

On-Road Evaluation of a PEMS for Measuring Gaseous In-Use Emissions from a Heavy-Duty Diesel Vehicle

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ABSTRACT

On-road comparisons were made between a federal reference method mobile emissions laboratory (MEL) and a portable emissions measurement system (PEMS) to support validation of the engine "Not To Exceed" (NTE) emissions design and to evaluate the accuracy of PEMS. Three different brake specific emissions calculation equations (methods) were used as part of this research, with method one directly using engine speed and torque, and methods two and three including ECM fuel consumption and carbon balance fuel consumption. The brake specific NO_x emissions for the particular PEMS unit utilized in this program were consistently higher than those for the MEL. The brake specific (bs) NO_x NTE deltas were $+0.63 \pm 0.31$ g/kW-h (0.47 ± 0.23 g/hp-h), $+0.55 \pm 0.17$ g/kW-h (0.41 ± 0.13 g/hp-h), and $+0.54 \pm 0.17$ g/kW-h (0.40 ± 0.13 g/hp-h) for methods one, two, and three respectively. The method one MEL bsNO_x average value was 3.17 g/kW-h (2.36 g/hp-h) relative to the applicable in-use NTE standard of 4.20 g/kW-h (3.13 g/hp-h). The percent difference relative to the NO_x NTE in-use standard ranged from 6% to 25% higher for method one, from 7 to 19% higher for method two, and from 7% to 19% for method three. The brake specific CO₂ emissions for the PEMS were consistently biased high relative to the MEL, with an average bias of 4.5% $\pm$ 4%. Consistent differences between the PEMS were also measured for NMHC and CO emissions. These absolute differences were relatively small compared to the in-use NTE standards due to the low NMHC and CO emission levels.

INTRODUCTION

Diesel engines are one the most important emissions sources to control for continued improvement in air quality due to their contribution to the emissions inventory for oxides of nitrogen (NO_x) and particulate matter (PM). In recent years, the US Environmental Protection Agency (EPA) and the California Air

Resources Board (CARB) have promulgated regulations to further control diesel emissions. The most recent regulation has targeted in-use emissions in a defined portion of the engine map known as the Not-To-Exceed (NTE) control area and defined the test protocols required to make those measurements [11, 1].

The new requirement to measure in-use emissions means that portable emissions measurement systems (PEMS) will be needed in addition to the fixed laboratory emissions measurements performed on engine dynamometers as part of the engine certification process. These new regulations, as well as an interest in better understanding in-use emissions and emissions inventories, have inspired the development of PEMS for both commercial and research purposes [2-8].

Aside from the required in-use emissions testing for emissions compliance, the use of PEMS has shown to be a considerable asset for engine manufacturers and their engine development programs. With the ability to measure emissions and engine performance during real-world operations, manufacturers have the ability to reasonably test their engines under a wide range of environmental conditions which would be nearly impossible to re-create within traditional engine test cells.

The University of California at Riverside has developed a portable emissions measurement laboratory designed within an enclosed 53 foot on-highway trailer, which is compliant with 40 CFR Part 1065 regulations. There are many advantages to having developed this "rolling" laboratory, two of which were focused on for the research described in this paper below:

- Collect Emissions Measurements from an on-highway vehicle / engine during real-world operations using laboratory grade equipment.
- Validate & Quantify simultaneous measurements collected with a Gaseous Emissions PEMS device.

with focus not only on emissions magnitudes but variability as well.

EXPERIMENTAL PROCEDURES

Test Vehicle

A field test truck utilized by Caterpillar Inc. for their engine validation programs was used for this program. The test truck was equipped with a 2004 model year (MY) developed, 475hp / 1650ft-lb Caterpillar C-15 ACERT on-highway engine. The certification standard for a 2004 MY engine is 3.35 g/kW-h (2.50 g/hp-h) $\text{NO}_x + \text{NMHC}$ and 0.13 g/kW-h (0.10 g/hp-h) PM. The in-use $\text{NO}_x + \text{NMHC}$ NTE standard is 4.20 g/kW-h (3.13 g/hp-h). This engine meets emission regulations with a diesel oxidation catalyst and without the use of any exhaust gas recirculation (EGR). The engine was installed in a 1993 Kenworth T600 Chassis. The GVW for the truck and trailer was estimated at 65,000lb based on the standard fixed weight of the MEL and the known weight of the truck.

PEMS Operation

A 2003 model year Semtech-D PEMS unit was used for the on-road testing [9]. The PEMS uses NDIR for CO and CO_2 ; FID for THC; and NDUV for NO and NO_2 ($\text{NO}_x = \text{NO} + \text{NO}_2$). In operating the PEMS, the newest firmware version of software that was available at the time of testing was used, which was Version 2.008 build 35. The PEMS unit was supplied and operated by Caterpillar Inc., and at the time of testing was technologically up to date. Upgrades became available for Semtech units at a later date which included modifications to allow improvements in the accuracy of measurements of higher NO_2 emissions. This was not a significant issue for this testing due to the fact that this engine's after-treatment does not emit high amounts of NO_2 . NO_2 levels measured during the on-road testing were typically around 1% of NO.

The set up included the installation of the exhaust flow meter, sample lines, and the Semtech-D emissions analyzer. The analyzer itself was mounted in the "sleeper-cab" of the Kenworth chassis and the sample lines were routed through an access door in the side.

The flow monitoring and sample probe was installed in roughly the middle of a straight pipe section leading from the end of the exhaust towards the dilution tunnel (see Figure 1). The sample probe and exhaust flow meter (EFM) were installed more than ten exhaust pipe diameters (50 inches) after the final exhaust bend to ensure full mixing prior to the sample point. An additional straight section of five exhaust diameters was also added after the sample probe prior to the next flow disturbance. Appendix Table A5 has specific configurations settings for the EFM used during this project. The relative humidity sensor was mounted vertically on the outside of the cab on the driver's side, following the PEMS supplier's recommendations [9].



Figure 1: Exhaust flow meter location and MEL sample transfer line

The PEMS software was loaded with the Lug Curve for the C15 ACERT engine in order to define this engine's specific NTE zone boundaries. The nominal advertised lug curve for this engine rating configuration is shown in Figure 2.

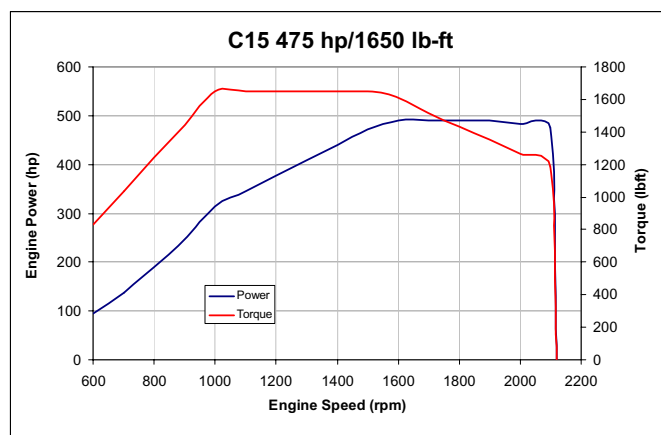


Figure 2: Advertised lug curve for the C15 test engine

The ECM module was set up for J1939, however the PEMS vehicle interface connection was unable to record percent friction torque off of the public CAN bus. This data was recorded using the MEL interface and the friction torque was added post-testing in order to accurately calculate brake specific emissions. The difficulty in measuring the friction torque was not a problem with the PEMS, but was an oversight on its operation. A GPS unit, as a part of the complete system, was installed on the chassis which would provide values such as the vehicle's altitude, location, as well as an additional vehicle speed measurement.

MEL Operation

The University of California at Riverside's Mobile Emissions Laboratory (MEL) was used for cross comparisons with the PEMS and was considered the reference method for these comparisons. The MEL is equipped with a full dilution tunnel, standard gas-phase analytical instruments on shock-mounted benches, inside a climate controlled 53 foot tractor trailer. Further details of the gas-phase and PM measurements can be found in ref. [10]. The MEL employs NDIR for CO and CO₂; FID for THC; and CLD for NO (converter for NO₂ to NO). The MEL has been cross correlated with the California Air Resources Board's heavy-duty chassis dynamometer in Los Angeles, CA [10] and more recently with an engine test cell at the Southwest Research Institute, in San Antonio, TX [11]. A 1065 self-audit was also performed on the MEL as part of the recent gas-phase measurement allowance program [11].

The MEL was operated using standard operating procedures. A standard zero span calibration was performed every hour throughout the correlation and an audit was performed at the end of the day. The audit check for each measurement was within 2% of point. Ambient concentrations were obtained from typical MEL default values and accounted for less than 1% of the measured NTE values for NO_x, CO₂ and CO. Ambient hydrocarbon levels accounted for less than 5% of the NMHC NTE measured values.

CE-CERT's MEL routinely performs CFR required verification checks such as linearity, NO_x converter, and propane verification checks for the gas phase species. The MELs most recent pre and post test verifications were one week before and after for the propane verification and three weeks before and one week after for the NO_x converter check and linearity checks. All verifications meet CFR specifications. Other internal verification checks were also performed on the MEL to help prevent data drift. All internal verifications were met, and the data presented is fully validated.

Test Routes

The designed routes were selected by utilizing local freeways in the Riverside area with the goal of performing flow-of-traffic sampling with some elevation change. The routes covered three major freeways in the Riverside area, the I-15, Highway 60 and I-215 freeways. Run One included an elevation change from 1000 to 4500 feet. Run Two was the test returning down hill from the 4500 feet to 1000 feet. The last run (Run Three) was on relatively flat freeways with slight grade changes.

Calculations and Corrections

The data from the test runs was compiled by CE-CERT for both the MEL and the PEMS. All calculations for the

MEL data were performed by CE-CERT. The data files for the PEMS were subsequently corrected for measurement drift following Equation 1 as per CFR. The drift correction reduced the PEMS bsNO_x NTE values on Run One and increased them on Run Two and Three. The CFR requires bsNTE data with drift exceeding 4% (relative to pre drift correction) to be discarded, see 1065.550(b)(1). During this small study three PEMS data points failed the drift validation criteria for bsNO_x method one and thus those NTE points were eliminated from the comparison, see Table 1. Two of the three discarded points had additional reasons to be removed from the study as will be described later. The data presented in this paper only considers valid drift corrected PEMS data.

$$x_{\text{idrift corrected}} = x_{\text{refzero}} + \frac{2 \cdot x_{\text{refspan}}}{x_{\text{prespan}} + x_{\text{postspan}}} \cdot \left(x_i - \frac{x_{\text{prezero}} + x_{\text{postzero}}}{2} \right)$$

Equation 1: Drift Correction Calculation 40 CFR Equation 1065.672-1 (actual pre and post test zero/span values are included in the appendix)

Of the three tests conducted, Run One did not have recorded pre-test calibration values to be used in the drift correction calculations. Reference values were assumed for the pre-test readings. The manufacturer felt that this assumption would increase the PEMS accuracy of the measurement as opposed to applying no drift correction at all. The time alignment was performed using the standard post processing feature in the PEMS software (Semtech software version 5.96). The specific time alignment values used for the analyzers and other systems is listed in the appendix Table A6.

The MEL laboratory typically measures THC and CH₄ and calculates NMHC as per 40 CFR Equation 1065.660-2, but during this project the CH₄ instrument was being repaired so all NMHC values are based on an estimate of total THC as per 40 CFR Equation 1065.660-1 which is $0.98 \cdot X_{\text{THC}}$.

The MEL data was not drift corrected following the same practices as performed for the PEMS. The MEL operates with hourly calibrations. The hourly calibrations are used to adjust for instrument drift during operation. The MEL data is in effect drift corrected by this operating procedure. The magnitude of all MEL instrument drift were below the requirements listed in 40 CFR 1065.550(b)(1) and are typically less than 2%.

The MEL is a mobile laboratory and requires absolute barometric pressure corrections to maintain proper concentration measurements when dynamically sampling between high and low elevations. During this study the MEL operated from 1000 to 4500 feet. This subjected the MEL analyzers to barometric pressure changes from 28.8 inHg at 1000 ft to 25.8 inHg at 4500 ft, a change of 3.0 inHg. The change in pressure has a direct effect on each instrument's response for zero and