration deltas were calculated from the pooled data. For the gaseous measurement allowance program these values were used as the error surface as the input to the Monte Carlo model. The measurement errors were sampled by the model using a normal distribution truncated at the 5th and 95th percentile. For the PM measurement allowance program it was decided by the steering committee to expand the tails of the truncated normal distribution in the error surface formation in order to allow larger PM deltas to be sampled during the Monte Carlo simulation. Instead of truncating the lower tail at the 5th percentile, it was moved to the 1st percentile. Likewise on the upper tail, the 95th percentile was moved to the 99th percentile. Because of the limited number of data points in each bin, it was not practical to calculate the 1st and 99th percentiles directly from the data. Instead the 5th, 50th, and 95th percentiles were calculated from the data. The spread between the 50th and 95th percentiles was used to calculate a standard deviation assuming a normal distribution, which was then used to calculate a 99th percentile. The same procedure was used with the 50th and 5th percentiles to calculate the 1st percentile. The constructed model was simulated for thousands of trials (i.e., iterations) using data taken from a reference data set of 141 unique NTE events. The model results were used to determine the brake-specific additive measurement allowances for PM by three different calculation methods for three different PEMS model units. A total of 31 error surfaces were used as input to the statistical model. Twenty five of the error surfaces were created during the gaseous measurement allowance program, while six new error surfaces were created in this program. The pre-existing error surfaces are CO₂, CO, NMHC, exhaust flow, torque, fuel rate, engine speed, with multiple error surfaces based on different environmental and operating conditions. The six new error surfaces generated in this work are: steady state PM, transient PM, pressure PM, temperature PM, engine manufacturers torque, and engine manufacturers fuel rate. The statistical model will then output a 50th, 5th, and 95th percentile measurement error for PM that is comprised of thousands of random samples incorporating errors from all 31 error surfaces. The PEMS with the lowest positive 95th percentile would be used as the measurement allowance.

CFR PART 1065 AUDITS

The first portion of the verification procedure involved completing the analyzer checks and verifications, stipulated in 40 CFR Part 1065 Subpart D, which apply to all analyzers used for emissions measurements. Both the lab and PEMS were subjected to the appropriate verifications.

The 1065 audit of the PM-PEMS was limited to linearity for pressure, temperature, and flow measurements. There were some difficulties in performing linearity verifications on PEMS flow meters in accordance with CFR Part 1065.307 due to limitations of the flow systems. The regulation states that ten or more measurements must be taken between zero and 100 percent of the flow range; however, many of the flows in the PEMS were designed to be constant. Therefore it was not feasible nor relevant to measure the accuracy at zero or 10 percent of the flow range. The flows were varied over practical ranges of operation and passed the linearity verifications in nearly all cases. In one case a flow measurement failed with a slope of 0.97 (requirement of between 0.98 and 1.02) even though each of the 11 test points were better than 0.5 percent in accuracy. The source of the error was that the 11 test points were clustered around a flow set point with none near zero. Given the excellent point-by-point accuracy of this flow meter, the steering committee elected to proceed using this result. The laboratory equipment passed all of the necessary verifications without incident. A more complete description of the laboratory audits can be found in the final report [6].

ENGINE TESTING

EXPERIMENTAL SETUP

A model-year 2007 Mack MP7-395C heavy-duty diesel engine produced by Volvo Powertrain was installed in a transient-capable CVS test cell. Initially the test plan called for testing with multiple engines, but funding limited the testing to a single engine. The engine has a displacement of 10.8 liters and a rating of 295 kW / 2115 Nm. The engine was equipped with a close-coupled diesel oxidation catalyst (DOC) and a diesel particulate filter (DPF) combination. For the purpose of producing higher PM emission levels, a bypass was created around the aftertreatment system to allow an adjustable amount of exhaust flow around the DPF. A DOC was added to the bypass so that all of the PM in the exhaust would pass through an oxidation catalyst simulating a scenario of a cracked DPF. A picture of the experimental setup including the bypass is shown in [Figure 1](#).

Valves in the exhaust pipe before the DOC/DPF, after the DOC/DPF, and after the bypass DOC were used to control the amount of exhaust bypassing the DPF, and hence the PM emission level. The goal of the bypass was to produce an emission level of 25 mg/hp-hr during both steady state and transient cycles. This is because the accuracy of the PEMS was to be challenged near the emission threshold which was 30 and 20 mg/hp-hr (30 mg/hp-hr will be used for the first year of compliance testing and 20 mg/hp-hr will be used for subsequent years). Achieving 25 mg/hp-hr PM emission during transient testing was relatively easy due to the large PM spikes during accelerations. The bypass had to be reconfigured several times to produce a high enough PM level during steady state operation. It was estimated that more



The PM sampling system was operated at a nominal total flow of 56 slpm (2 scfm) which results in a filter face velocity of approximately 100 cm/s. The nominal dilution flow is 28

Six engine operating conditions were chosen for steady state testing to provide a range of PM concentration, exhaust flow rates, and engine operating conditions. The six points that were chosen are shown in [Figure 2](#) in reference to the NTE zone of the test engine.