Final Report

Evaluation of Portable Emissions Measurement Systems (PEMS) for Inventory Purposes and the Not-To-Exceed Heavy-Duty Diesel Engine Regulation

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Disclaimer

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Executive Summary

Diesel engines are significant contributors of emissions in air basins and diesel emissions have become increasingly scrutinized. This scrutiny has resulted in more regulation of diesel emissions and a desire to learn more about the actual in-use emissions from these engines rather than values measured with engine and chassis dynamometers. However, measuring on-board, in-use emissions is problematic, especially if current EPA reference methods must be used. This project was launched with a goal of measuring the performance of alternatives to EPA reference methods. Toward that end, the practical alternative to fixed laboratory measurements with EPA reference methods is the use of portable emissions measurement systems (PEMS) which became the focus of this research. The intent of this project was to test the PEMS over a wide range of engine operating conditions so the results would provide insight for PEMS use for emission inventories and for regulatory applications, especially compliance with the Not-To-Exceed (NTE) regulations. The specific project deliverables included quantifying both the accuracy and precision of commercially available PEMS relative to the federal reference methods (FRM) in the University of California, Riverside's (UCR's) mobile emissions laboratory (MEL).

Emission Measurement Tests –Common Elements

The exact emission measurements were divided into two tests. First we measured emissions from a backup generator (BUG) representing a stationary source and true steady-state engine operation. Second, we measured emissions from a heavy, heavy-duty diesel truck (HHDDT), representing a mobile source at quasi-steady-state and transient engine operation. Common elements in both series of tests included a test matrix that was designed to represent a broad range of operating conditions and was accepted by the stakeholder group before testing was initiated. For the actual engine operation and testing, all PEMS and MEL were simultaneously connected to minimize errors due to sample variation. Furthermore, the PEMS manufacturers provided staff, instruments and technical expertise so the instruments were operated as designed.

Another common test element was that all measured values from the FRMs were blind to the PEMS manufacturers until they reported their data. After the analyses, we reported the deviations in concentration and flow rate between the PEMS and the FRMs, the two independent and critical values needed for calculating emission rates.

PEMS Units Tested

At the beginning of the research program, ARB solicited participation from a number of PEMS manufacturers. As a consequence, a total of seven PEMS manufacturers were represented in this research program and as one manufacturer provided two instruments, a total of eight instruments were tested. Three instruments measured solely particulate matter (PM), three measured solely gaseous emissions and the last two units measured both PM and gaseous emissions. Several points need to be made about the test program.

First, the highest priority was establishing data for the gaseous instruments, and second, not all the PEMS systems were used for both the stationary and the mobile source units. The PEMS tested are listed below in alphabetic order and throughout the text are identified using a specific number that is included in the table.

The Horiba OBS-2200 unit (PEMS4b) used for the chassis dynamometer test program at the ARB laboratory in Los Angeles was an early prototype instrument with unproven software at the time it was provided for the test program. Horiba submitted this unit in response to strong urging from both EPA and ARB even though the product development team had not had the opportunity to test the prototype with a vehicle. During the week of testing several software related problems were discovered, which required on-site software revisions. Consequently, the early runs in this program produced no viable data because of software bugs. The later data presented in this report is still prototype quality with incorrect software compensations applied. Results are preliminary to finishing the product development and should not be considered representative of the production model performance. Additionally, PEMS6 for measuring PM was included in the study for the chassis dynamometer testing. After the testing, it was determined that the instrument had not been operating within manufacturers' specifications, so these data were not reported.

Manufacturer	**Unit/Model**	**PEMS #**	**Gases**	**PM**	**Gas/PM**
Artium	Laser Induced Incandescence (LII)	5		X	
AVL	Photoacoustic Microsoot Sensor	7		X	
Clean Air Technology	Montana system	1			X
TSI	DustTrak	8		X	
Engine, Fuels and Emissions Engineering	RAVEM system	3			X
Horiba	OBS-1300	4a	X		
Horiba	OBS-2200 (early prototype)	4b	X		
Sensors	Semtech D system	2	X		

Emission Measurement Tests –Stationary Source/Backup Generator

In the first phase, flow rates and emission measurements from a backup generator were measured with four PEMS and compared with the values from the FRMs. The diesel engine was a CAT 3406C, similar in size to the HHDDT engine for the second phase and the selected loads ranged from 5% to 100% to allow a comparison of concentrations representative of levels found over a wide operating range of a diesel engine.

Comparative results are shown in Figure ES-1 for the critical gases, NO_x and CO_2. Note for NO_x, and CO_2, the deviation range depended strongly on the PEMS and the load. For NO_x, PEMS #2 and #4 showed the best agreement with the FRM, ranging from about 1 to

10% of the FRM. Reasons for observed deviations with the other PEMS are discussed in the report.

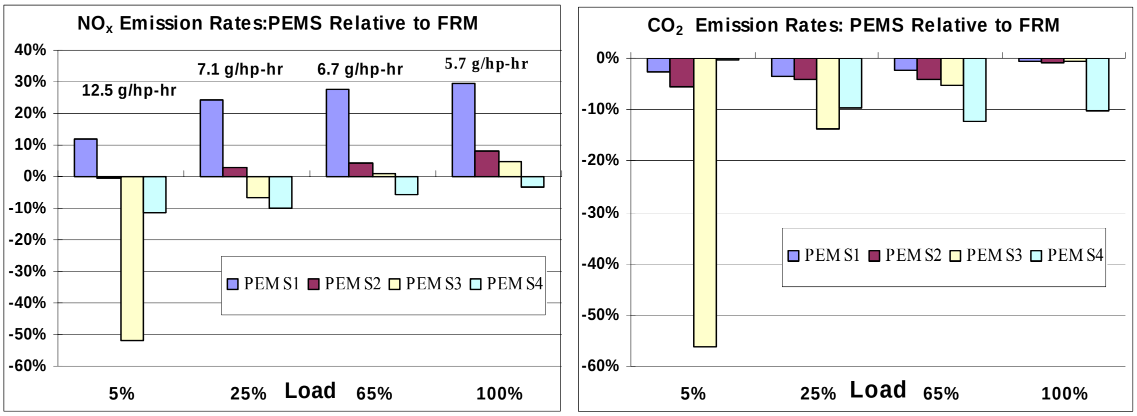


Figure ES-1. PEMS Emission Rates Relative to FRM. Actual Emissions (g/hp-hr) Overlaid for Reference.

Comparative results for PM and THC are shown in Figure ES-2 for the BUG testing. Overall, the PEMS also showed relatively large differences relative to the FRM for THC. It should be noted that the absolute THC values overall are low, even in comparisons with the upcoming proposed NTE standards (see section 1.1 for a discussion of NTE control areas). The PM measurements for PEMS1 were considerably lower than those of the FRM while those for PEMS 3 were ~25% lower than the FRM at the high low points. The larger differences at the lower flow rates for PEMS3 can be attributed to a problem with flow measurement.

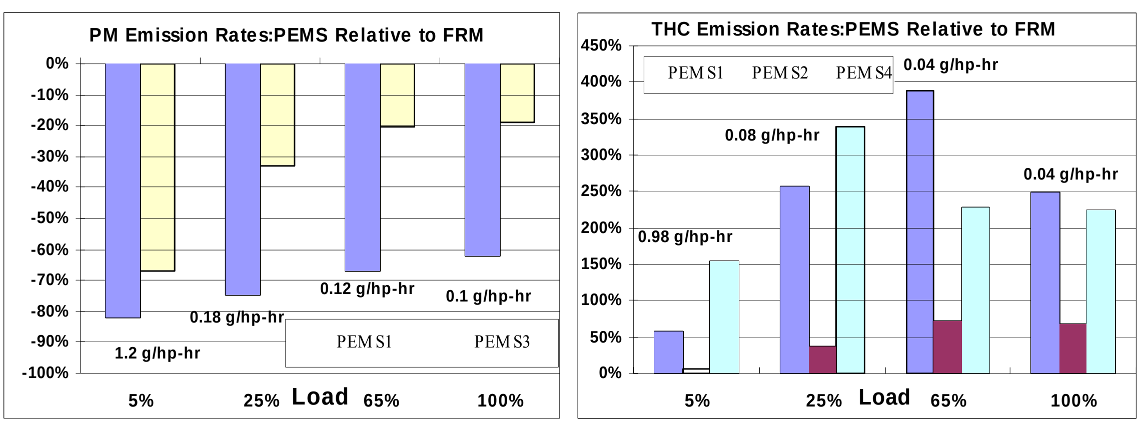


Figure ES-2 PEMS Emission Rates (g/hr) Relative to FRM at Several Loads.

Emission Measurement Tests –Mobile Source/ Heavy-duty Diesel Truck

In the second phase of testing, emissions were measured from truck with a 475 hp Caterpillar C-15 ACERT engine certified to the 2.5 g/bhp-hr NO_x + NMHC and 0.1 g/bhp-hr PM standards. The testing compared emission measurements from seven PEMS with values from the FRM. Three of the PEMS measured only PM, three PEMS measured only gases and the remaining PEMS measured both gas and PM. The ACERT engine/vehicle system was tested on the ARB's heavy-duty chassis dynamometer.

Testing for this phase received much attention because results were likely to aid in the ongoing discussions about the measurement allowance for EPA's new regulation on in-use testing of diesel engines. The new regulation covers measurement of emissions from in-use diesel engines, especially when the engine operated in the Not to Exceed (NTE) region of the engine map. Accordingly, the testing was carried out while following a carefully planned series of quasi steady state and transient driving schedules. The four driving schedules included:

1) Three-mode quasi steady-state NTE test cycle.
2) Stepped NTE test cycle
3) The Urban Dynamometer Driving Schedule (UDDS)
4) The 50-mph Cruise mode from the ARB 5-mode HHDDT test cycle

The steady-state NTE cycle was run at three different engine speeds with events in the NTE region. A second NTE cycle was designed with a "stepped" pattern, intended to simulate NTE-type vehicle/engine operation with gentle accelerations between modes and steady-state operation at each load point. The NTE driving schedules test cycles were designed to clearly delineate entry into, operation within, and exit from the NTE-defined zone of engine operation. The UDDS and 50-mph cruise cycle were included to better represent 'real-world' operation and data in current emission inventories.

While data were collected for all four driving schedules, the executive summary focuses on results for the 3-Mode steady state NTE cycle since the results from other cycles were generally comparable. The executive summary details results for solely NO_x, the highest priority target during the first phase of NTE regulation. Results for the 3-mode steady state cycle were averaged over the NTE events for a particular speed/load point for both PEMS and the FRMs. Figure ES-2a provides the average NTE results in g/bhp-hr for NO_x over the various modes and Figure ES-2b shows the differences relative to the NTE threshold value as the error margin relative to the standard is an important regulatory consideration. A total of 16 speed/load points are included in the Figures. Data collected at 1290 rpm, 40% load did not meet the criteria for an NTE event and not included in the Figures.

Again results depended on the PEMS. For PEMS2 the NO_x emission rates were approximately 3 to 17% higher than those for the FRM in g/bhp-hr units relative to an NTE threshold of 2.0 g/bhp-hr. PEMS 4 showed larger differences compared to the FRM, with percent differences ranging from 26 to 47%. It should be noted that PEMS4 for the chassis dynamometer testing was a prototype. As explained in the report, an extensive data analysis of the emissions, engine operation and other factors was possible for only two of the four gaseous PEMS.

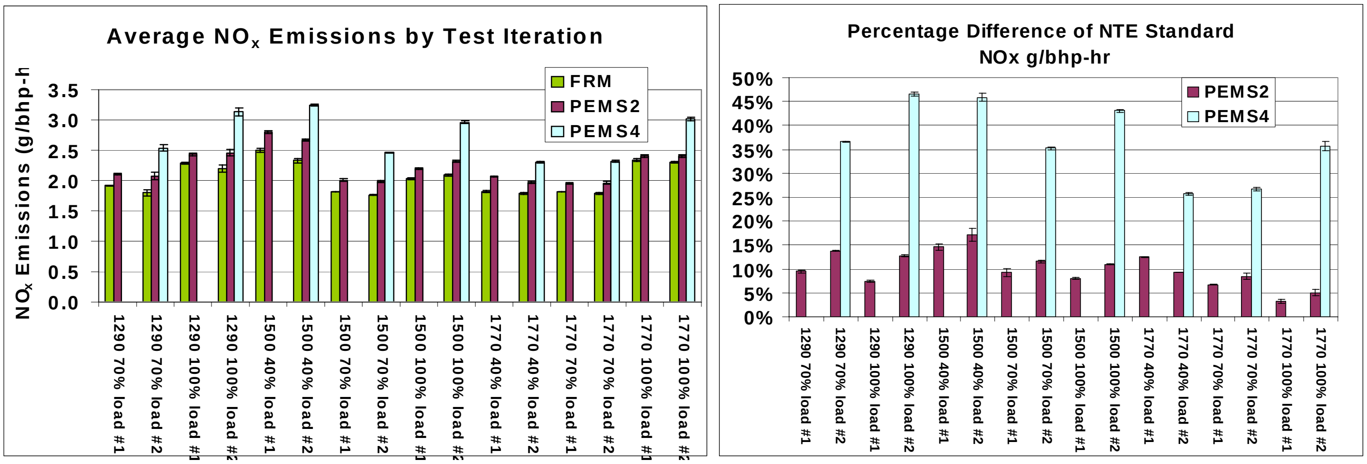


Figure ES-3. (a) Comparison of NO_x Emission Rates and 95% Confidence Limits. (b) Comparison of Percentage Differences in NO_x Emission Rates for Different PEMS.

The CO_2 emissions are important since CO_2 is often used in determining fuel specific (fs) emissions. Results in Figure ES-3 indicate that during steady state NTE events, CO_2 emissions for PEMS2 were generally about 5% higher than those of the FRM and PEMS4 values were 9 to 30% higher than those the FRM. Further analysis is offered in the main report.

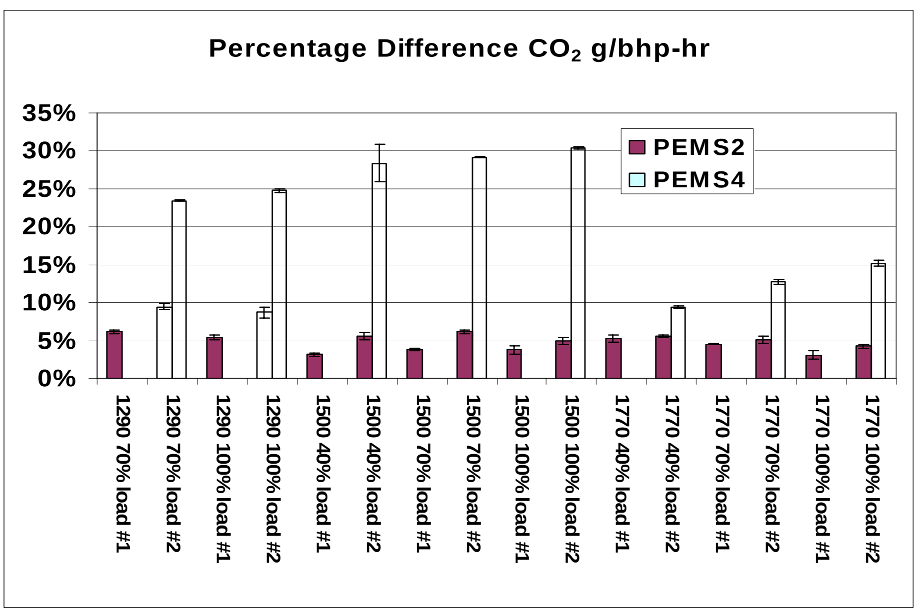


Figure ES-4. Percentage Difference between PEMS and FRM for CO_2 in g/bhp-hr for NTE Steady State Cycle

THC over the NTE steady state cycle was generally lower for both PEMS2 and PEMS4 compared with the FRM. THC emissions were below the NTE threshold standards for these measurements. Relative to the approximate NTE threshold for THC of 0.21 g/bhp-hr, the percentage differences were all within 10%, with most being within 5%.

CO emissions for PEMS2 showed good correlation with the FRM, but measurements were consistently higher than those for the FRM. Again, however, the CO emissions were well below the NTE threshold of 19.4 g/bhp-hr, and the percentage differences between the FRM and PEMS2 were all within 2% relative to the NTE CO threshold.

During the mobile source testing, an exploratory trial was made of four PM-capable PEMS. Results showed real promise for the new instruments to follow the modal behavior of the PM emissions. PEMS3 and PEMS7 showed the best correlation with values within 15-25% of the PM mass emissions measured by the FRM, with considerably larger deviations seem for some other instruments.

Findings & Recommendations

The results of this research show that of the four gaseous PEMS that PEMS2 compared better with the FRM for NO_x and CO_2 than other units. An exploratory trial of PM-capable PEMS show great promise for real-time PM measurements but more development is needed. The following recommendations are made based on the observations in this research:

- More attention is needed to establish detailed use protocols and performance limits as specified for a CFR method. For example, the CFR specifies a particular type of analyzer for NO_x as well as the specifications.
- Even the best PEMS with an experienced operator had problems so PEMS require experienced operators.
- It is suggested that more frequent calibrations are needed to establish confidence intervals and ensure reliable operation of the PEMS during sampling in the field.
- For the best progress, measurement programs must be collaborative in design and analysis between the PEMS manufacturer, ARB, EPA, EMA and the contract lab making measurements.

Looking ahead, we expect PEMS confidence limits to improve from that observed in this research as a result of the ARB/EPA/EMA's Measurement Allowance Program.

Next Steps

The original scope for this project included four main emissions testing tasks: 1) stationary source/backup generator testing of all participating PEMS, 2) mobile source/heavy-duty truck chassis dynamometer testing of all participating PEMS, 3) On-vehicle, over-the-road testing of all participating PEMS using pre-selected test routes, and 4) on-board, over-the-road testing of "the most suitable" PEMS under conditions meant to mimic the actual in-use compliance program (i.e., real vehicles in actual revenue service). However, since this project began, the ARB, US EPA and heavy-duty engine companies (as represented by the Engine Manufacturers Association) agreed to a measurement allowance program to determine exactly what numerical values should be assigned, as referenced in the Memorandum of Agreement (MoA) signed by the above parties in June, 2005. The original scope of this project is being revised so that the resources originally allocated for this project can reallocated to support this measurement allowance program. The measurement allowance program will be examining topics and issues similar to those studied in this project - how PEMS compare against the reference methods, but will do so in a more focused and extensive manner. Specifically, all factors expected or suspected to influence PEMS emissions measurements such as vibration, ambient conditions (such as changes and variations in pressure, temperature. and humidity, ambient background HC concentrations), radio frequency and electromagnetic interference, etc. will be studied with the goal of developing actual, pollutant-specific, numerical measurement allowances for NO_x, THC, and CO. In addition, the measurement allowance program will also quantify variability between engine dynamometer measurements of engine torque and speed. The current project scope is being revised to support this measurement allowance program. Specifically, CE-CERT will: 1) perform a Code of Federal Regulations Part 1065 audit of the CE-CERT mobile emissions laboratory, 2) perform side-by-side testing at SwRI, and 3) perform a validation of SwRI's Monte Carlo model used to develop the measurement allowance by collecting over-the-road emissions data using the MEL.

1.0 Background

On-road heavy-duty diesel (HDD) engines/vehicles are projected to be a significant contributor to the emissions inventories for oxides of nitrogen (NO_{x}) and particulate matter (PM), even in 2010, because of their high emission rates and the long lifetimes of the vehicles. While the regulatory emission standards have become more stringent over time, the introduction of electronic controls allowed engines to operate with advanced timing and to generate “off-cycle” emissions, specifically higher NO_x and lower PM levels than produced over the laboratory engine dynamometer certification test cycle. In the late 1990's, the US Environmental Protective Agency (EPA) and the California Air Resources Board (CARB) signed agreements with some engine companies that required, among other things, supplemental tests used for certification of heavy-duty diesel engines. The supplemental tests include the in-use Not-To-Exceed (NTE) test procedure, the EURO III European Stationary Cycle (ESC) test procedure, and measurement of emissions within the NTE control area.

Effective monitoring equipment is needed to assess in-use HDD emissions. This project evaluated current commercially available portable emissions measurement systems (PEMS). The project is intended to represent a snapshot of the current state-of-art and a reference point from which PEMS could be evaluated as a tool for either emissions inventory development or in-use compliance. This PEMS evaluation determined the basic measurement capabilities (e.g., accuracy, precision, etc.) and compare those results with measurements made with laboratory grade emissions analyzers that are specified in the federal reference methods (FRM) and as used in the University of California at Riverside’s (UCR)’s mobile emissions laboratory (MEL). The goal of the project is to evaluate the PEMS suitability for inventory/model building work and for the NTE compliance work.

The PEMS systems selected for inclusion in the project were evaluated over two main test programs with increasing levels of complexity in measurement and potential variability in operation. In the first test, the PEMS were evaluated using emissions from a diesel engine driving a back-up generator (BUG) over a series of load points. In the second portion of the test program, the PEMS were compared over chassis dynamometer test cycles. The chassis dynamometer tests included transient cycles, steady state cycles, and cycles designed to provide test conditions that will create NTE events and the transition into and out of the NTE zone. The chassis dynamometer transient tests represent an additional level of complexity for the PEMS measurements in that they require accurate measurement and correlation of the exhaust concentrations and the exhaust flow rate. The chassis dynamometer testing was designed to operate the PEMS under conditions with the engine having more degrees of freedom or sources of error and closer to the NTE test conditions than the backup generator testing. Both tasks represent conditions that are more controlled than actual over-the-road operation. Additional work for comparisons of PEMS with the UCR MEL during over the road measurements is currently being planned as part of the ARB/EPA/EMA’s Measurement Allowance Program.

1.1 Data Analysis with a Focus on the NTE Zone

The original intent of the project was to broadly survey the accuracy of the PEMS when applied to data gathering for either NTE or inventory purposes. However, as the project developed, a greater interest was assigned to defining the accuracy and percent deviation of the PEMS within the NTE zones. The NTE zones were defined by agreements between the US EPA, CARB and the engine manufacturers with more information provided in the EPA documents[1]. Paraphrasing the reference: An NTE event is generated when all of the following conditions are simultaneously met for at least 30 seconds or longer if an after treatment device is regenerating.

A listing of NTE conditions is provided in Table 1-1 and the NTE region is illustrated graphically in the Figure 1-1.

1. Speed >15%(n_{hi}-n_{lo}) + n_{lo}	7. Outside petitioned exclusion zones
2. Torque ≥ 30% max	8. Outside of any NTE region in which a manufacturer states that less than 5% of in-use time will be spent.
3. Power ≥ 30% max	9. With EGR, intake manifold temperature ≥ 86-100ºF, depending upon intake manifold pressure.
4. Altitude ≤ 5500 feet	10. With EGR engines, the engine coolant temperature ≥ 125-140ºF, depending on intake manifold pressure.
5. Amb temp ≤ 100ºF sea level to 86ºF at 5500 feet	11. Engine after treatment systems' temperature ≥ 250ºC. Only for NO_x and HC aftertreatment.
6. BSFC ≤ 105% min, non-automatic, non-manual transmission; essentially for series hybrids	

Table 1-1. Specifications for Events Classified in the NTE Zone

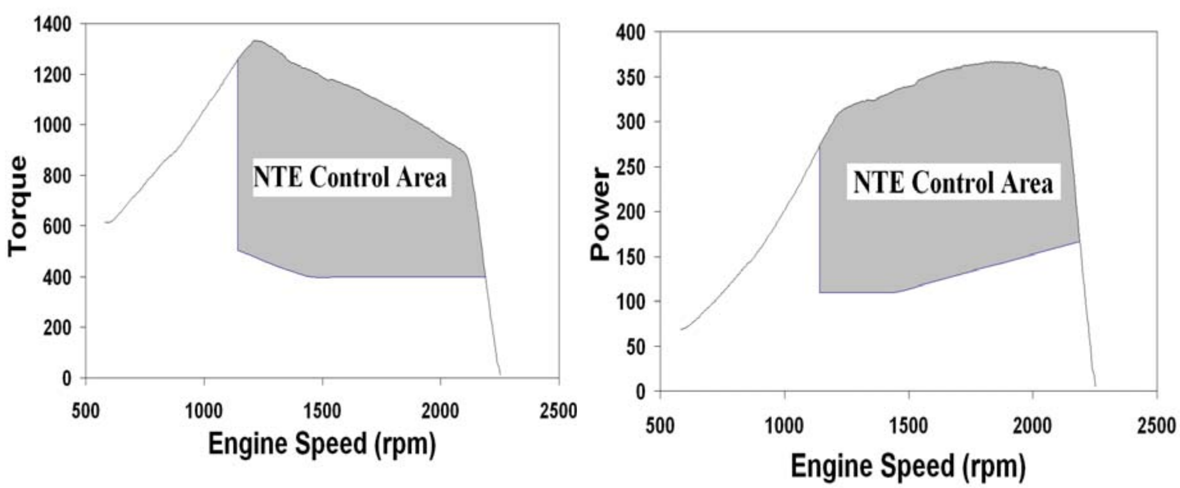


Figure 1-1. Graphical Examples of the NTE Control Area

2.0 Experimental Design and Procedures

The emission factors used to characterize diesel engines are often based on engine and chassis dynamometer data rather than real-world, on-board, in-use measurements. However, measuring on-board emissions is problematic, especially if current EPA reference methods must be used. This project was launched with a goal of measuring the performance of alternatives to EPA reference methods. Toward that end, the practical alternative to fixed laboratory measurements with EPA reference methods is the use of portable emissions measurement systems (PEMS) which became the focus of this research. The intent was to test the PEMS over a wide range of engine operating conditions so the results could provide insight for PEMS use for emission inventories and for regulatory applications, especially compliance with the Not-To-Exceed (NTE) regulations. The specific project deliverables included quantifying both the accuracy and precision of commercially available PEMS relative to the federal reference methods (FRM) in the University of California, Riverside's (UCR's) mobile emissions laboratory (MEL).

2.1 Emission Measurement Tests –Common Elements

The exact emission measurement program was divided into two major test sequences. First, measure emissions from a diesel engine in a backup generator (BUG) representing a stationary source, and second, measure emissions from a heavy, heavy-duty diesel truck (HHDDT), representing a mobile source. Common elements in both series of tests included a test matrix that was designed to represent a broad range of operating conditions and was accepted by the stakeholder group before testing was initiated. CARB diesel fuel was used for all testing. For the actual engine operation and testing, all PEMS and MEL were simultaneously connected to minimize errors due to sample variation. Furthermore, the PEMS manufacturers provided staff, instruments and technical expertise so the instruments were installed, calibrated (QC/QA) and operated as designed. There were two exceptions to the PEMS manufacturers' staff operating the instruments. During the HHDDT test, one gaseous analyzer was operated by ARB staff and the PM devices were operated by UCR staff.

Another common test element was that all testing started with a comparison between the FRM and PEMS for 1% audit and blended calibration gases. Next the comparative data was obtained for both the FRMs and PEMS while the engines operated over the planned driving schedules. In any case, as part of the analyses protocol, all measured values from the FRMs were blind to the PEMS manufacturers until they reported their data. After the analyses, we reported the deviations between the PEMS and the FRMs in concentration and flow rate, the two independent and critical values needed for emission factors.

2.2 Measurement Method – CE-CERT's MEL with FRMs

A full description of UCR's MEL is available in the peer-reviewed literature and a synopsis of key points are provided in Appendix A.[2] During all of the comparative testing, CE-CERT's MEL measured nitrogen oxides (NO_x), nitrogen dioxide (NO_2), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and carbon dioxide (CO_2) and particulate matter (PM) emissions. The key experimental point is that all pollutants were measured using analyzers and the methodologies for calibration and operation that carefully followed the Code of Federal Regulations (CFR). These methods are referred in this report as Federal Reference Methods (FRMs). During each test cycle, both modal (second-by-second) and bag data for gaseous emissions were collected and analyzed. The bag data served as an independent check of the modal values as part of the quality assurance program. For PM mass emissions, the MEL collected a single, integrated sample for each test cycle run. A limited number of PM samples were collected on quartz filter in MEL to measure the elemental and organic (EC/OC) fraction of the PM emissions during the chassis dynamometer testing.

2.3 Measurement Method -- PEMS Units Tested

At the beginning of the research program, ARB solicited participation from a number of PEMS manufacturers. A total of seven PEMS manufacturers participated and were represented in this research program and as one manufacturer provided two instruments, a total of eight instruments were tested. A listing of the instruments is provided in Table 2-1, with a more detailed description of the instruments in Appendix B. Three instruments measured solely particulate matter (PM), three measured solely gaseous emissions and the last two units measured both PM and gaseous emissions. Several points need to be made. First, the highest priority was establishing data for the gaseous instruments, and second, not all the PEMS systems were used for both the stationary and the mobile source tests. The PEMS tested are listed below in alphabetic order and throughout the text are identified using a specific number that is included in the table. One additional PEMS for measuring PM was also initially included in the study for the chassis dynamometer testing. After completion of testing, however, it was determined that the instrument had not been operating with manufacturers specifications. These data are not included in the report.

Manufacturer	Unit/Model	PEMS #	Gases	PM	Gas/PM
Artium	Laser Induced Incandescence (LII)	5		X	
AVL	Photoacoustic Microsoot Sensor	8		X	
Clean Air Technology	Montana system	1			X
TSI	DustTrak	8		X	
Engine, Fuels and Emissions Engineering	RAVEM system	3			X
Horiba	OBS-1300	4a	X		
Horiba	OBS-2200 (early prototype)	4b	X		
Sensors	Semtech D system	2	X		

Table 2-1 List of PEMS Manufacturers and Capabilities

As each PEMS manufacturer approached their instrument design in a unique manner, the measurement capabilities of each PEMS differed. Four of the systems had capabilities for measurement of gaseous emissions, with two these systems also capable of PM measurements. As the project evolved gaseous measurements became the highest priority so a summary of the measurement techniques for each of the PEMS capable of gaseous emissions measurements is provided in Table 2-2. The PEMS units for gaseous emissions are identified as PEMS1, 2, 3 and 4 throughout the report since the focus of the work was to provide a broad characterization of PEMS and their application for in-use measurements of diesel emissions, as opposed to an evaluation of specific technologies. The PEMS capable of only measuring PM are discussed in greater detailed in the results section below.

The Horiba OBS-2200 unit (PEMS4b) used for the chassis dynamometer test program at the ARB laboratory in Los Angeles was an early prototype instrument with unproven software at the time it was provided for the test program. Horiba submitted this unit in response to strong urging from both EPA and ARB even though the product development team had not had the opportunity to test the prototype with a vehicle. During the week of testing several software related problems were discovered, which required on-site software revisions. Consequently, the early runs in this program produced no viable data because of software bugs. The later data presented in this report is still prototype quality with incorrect software compensations applied. Results are preliminary to finishing the product development and should not be considered representative of the production model performance.

	PEMS1	PEMS2	PEMS3	PEMS4
THC	NDIR	FID	Not measured	NDIR// FID**
CO	NDIR	NDIR	NDIR	NDIR
CO_2	NDIR	NDIR	NDIR	NDIR
NO_x	Electrochemical cell	ND-UV*	Chemiluminescence	Zirconia Sensor Chemiluminescence**
NO_2	Not measured	ND-UV	Not measured	Not measured
PM	Light scattering	Not measured	filter	Not measured
Flow	calculated	Differential pressure	Not directly measured	Differential pressure
Sample	Raw exhaust	Raw exhaust	Dilute exhaust	Raw exhaust

* ND-UV measures NO and NO_2 separately and combines these measurements to determine NO_x

** The OBS-1300 used for the BUG testing uses NDIR for hydrocarbons and a zirconia sensor for NO_x; The OBS-2200 used for the Chassis testing uses FID for THC and Chemiluminescence for NO_x

Table 2-2. Description of Measurement Capabilities of Individual PEMS

The fact that Table 3 shows diversity in PEMS product approach and offering is quite common at this stage of commercialization for an evolving product line. In fact, this diversity usually continues until standardization and specifications are established. For example, consider the CFR standard for measuring NO_x in diesel exhaust, the measurement of oxygen in gasoline or any of the SAE protocols for vehicle interconnections. In these cases standardization took time and during that period the product performance specifications and operating tolerances were tightened as a result of the many discussions by the user and stakeholders groups. It is also common that during standardization, that scientific approaches are narrowed and several manufacturers will offer products meeting standards but with their unique approach. Witness the number of companies offering NO_x analyzers. Thus this research was important as it offered a quantitative review of current PEMS offerings and a forum for discussion of the future direction of performance standards.

2.4 First Comparative Test: Audit Bottle and Blended Audit Gas Checks

The PEMS and FRM were compared over a series of concentrations delivered from an audit bottle. An additional blended gas check was also carried out during the stationary source/backup generator testing using audit bottle gases that were generated from a gas divider. The audit bottle and blended audit gas checks were done as blind comparisons with the concentration values not provided to the PEMS manufacturers until after the testing. As such, the analyzer ranges for the PEMS were not necessarily optimized for the concentration levels measured.

The audit bottle checks conducted during the BUG testing were with concentration levels representative of values typically found in the diluted exhaust as measured by UCR's FRM, rather than values in raw exhaust gas for which some PEMS were designed. Based on that observation, the audit bottles were designed before the mobile source tests so the audit bottle better represented the average concentrations that would be found in the dilute or raw exhaust depending on whether the PEMS was configured to sample a dilute or raw sample. All audit bottles were NIST traceable with ±1% accuracy with a mixture of NO, THC, CO, and CO_2.

During the BUG testing, measurements were also made at four concentration levels from a primary audit bottle diluted using a gas divider with ±1.5% accuracy mass flow controllers. The four concentration levels were designed to span the ranges of concentrations that would be found in both raw and diluted exhaust.

2.5 Emission Measurement Tests –Backup Generator/Stationary Source

In the first phase of testing, the flow rates and emission measurements from a backup generator were measured with four PEMS and compared with the values from the FRMs. The engine used for this testing was a model year 2000 CAT 3406C engine (serial number 4JK00740) that powered a backup generator rated at 350 kW. This same diesel engine was used in previous studies by UCR so there is a considerable record of the emissions history of the engine. Note the size of the engine was selected since it was similar in size to the CAT C-15 engine to be used in the second phase of the program. The engine was tested without a muffler. The experimental set-up for the BUG Testing is shown in Figure 2-1.

Figure 2-1. Experimental Set-up for BUG Testing

The exhaust measurements were made on the BUG at four different load points at the rated speed, 1800 revolutions per minute (RPM). The load points were selected so as to represent a wide range of different flows and load conditions, both within and outside the NTE zones. This includes some test points standard and non-standard to the CFR test protocol, as UCR has published emissions at the standard load points. The actual test points are presented below:

Mode 1	100%	Load
Mode 2	65%	Load
Mode 3	25%	Load
Mode 4	5%	Load

During the testing, the engine was operated following the protocols specified in 40 CFR Part 89, except that the load points differed from the levels specified in the CFR. The engine was run at 100% load for approximately 30 minutes to precondition or warm-up the engine. Then the emissions were measured at the four-modes starting with the highest load point as per the protocol. The loading of the BUG was provided by a resistive load bank capable of providing 100% of the maximum load listed by the BUG manufacturer and power was calculated based on the amps and voltage measured for each leg of the 3-phase, 480 volt circuit. Data were collected at each mode for at least five minutes after the unit had stabilized.

To allow a determination of the precision of the measurement, tests were run seven times during each of the test periods. Flow and all exhaust emissions, including CO, CO_2, THC, NO_x, NO_2, and PM mass, were measured with the CFR-specified laboratory instruments in UCR's MEL and with the PEMS instruments, depending on the capability of the individual PEMS. Each test run was set-up such that all of the PEMS units were sampling simultaneously from the exhaust stream at the same time. The exhaust was sampled upstream of the inlet to the dilution tunnel used in the FRM. The volume sampled by the PEMS by the PEMS represented between 1% (at idle) to 0.25% (at full load) of the total exhaust volume and was not accounted for in the CVS calculations.

The BUG testing was conducted at two different times to accommodate as many PEMS as possible. PEMS 1, 2, and 3, were tested in November of 2004. PEMS 4 later became available and was tested in February of 2005. The measurements made with the FRM in February are slightly different from those of November, which can be traced to the load bank being changed from the November testing.

The fuel used for this testing was a CARB ultra low sulfur diesel (ULSD or sulfur <15 ppmw) fuel that was readily available through a local retail outlet.

2.6 Emission Measurement Tests –Heavy-duty Diesel Truck/Mobile Source

Planning the second major phase of testing with the HHDDT/mobile source received much more attention than the first phase of testing with the Stationary engine as results were likely to aide in the ongoing discussions about a measurement allowance for the new EPA Changes to Test Procedures for Nonroad Engines and Heavy-duty Highway Engines. The new regulation covers measurement of emissions from in-use diesel engines, especially when the engine operated in the Not to Exceed (NTE) region of the engine map. The discussions soon pointed to the need for a developmental, low emission engine and Caterpillar offered a 475 hp Caterpillar C-15 ACERT engine with 200 hours or about 5,000 miles on it since being rebuilt. The engine was equipped with dual exhausts and a pair of oxidation catalysts and was certified to the 2.5 g/bhp-hr NO_x + NMHC and 0.1 g/bhp-hr PM. The plan was to compare emissions measured with eight PEMS to values measured with the FRMs. Four of the PEMS measured only PM, three PEMS measured only gases and the remaining PEMS measured both gases and PM. However, one of the PM PEMS was not run within manufacturer's specifications and was excluded from the dataset. The chassis dynamometer tests were performed at CARB's heavy-duty vehicle laboratory (HDV lab) located in Los Angeles, CA.

The heart of the active testing phase was extensively discussed and those discussions resulted in a carefully planned series of steady state and transient driving schedules. These four driving schedules included:

1) Three-mode steady-state NTE test cycle run.
2) Stepped NTE test cycle
3) The Urban Dynamometer Driving Schedule (UDDS)
4) The 50-mph Cruise mode from the ARB 5-mode HHDDT test cycle

Test cycles 1) and 2) were specifically designed for the chassis dynamometer testing by members of the Calibrations and Standards task Force (CSTF) [now called the Emissions Measurement & Testing Committee], ARB, and UCR. The NTE driving schedules test cycles were designed to clearly delineate entry into, operation within, and exit, from the

NTE-defined zone of engine operation. The steady-state NTE cycle was run at three different engine speeds with events in the NTE region. A second NTE cycle was designed with a “stepped” pattern, intended to simulate NTE-type vehicle/engine operation with gentle accelerations between modes and steady-state operation at each load point. More detail is provided below on the special NTE cycles.

The UDDS and 50-mph cruise driving schedules were intended to better represent 'real-world' operation, including stop-and-go transient operation and high speed cruise operation.

2.6.1 Steady-State NTE test cycle

The steady-state NTE cycle was run with a vehicle speed of 40 miles per hour and included three different engine speeds and three different load points within each engine speed. The engine speeds were 1290, 1550, and 1770 rpm and the load points within each engine speed were 40%, 70%, and 100% load. Within each engine speed/load point, changes in grade were used to provide transitions into and out of the NTE zone. The determination of the specific engine speed and load points was done experimentally at the ARB HDV Lab in coordination with a Caterpillar representative. The changes in grade were repeated 7 times for each speed/load point within the cycle. Thus, each test run at a specific speed/load point includes 7 replicates of a specific NTE event. A description of the steady state NTE cycle at each speed is provided in Table 2-3. The cycle is shown graphically in Figure 2-2 using load data broadcast from the ECM via J1939 protocol. The NTE steady state cycle was repeated twice for each engine speed, with one run each on two different days.

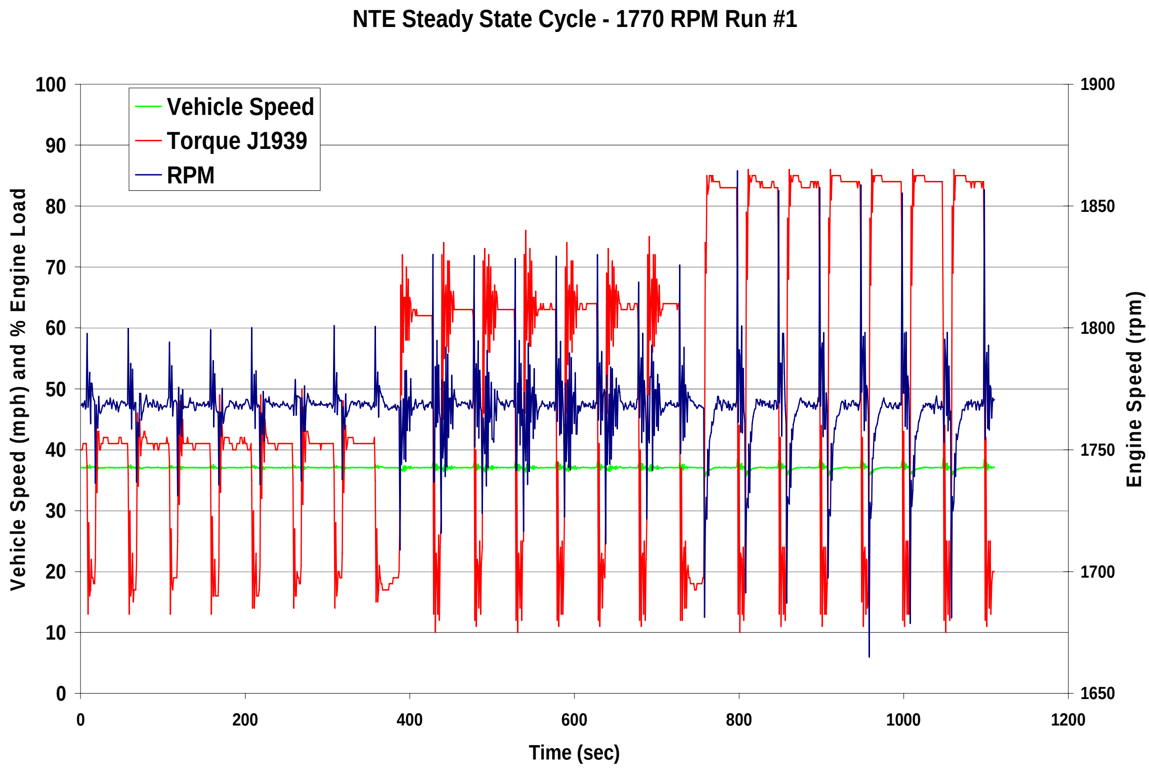


Figure 2-2. NTE Steady State Cycle

1290 rpm steady state cycle (40%, 70%, 100% load)
7 repeats per point, 50 sec NTE events **[22 minutes]**

time step	time (test)	gear	mph	grade (deg)	repeats	
	warmup	7H	40	1.1		
	0	7H	40	1.1		
0:10	0:10	7H	40	0		
0:10	0:20	7H	40	1.1	1	1290 rpm 40%load
0:40	1:00	7H	40	0		
0:10	1:10	7H	40	1.1	2	
0:40	1:50	7H	40	0		
0:10	2:00	7H	40	1.1	3	
0:40	2:40	7H	40	0		
0:10	2:50	7H	40	1.1	4	
0:40	3:30	7H	40	0		
0:10	3:40	7H	40	1.1	5	
0:40	4:20	7H	40	0		
0:10	4:30	7H	40	1.1	6	
0:40	5:10	7H	40	0		
0:10	5:20	7H	40	1.1	7	
0:40	6:00	7H	40	0		
0:30	6:30	7H	40	2.7	1	1290 rpm 70%load
0:40	7:10	7H	40	0		
0:10	7:20	7H	40	2.7	2	
0:40	8:00	7H	40	0		
0:10	8:10	7H	40	2.7	3	
0:40	8:50	7H	40	0		
0:10	9:00	7H	40	2.7	4	
0:40	9:40	7H	40	0		
0:10	9:50	7H	40	2.7	5	
0:40	10:30	7H	40	0		
0:10	10:40	7H	40	2.7	6	
0:40	11:20	7H	40	0		
0:10	11:30	7H	40	2.7	7	
0:40	12:10	7H	40	0		
0:30	12:40	7H	40	4.4	1	1290 rpm 100%load
0:40	13:20	7H	40	0		
0:10	13:30	7H	40	4.4	2	
0:40	14:10	7H	40	0		
0:10	14:20	7H	40	4.4	3	
0:40	15:00	7H	40	0		
0:10	15:10	7H	40	4.4	4	
0:40	15:50	7H	40	0		
0:10	16:00	7H	40	4.4	5	
0:40	16:40	7H	40	0		
0:10	16:50	7H	40	4.4	6	
0:40	17:30	7H	40	0		
0:10	17:40	7H	40	4.4	7	
0:40	18:20	7H	40	0		
0:10	18:30	7H	idle	0		

1500 rpm steady state cycle (40%, 70%, 100% load)
7 repeats per point, 50 sec NTE events **[22 minutes]**

time step	time (test)	gear	mph	grade (deg)	repeats	
	warmup	7L	40	1.7		
	0	7L	40	1.7		
0:10	0:10	7L	40	0		
0:10	0:20	7L	40	1.7	1	1500 rpm 40%load
0:40	1:00	7L	40	0		
0:10	1:10	7L	40	1.7	2	
0:40	1:50	7L	40	0		
0:10	2:00	7L	40	1.7	3	
0:40	2:40	7L	40	0		
0:10	2:50	7L	40	1.7	4	
0:40	3:30	7L	40	0		
0:10	3:40	7L	40	1.7	5	
0:40	4:20	7L	40	0		
0:10	4:30	7L	40	1.7	6	
0:40	5:10	7L	40	0		
0:10	5:20	7L	40	1.7	7	
0:40	6:00	7L	40	0		
0:30	6:30	7L	40	3.1	1	1500 rpm 70%load
0:40	7:10	7L	40	0		
0:10	7:20	7L	40	3.1	2	
0:40	8:00	7L	40	0		
0:10	8:10	7L	40	3.1	3	
0:40	8:50	7L	40	0		
0:10	9:00	7L	40	3.1	4	
0:40	9:40	7L	40	0		
0:10	9:50	7L	40	3.1	5	
0:40	10:30	7L	40	0		
0:10	10:40	7L	40	3.1	6	
0:40	11:20	7L	40	0		
0:10	11:30	7L	40	3.1	7	
0:40	12:10	7L	40	0		
0:30	12:40	7L	40	4.8	1	1500 rpm 100%load
0:40	13:20	7L	40	0		
0:10	13:30	7L	40	4.8	2	
0:40	14:10	7L	40	0		
0:10	14:20	7L	40	4.8	3	
0:40	15:00	7L	40	0		
0:10	15:10	7L	40	4.8	4	
0:40	15:50	7L	40	0		
0:10	16:00	7L	40	4.8	5	
0:40	16:40	7L	40	0		
0:10	16:50	7L	40	4.8	6	
0:40	17:30	7L	40	0		
0:10	17:40	7L	40	4.8	7	
0:40	18:20	7L	40	0		
0:10	18:30	7L	idle	0		

1770 rpm steady state cycle (40%, 70%, 100% load)
7 repeats per point, 50 sec NTE events **[22 minutes]**

time step	time (test)	gear	mph	grade (deg	repeats	
	warmup	6H	40	1.7		
	0	6H	40	1.7		
0:10	0:10	6H	40	0		
0:10	0:20	6H	40	1.7	1	1770 rpm 40%load
0:40	1:00	6H	40	0		
0:10	1:10	6H	40	1.7	2	
0:40	1:50	6H	40	0		
0:10	2:00	6H	40	1.7	3	
0:40	2:40	6H	40	0		
0:10	2:50	6H	40	1.7	4	
0:40	3:30	6H	40	0		
0:10	3:40	6H	40	1.7	5	
0:40	4:20	6H	40	0		
0:10	4:30	6H	40	1.7	6	
0:40	5:10	6H	40	0		
0:10	5:20	6H	40	1.7	7	
0:40	6:00	6H	40	0		
0:30	6:30	6H	40	3.5	1	1770 rpm 70%load
0:40	7:10	6H	40	0		
0:10	7:20	6H	40	3.5	2	
0:40	8:00	6H	40	0		
0:10	8:10	6H	40	3.5	3	
0:40	8:50	6H	40	0		
0:10	9:00	6H	40	3.5	4	
0:40	9:40	6H	40	0		
0:10	9:50	6H	40	3.5	5	
0:40	10:30	6H	40	0		
0:10	10:40	6H	40	3.5	6	
0:40	11:20	6H	40	0		
0:10	11:30	6H	40	3.5	7	
0:40	12:10	6H	40	0		
0:30	12:40	6H	40	5.5	1	1770 rpm 100%load
0:40	13:20	6H	40	0		
0:10	13:30	6H	40	5.5	2	
0:40	14:10	6H	40	0		
0:10	14:20	6H	40	5.5	3	
0:40	15:00	6H	40	0		
0:10	15:10	6H	40	5.5	4	
0:40	15:50	6H	40	0		
0:10	16:00	6H	40	5.5	5	
0:40	16:40	6H	40	0		
0:10	16:50	6H	40	5.5	6	
0:40	17:30	6H	40	0		
0:10	17:40	6H	40	5.5	7	
0:40	18:20	6H	40	0		
0:10	18:30	6H	idle	0		

Table 2-3. Description of Steady state Cycle

2.6.2 Stepped NTE cycle

The stepped NTE test cycle consists of seven separate modes at four different vehicle speeds that "stair-step" increases in vehicle speed from 10 mph to 60 mph, and then decreases in vehicle speed back to 10 mph in the reverse order. Each mode is separated by an acceleration or deceleration event. This pattern is repeated twice within each cycle. The test schedule is provided in Table 2-4, including vehicle speed, grade, engine speed, and load. The grade was fixed for this cycle to maintain the appropriate load. The cycle is shown graphically in Figure 2-3 using loads based on J1939 data. The intent of the cycle is to exercise the vehicle/engine in a predictable and repeatable manner. The determination of the specific engine speed and load points was done experimentally at the ARB HDV Lab in coordination with a Caterpillar representative. Two sets of three repetitions of the entire stepped NTE cycle were performed on two different days.

stepped cycle, variable mph, **constant grade**						
time step	time (test)	gear	mph	grade (deg)	N (rpm)	% load
	warmup	any	10	**2.7**		
	0	6L	25	**2.7**	1300	45
1:30	1:30	7L	38	**2.7**	1433	65
1:30	3:00	7H	48	**2.7**	1530	~75
1:30	4:30	8L	59	**2.7**	ramp	100
1:30	6:00	7H	48	**2.7**	1560	~77
1:30	7:30	7L	38	**2.7**	1420	65
1:30	9:00	6L	25	**2.7**	1300	44
1:30	10:30	any	10	**2.7**		
1:30	12:00	6L	25	**2.7**	1300	45
1:30	13:30	7L	38	**2.7**	1433	65
1:30	15:00	7H	48	**2.7**	1530	~75
1:30	16:30	8L	59	**2.7**	ramp	100
1:30	18:00	7H	48	**2.7**	1560	~77
1:30	19:30	7L	38	**2.7**	1420	65
1:30	21:00	6L	25	**2.7**	1300	44
1:30	22:30	any	10, idle	**0**		

Table 2-4. Description of Stepped NTE Cycle.

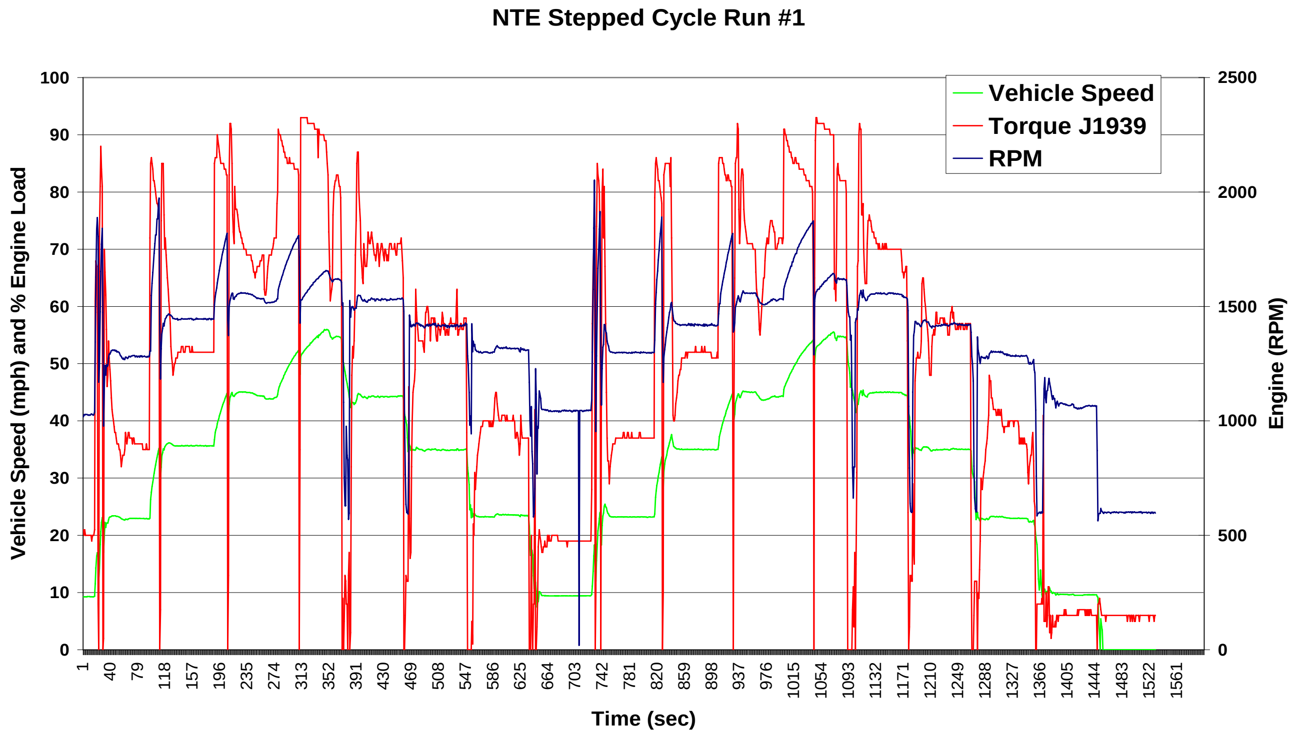


Figure 2-3. NTE Stepped Cycle Plot

2.6.3 Emissions inventory test cycles

Two existing dynamometer driving schedules were utilized to try to better represent real-world engine/vehicle operation. The first test cycle is the federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) and is often used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. The test cycle is a transient test cycle with a short cruise section, and hence exercises both the test vehicle and PEMS over a fairly wide range of operation. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph and maximum speed of 58 mph. This cycle is shown in Figure 2-4.

The second test cycle is a "real-world", emissions inventory cycle, the ARB-developed "50 mph Cruise Mode" which is part of the ARB 5-mode heavy-heavy-duty diesel vehicle test cycle. In addition to including some operation within the NTE-zone, this test cycle exercises the PEMS in a manner similar to what would actually occur if the vehicle were operated over-the-road under highway cruise conditions. The test cycle has a cycle-average-speed of 50.4 mph, a maximum speed of 67.1 mph, is about 12.6 minutes in duration, and is about 10.6 miles long. This cycle is shown in Figure 2-5.

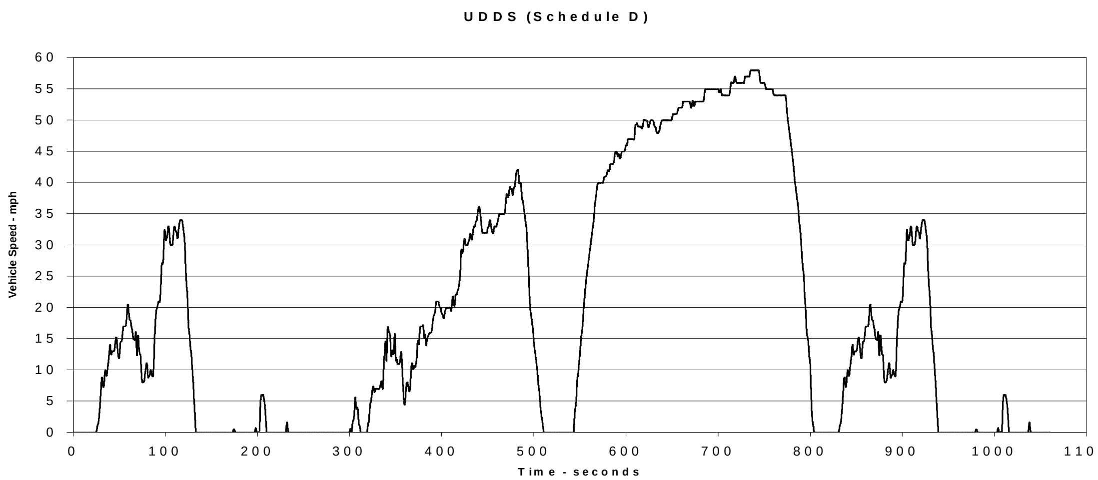


Figure 2-4. UDDS Cycle

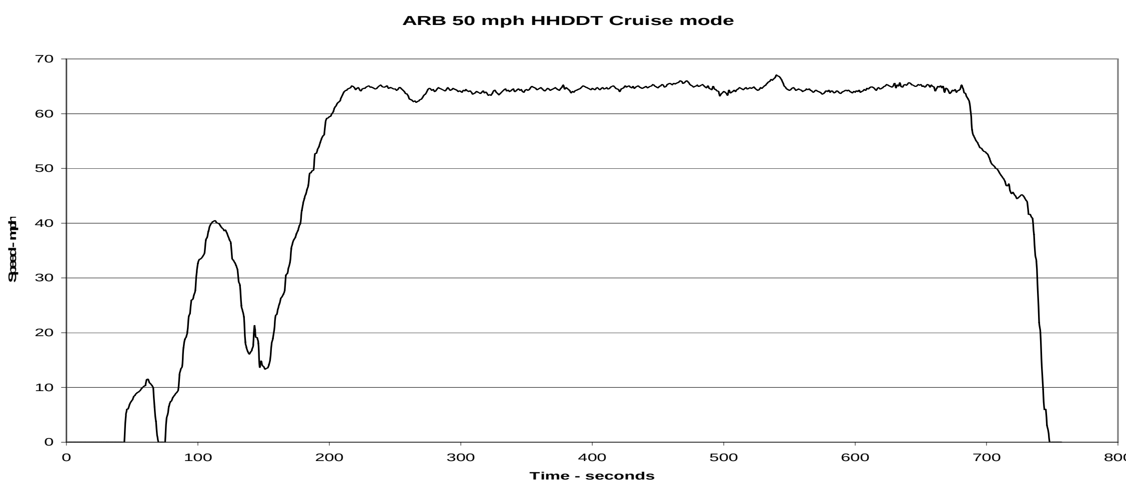


Figure 2-5. 50 mph Cruise Cycle

2.6.4 Test weight and road-load horsepower

For the emissions inventory test cycles (UDDS and 50-mph Cruise mode) the test weight was set at approximately 53,000 lbs. This test weight is similar to the gross vehicle weight of the CE-CERT mobile emissions lab plus the weight of the test vehicle. This provided test conditions similar to those that will be utilized during future on-road testing. This value is also similar to the average load for HHD trucks on California roads. For the three-mode steady-state test cycle and the four-speed, seven-mode steady state test cycle, the dynamometer settings were determined iteratively, based on achieving the desired engine speeds, loads and vehicle speeds. The experimental set-up for the chassis dynamometer testing is shown in Figure 2-6.

Figure 2-6. Experimental Set-up for the Chassis Dynamometer Testing

2.6.5 Engine/vehicle preconditioning

The vehicle was "soaked" (parked) in the chassis dynamometer test cell, which was not temperature controlled, prior to testing and between each of the test days. The test vehicle was fully warmed up to its normal operating temperature at the start of each test day using the test cycle to be used that day, followed by steady-state operation at speed of 50 mph for a period of ten minutes. The first test cycle for the day was run immediately after this sequence.

In order to permit PM filter changes, monitor PEMS operation, etc., a period of 30 minutes was included between each run. In order to improve repeatability, the 10-minutes- at-50-mph preconditioning was performed between each successive run.

3.0 Emissions Results – Stationary Source/Backup Generator

The PEMS tested for the BUG were PEMS1 (Montana System), PEMS2 (Semtech D system), PEMS3 (the RAVEM system), and PEMS4 (the OBS-1300).

3.1 Audit Bottle and Blended Gas Checks

A primary audit calibration bottle was used as a checkpoint between the PEMS and the FRM. The bottle was NIST traceable with ±1% accuracy with a mixture of NO, THC, CO, and CO_2. The percent differences between the PEMS and the FRM are shown below in the Figure 3-1 and details provided in Table 3-1. As noted earlier, the concentration ranges in the audit gas were representative of those found in dilute exhaust measurements and not suitable for some of the PEMS measuring raw exhaust concentrations. For example, PEMS2 manufacturer indicated the values were below the design specifications for their instrument. PEMS3 did not measure THC and no THC data were available from PEMS2. The audit bottle concentrations for PEMS4 also showed considerable deviation for NO. Note that the audit bottle tests with PEMS4 were completed after the testing on the BUG and the manufacturer of PEMS4 noted that after the exhaust test measurements, but before the audit, the zirconia sensor for NO_x was exposed to water. They suspected the water exposure damaged the unit, leading to potentially erroneous readings of the audit bottle and the calibration gas checks below. Since the unit was damaged after the BUG testing, only the audit bottle measurements would have been affected. It should be noted that hydrocarbons for this section are denoted as THC, although two PEMS utilized NDIR for these measurements.

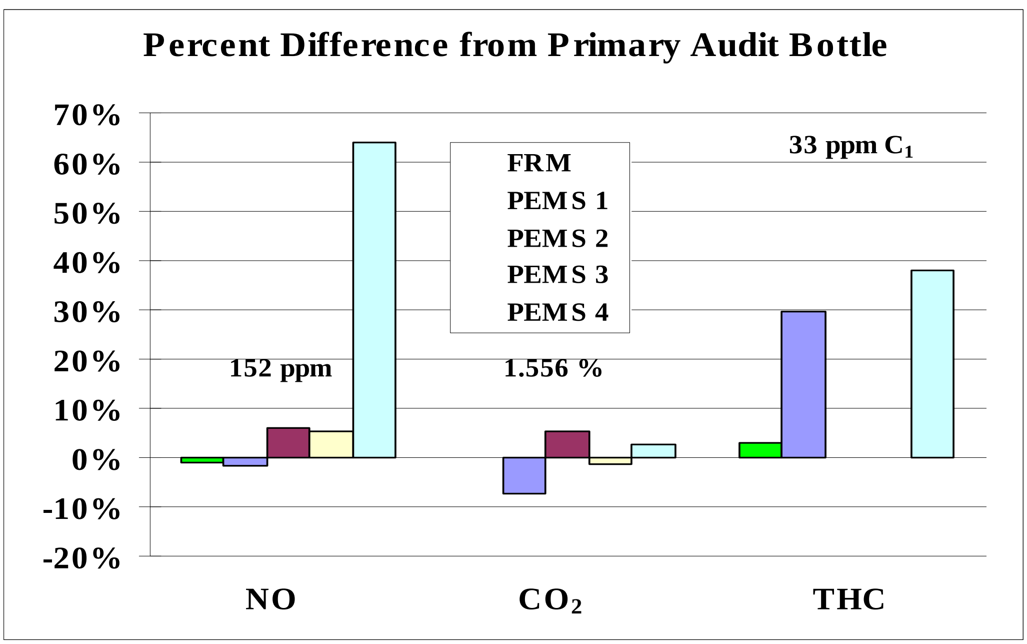


Figure 3-1 Percent Differences from the Primary Audit Bottle. Audit bottle concentrations included in the Figure.

Except for the previously noted differences, all instruments measured CO_2 and NO levels in primary audit gas within ~5%. The best agreement is found with the FRM instruments, including an exact match with the CO_2 value.

It is important to recognize that the concentrations of the primary audit gas were more similar to the values found in diluted streams rather than raw. Since most of the PEMS surveyed are designed to measure the emissions in raw gas streams, differences in concentrations at these levels would not necessarily indicate that a similar difference would be found at the higher concentration levels found in raw exhaust. The audit bottle concentration measurements are compared with the range of concentration values observed in the raw and dilute exhaust in Table 3-1.

The differences for CO were not included in Figure 3-1 as some of the values would skew the presentation of the data in the figure. For CO, the differences were -40% for PEMS1, 59% for PEMS2 and 1.4% for the FRM. PEMS3 and PEMS4 did not provide CO data.

			Concentration Measured			
ID	Cal Type	Date	NO ppm	THC ppmC1	CO ppm	CO2 %
PEMS 1	Bottle	2-Nov	149.5	31.00	15.00	1.440
PEMS 2	Bottle	2-Nov	161.0	-	40.00	1.640
PEMS 3	Bottle	2-Nov	160.0	-	-	1.533
FRM	Bottle	4-Nov	150.5	24.67	25.49	1.556
PEMS 4	Bottle	3-Feb	249.0	33.00	-	1.600
FRM	Bottle	3-Feb	149.2	23.82	25.13	1.573
Audit			151.8	23.91	25.14	1.556
Raw Exhaust			250 – 1740	20 - 101	70 - 251	2.8 - 8.4
Dilute Exhaust			53 – 297	6.0 - 18	29 - 68	0.5 - 2.6

Table 3-1 Comparison of PEMS & FRM Measurement of 1% NIST Audit Bottle

3.2 Blended Audit Gas Check

Another set of tests were conducted using audit gases prepared using a gas divider with ±1.5% accuracy mass flow controllers (MFCs) and included a zero and four span ranges. The span gases were measured in the order of high to low concentration, with the higher concentrations intended to be closer to those expected for raw exhaust measurements (span 3 and 4), and the lower concentrations being more representative of the dilute concentrations measured with the FRM. Figure 3-2 below shows the percent difference between the measurements and the CO_2 and NO calibration gases for the measurements. Note PEMS4 was tested in February and slightly higher calibration gas levels were used for CO_2 and NO at that time. The concentrations provided on the right are from the February tests where there are differences from the values used in November. A duplicate run was conducted for the FRM during the November test period.

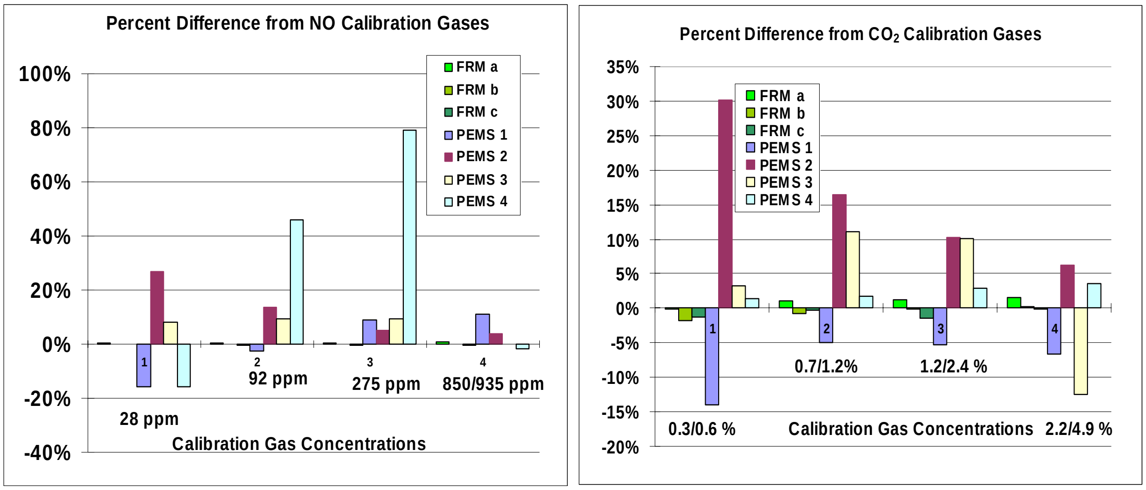


Figure 3-2 Percent Difference Between Measured Value & Calibration Gas Concentration a) NO and b) CO_2. Spans 3 and 4 were Close to the Raw Values Expected for a BUG.

As is evident in Figure 3-2, the percent difference between the true value and that measured by the FRM ranged from zero to a maximum of 1.8% for both NO and CO_2 gases. For the PEMS, the difference depended on the concentration of the blended audit gas. Further, some data in Figure 3-2 has all of the deviations to one side of the true value and is suggestive of bias for some PEMS. The question of bias will be addressed later.

An important point for proper analysis of the results plotted in Figure 3-2 is the relationship between the concentration of the audit gas and the design specification for the analyzer. For example, the differences for both gases for Spans 3 and 4 are generally within ±10%. For Spans 1 and 2, where the concentrations generally are outside the range of specification for the raw gas analyzers, the deviation ranged from –15% to +30% for CO_2 and from -15% to +27% for NO. This finding is not surprising as error generally increases when an instrument is operating near its lower detection limit. The point about the audit gases being outside the design range of the analyzers is well represented in a set of charts from one of the PEMS manufacturers. Note in Figure 3-3 that all the blended audit gases for the CO_2 are below the measured values during the testing while for NO only two of the blended audit values fell within the test range.

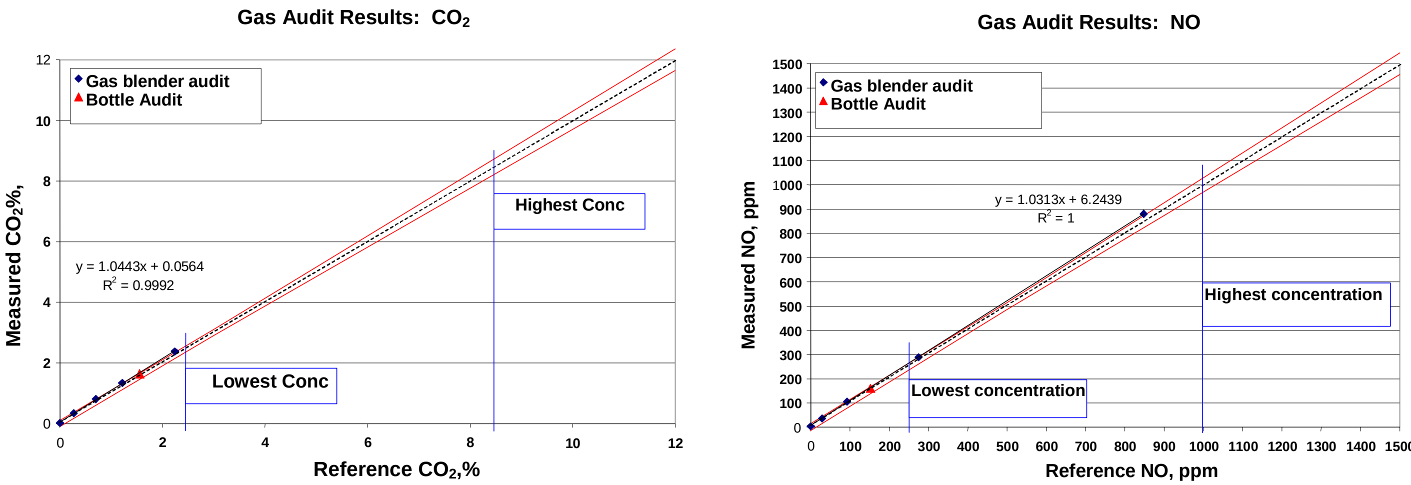


Figure 3-3 Comparison of Blended Audit Gases & Engine Emissions for CO_2 and NO_x

The results for CO and THC are not shown in the graph but values can be viewed in the detailed results of Appendix C. Some of the percent differences from the true values are rather high and most of these values suffer the problem of having the concentration outside the design value for the PEMS.

3.3 Exhaust Flow Rates

Both concentrations and flow rates must be accurately measured in order to obtain accurate emission rates. Exhaust flow rates for the FRM and PEMS 1, 2 and 4 were compared. The PEMS3's design uses a proportional partial flow dilution system, instead of direct measurement of the flow rate. Emission rates are determined using the ratio of the sampling probe diameter to the exhaust diameter.

Figure 3-4 below compares flow rates provided by the manufacturers of PEMS1, 2 and 4 with the flow rates measured with the FRM over the range of 420 to 1000 standard cubic feet per minute (SCFM) for the four load points used in the study. The PEMS flow rates were obtained from calculation (PEMS1) or direct measurement of exhaust flow (PEMS2 and 4). A description of the flow measurement method used in UCR's MEL is provided in Appendix A. MEL's primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. Tunnel flow rate is adjustable from 1000 to 4000 scfm with accuracy of 0.5% of full scale. The FRM exhaust flow was determined by subtracting the measured flow of the dilution air from the total CVS tunnel flow. A paired t-test showed that all flow differences between the FRM and the PEMS were statistically significant except for PEMS1 at the highest flow rate.

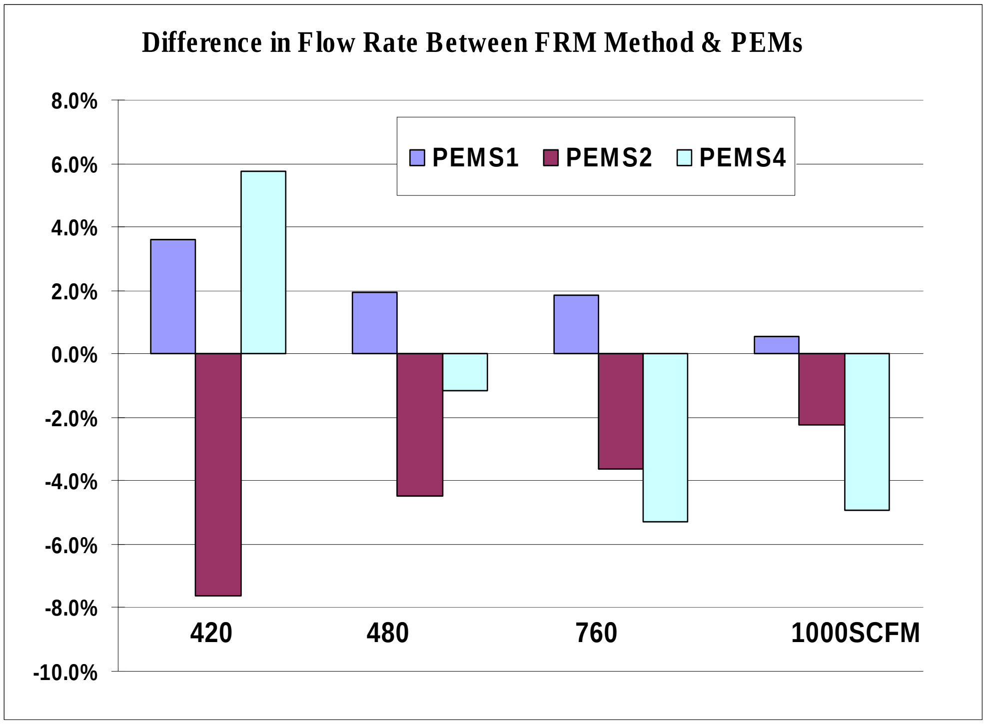


Figure 3-4 Relative Difference in Flow Rate Between FRM and PEMS

An experimental note is that the thermocouple for exhaust temperature measurement for PEMS2's flow measurement device was limited to 400°C, so the as supplied unit could not accurately compute the exhaust density and standard volumetric flow when the exhaust was above this temperature. UCR worked with the PEMS2 manufacturer to provide exhaust temperature during the BUG testing. PEMS2 subsequently used this supplied temperature and actual volumetric flow from their flow device during the entire test to compute standard volumetric flow and to calculate their mass emissions.

Another perspective of the quality of the data over the flow range is the trend analysis shown in Figure 3-5. From this analysis, the three measuring devices are very linear over the measured range as evident from the high values (closeness to 1) for the coefficient of determination (R^2). One consequence of the close agreement for flow of PEMS 1, 2 & 4 and the FRM is that any subsequent differences observed in measured emissions rates are likely due to concentration issues rather than flow measurements.

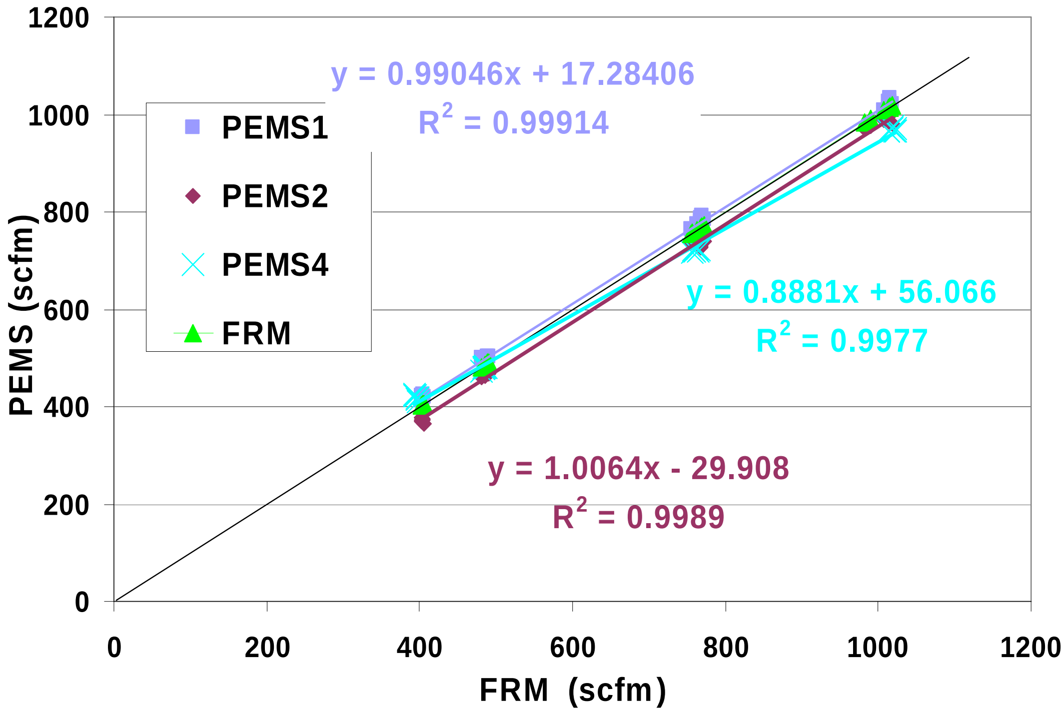
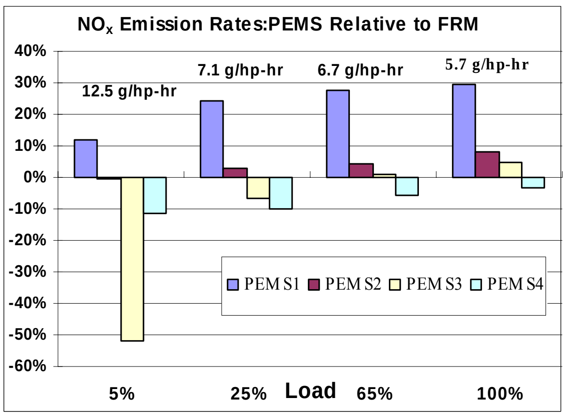


Figure 3-5 Correlation Plot for PEMS and FRM for Exhaust Flow Rate

3.4 Mass Emission Rates

BUG emission rates for each gas were calculated in grams per hour (g/hr) and the percentage difference relative to the FRM value is shown in the figures below. It was decided to evaluate the percentage differences and correlations on a g/hr basis since this is the purer measurement of the ability for the PEMS to make mass measurements over a specified cycle or time period than grams per horsepower-hour (g/hp-hr). Specifically, on a g/hp-hr basis, the highest emission rates are found at the load points where the horsepower is very low, resulting in an overemphasis of these values when looking at correlations between the PEMS and FRM. Measurements on a g/hp-hr basis are discussed below since the g/hp-hr measurements are important in understanding the measurement levels in relationship to the certification standards and applicability for NTE measurements. The g/hp-hr values for the FRM are also included in the figures relating the g/hr percentage differences. Note that results for the mass emissions in g/hr or g/hp-hr depend on the independent measurements of mass flow and concentration so errors in flow or concentration will carry through into the calculated mass emission rate. An alternative method for examining the data is to normalize the emissions rates for the regulated emissions to CO_2, which would automatically compensate for any differences in flow rate, as shown below. Detailed BUG emissions rates for the FRM and each PEMS are provided in Appendix D in both g/hr and g/hp-hr units. Statistical comparisons of the BUG emission rates in g/hr units are provided in Appendix E.

Figures 3-6a and 3-6b show the results for CO_2 and NO_x when the PEMS are compared with the FRM. The agreement for was CO_2 relatively good for PEMS1, 2, and 4, with PEMS4 having the highest overall difference, about 10%. The agreement of PEMS3 was good at the highest flow rates, but the difference was about 50% at the lowest load. This difference was identified as being related to a failed component used in controlling flow. Similar deviations are also found for PEMS3 for the other emissions at the lower load points. It is interesting to note that the FRM measured higher CO_2 emissions than all PEMS. For CO_2 emission rates, the differences between the FRM and the PEMS were statistically significant for all comparisons except PEMS 1, 2, and 3 at the highest load point and PEMS4 at the lowest load point.



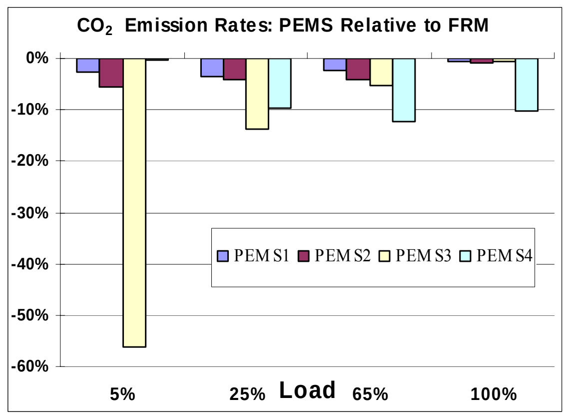


Figure 3-6 Mass Emissions (gm/hr) for PEMS Relative to FRM a) NO_x and b) CO_2. Emission Rates in gm/hp-hr provided for FRM.

NO_x values showed agreement within ~10% or better for PEMS2 and 4 with the FRM. PEMS3 values showed good agreement at high loads, with larger errors at the lowest load. For PEMS3, the NO_x/CO_2 ratios, which eliminate the effects of flow measurement, were within 10% of those measured by the FRM for all load points. PEMS1 values were 12% to 30% higher than the FRM values. Some of the differences in NO_x emissions for the PEMS1 are related to the omitted humidity correction (~10%) and a bias of about the same magnitude observed with the calibration gases, since the flow rates show good correlation with the FRM.

Figure 3-7 shows the difference in emission rates for THC and PM. Three manufacturers - PEMS1, PEMS2, and PEMS4 - reported hydrocarbons (HC) and resultant values were significantly different relative to the FRM. It should be noted that the actual HC concentrations are relatively low, even in comparisons with the upcoming proposed NTE standards (as discussed below). Since PEMS1, 2 and 4 had accurate flow measurements, the source of the difference must be in the measured concentration. The manufacturer of PEMS2 said the values in the raw gas were outside the range the instrument was set up to measure. The HC measurements for PEMS1 and 4 were measured with NDIR.

Two manufacturers, PEMS1 and PEMS3, measured particulate matter (PM). For PEMS1 results were significantly lower than the FRM at all ranges. For PEMS3 values were within ~20% of the FRM at higher loads, with larger deviation at the lower loads. PM/CO_2 ratios for PEMS3 for the 5 and 25% load points were 22-25% lower than those measured by the FRM.

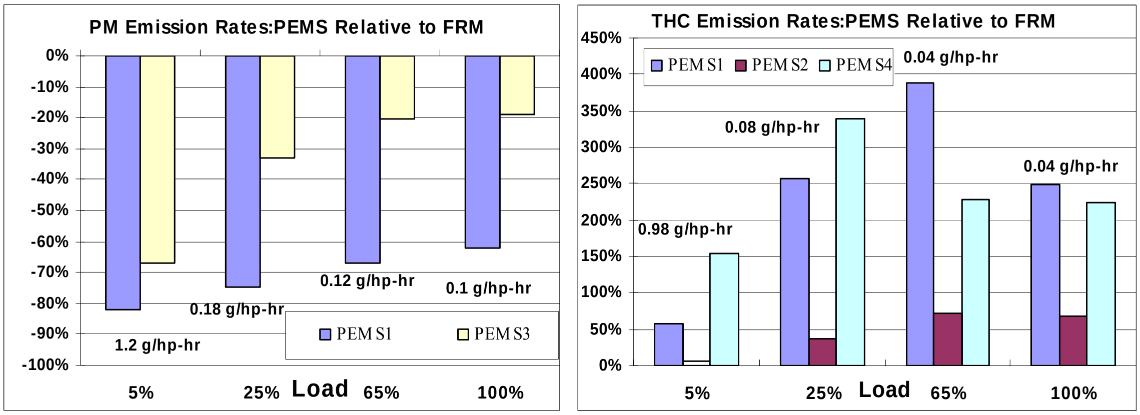


Figure 3-7. PEMS Mass Emissions Relative to FRM at Several Loads (a) THC and (b) PM. Emission Rates in gms/hp-hr provided for FRM.

Plots showing the correlation over a broad range are provided below in Figures 3-8 (a) (d).

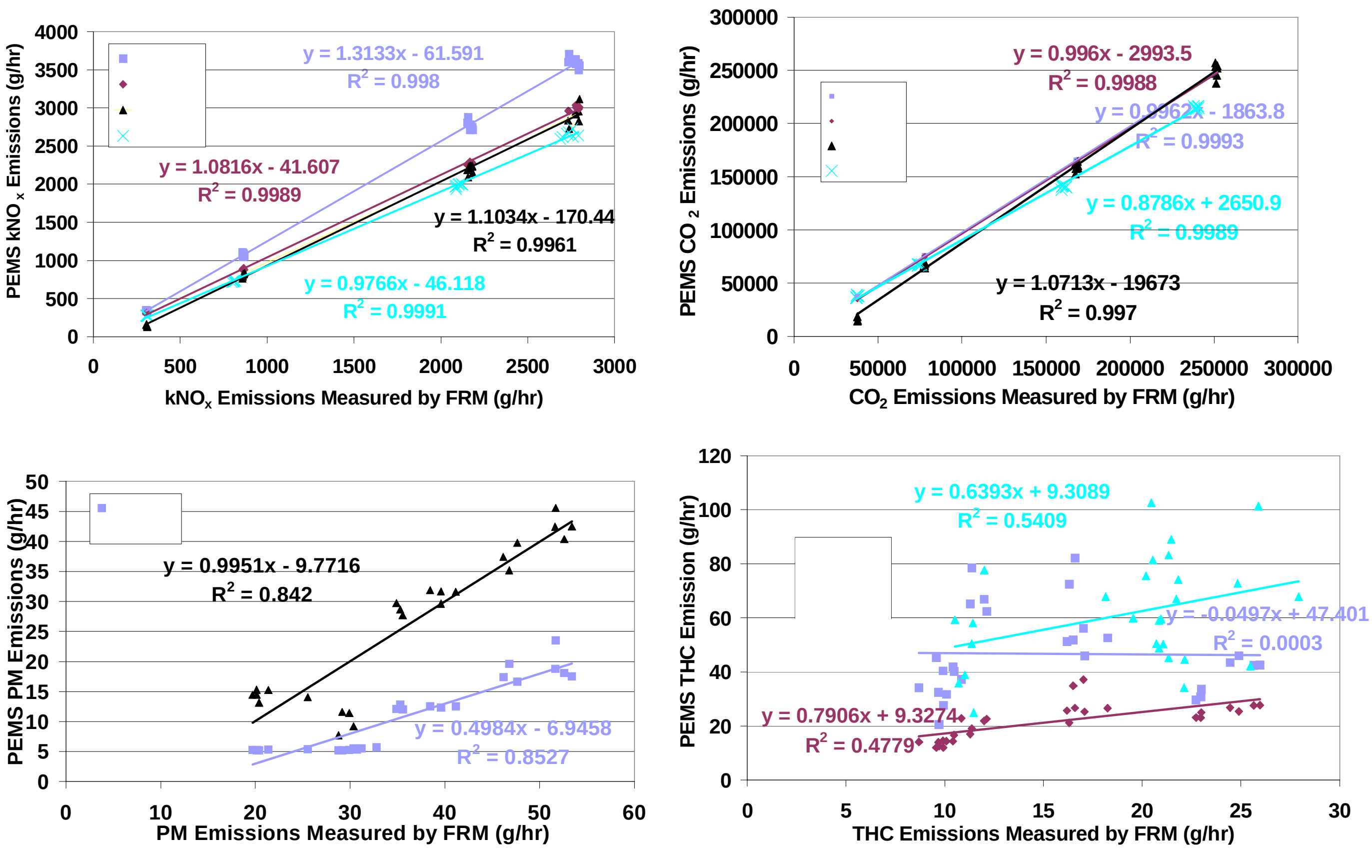


Figure 3-8 Plot of Correlation between FRM and PEMS for (a) NO_x (b) CO2 (c) PM & (d) THC

3.5 Results in Grams per Horsepower Hour

Figure 3-9 was developed to show the comparative emission rates on a g/hp-hr basis for NO_x, THC, and PM for the FRM measurements and each PEMS. The error bars on the graphs represent 95% confidence intervals. The emission rates were calculated using the measured mass emission rates and electrical power output from the load bank. The emissions rates and associated error bars for the 5% load point for THC and PM are divided by 5 to allow presentation of all modes on the same scale. One advantage of Figure 3-9 is that it visually allows a perspective on the closeness of the measurements among the different methods and the significance of the 95% confidence limits. Another feature in Figure 3-9 shows the emissions rate per unit of work increasing rapidly with at the lowest power as is usually reported.

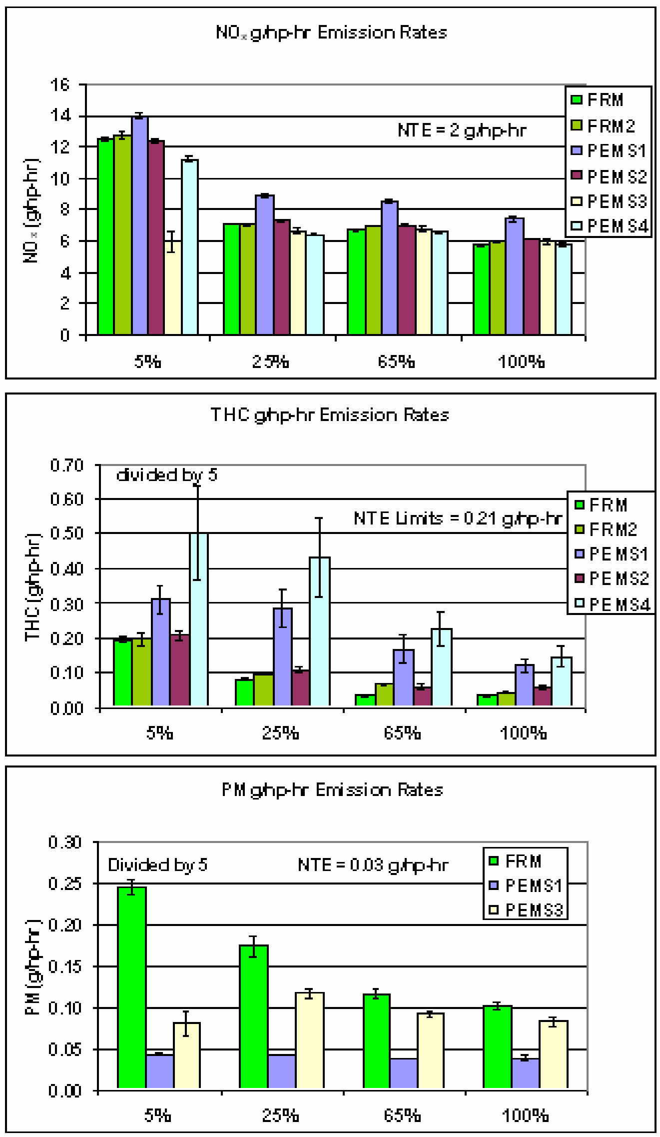


Figure 3-9 Comparison of g/hp-hr Emission Rates and 95% Confidence Limits. (a) NO_x, (b) THC, (c) PM

3.6 Data Analysis within the NTE Zone

As explained earlier, the original intent of the project was to broadly survey the accuracy of the PEMS when applied to data gathering for either NTE or inventory purposes. However, as the project developed, a greater interest was assigned to defining the accuracy and percent deviation of the PEMS within the NTE zones. The NTE zones were defined in earlier sections.

Even though the engine tested in the backup generator did not need to comply with NTE regulations, we thought it was of value to examine the points operating within the NTE zone, namely at 65% and 100% power. To gain some insight as to the closeness of the PEMS to the FRM within the NTE zone, EPA[3] provided values for the NTE limits so comparative analyses could be made of PEMS and the FRM. Table 3-2 below compares both the absolute difference of the emissions rates determined by the FRM and by the PEMS and the relative error when the absolute difference is divided by the NTE threshold limit. Because it might be close on a brake-basis, we included the point at 25% power as well.

NTE Limit	NOx g/hp-hr 2.0 g/bhp-hr				THC g/hp-hr 0.21 g/bhp-hr			PM g/hp-hr 0.03 g/bhp-hr	
	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS2	PEMS4	PEMS1	PEMS3
100% Load									
ABS(FRM-PEMS)	1.69	0.45	0.27	0.19	0.09	0.02	0.10	0.06	0.02
vs. NTE limits	85%	23%	13%	10%	41%	11%	48%	214%	65%
65% Load									
ABS(FRM-PEMS)	1.85	0.28	0.08	0.40	0.13	0.02	0.16	0.08	0.02
vs. NTE limits	93%	14%	4%	20%	64%	12%	75%	261%	79%
25% Load									
ABS(FRM-PEMS)	1.75	0.20	0.46	0.70	0.21	0.03	0.33	0.13	0.06
vs. NTE limits	87%	10%	23%	35%	98%	14%	159%	436%	191%

Differences represent the absolute value of the difference between the FRM and PEMS

Table 3-2 Comparison between Percentage Differences on g/hp-hr Basis Relative to NTE Limits Provided by the EPA[2]

Considering only the 65% and 100% load points in this analysis, the absolute differences between the FRM and the PEMS NO_x measurements were 4 to 23% of the NTE limit for PEMS2, 3 & 4, with significantly larger differences found for PEMS1. For THC, PEMS2 was most comparable with the FRM with the differences relative to the NTE limit being 11 and 12% while PEMS1 and 4 had relative differences ranging from 41 to 75%. For PM, PEMS1 and 3 showed differences of between 65 to 79% and 214 and 261%, respectively, from the FRM in comparison with the 0.03 g/hp-hr NTE standard that might be applicable in the future.

The goal in this section on the NTE perspective was to present an analysis that might provide some insight as to the allowable tolerance that is needed when enforcement of the NTE rule is based on in-use measurements with PEMS rather than with laboratory measurements and instruments. The analysis suggests that tolerances will depend on the PEMS unit and on what pollutant is being measured. For PM measurements, it appeared from these analyses that additional developments will be required to provide techniques suitable for PEMS/NTE testing.

3.7 Results Based on Fuel Consumed or CO_2

Emission rates per unit of fuel consumed or on a CO_2 basis are of interest for those involved with either/both determining emissions inventories or enforcing the not-to-exceed regulations. Harley and co-workers [4] shows that one advantage is a quick determination of the total emissions if the fuel consumed in a specific area is known. Another advantage of this approach is that calculations based on ratios of emissions to CO_2 are independent of exhaust flow rate. Thus determining the ratio of emission rates relative to the CO_2 rates can be useful in identifying whether the source of the difference between the FRM and PEMS is related to the measurement of concentration or flow rate. Figure 3-10 was provided to illustrate when the rates of NO_x, THC, and PM is divided by the rates of CO_2.

This approach and deeper analysis was particularly useful for the data from PEMS3, especially at the two lowest load points where the manufacturer indicated that the partial-flow sampling system appeared to be under-sampling by approximately 55% at the lowest load point and by approximately 12% at the second lowest load point. The manufacturer suspected that a differential pressure sensor, used to maintain isokinetic sampling, had malfunctioned during the testing and this malfunction lead to the under-sampled flow rates. Note in Figure 3-10 that the differences between the FRM and PEMS3 were considerably narrowed, confirming that the flow measurement error had propagated into the calculation of the emission rate. For example, the difference between the FRM and PEMS3 for the measurement of CO_2 and NO_x at the lowest power was reduced from 50% to about 10%.

Several other artifacts were noticed. For example, the NO_x/CO_2 emissions for PEMS1 were biased approximately 5 to 10 % higher relative to the FRM. This difference could be related to the concentration measurements and should be further investigated. For PEMS2, a slightly higher bias in NO_x/CO_2 ratios relative to the FRM was found compared to the straight NO_x emissions. This is probably due to the lower CO_2 emissions in comparison with the FRM at the three lowest load points. Similarly, for PEMS4, the biases in the NO_x/CO_2 ratios were higher (65% and 100%) or less negative (25%) compared to the FRM than the straight NO_x emissions at the three highest load points, due to lower CO_2 measurements compared to the FRM at those points.

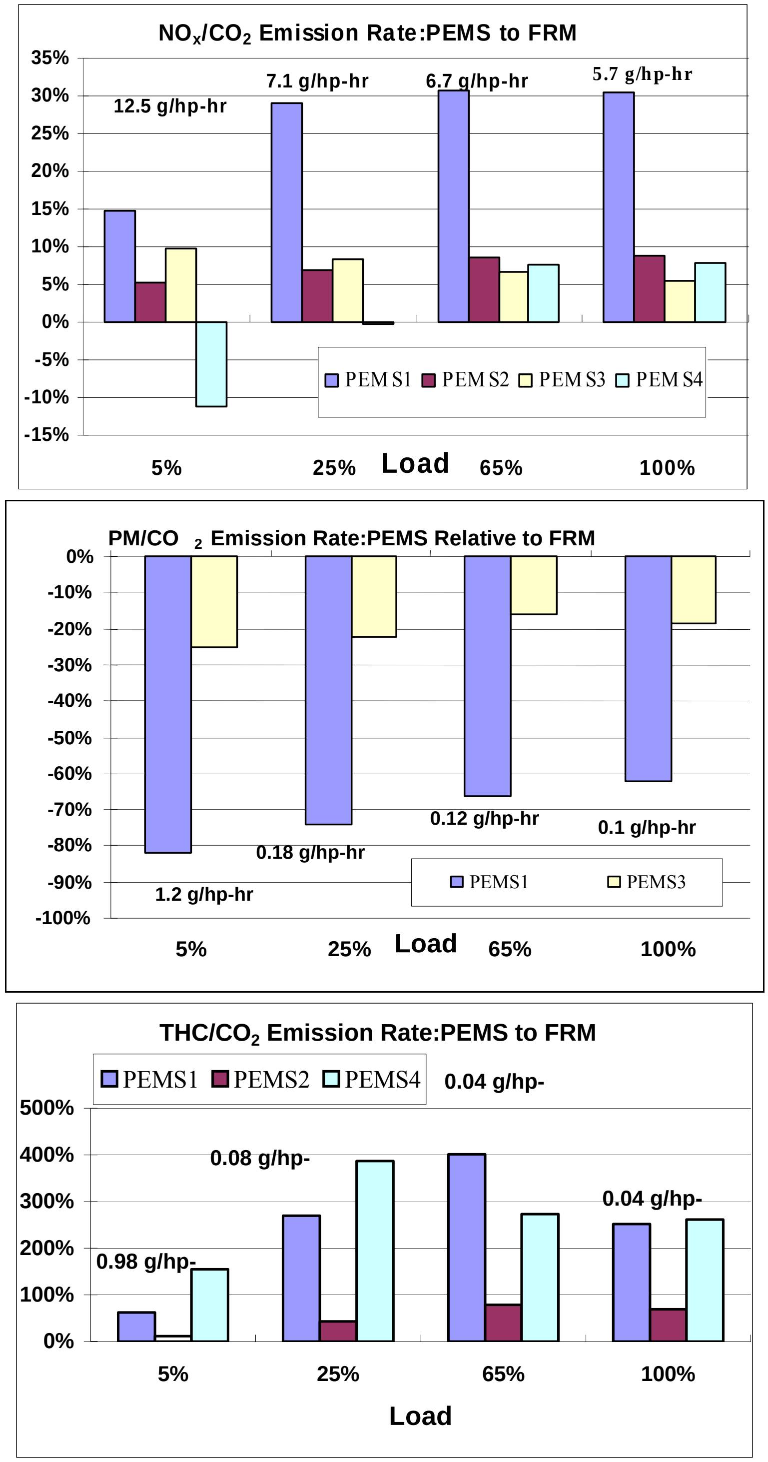


Figure 3-10 PEMS Emission Rate Relative to CO_2 When Compared with FRM Emission Rate Relative to CO_2. For: a) NO_x, b) PM, c) THC.

3.8 Precision

A definition of precision can be found in ASTM E-177: *Standard Practice for the Use of the terms Precision and Bias in ASTM Test Methods.* Therein precision is defined as a concept related to the closeness of agreement between test results obtained under like conditions when measurements are made for a test method in a state of statistical control. For this report, the precision of the different PEMS and the FRM were calculated using the coefficient of variation (COV) at one standard deviation derived from the average value of the seven repeat iterations at each load point. Plots of the results are shown in Figure 3-11 below.

Of the emission components, NO_x and CO_2 showed the lowest COVs or scatter across all of the measurement techniques. A one-tailed F-test showed no statistically significant differences in the precision of the NO_x measurements between the FRM and PEMS 2 and 4. The COVs for NO_x for the FRM were lower at a statistically significant level relative to PEMS 1 and 3, for all but the lowest load point for PEMS 1. For CO_2, the COVs for most PEMS and the FRM were within 2% for a majority of the test points. The COVs for the FRM were slightly lower than those for the PEMS, with this result being statistically significant for all but the 5 (p=0.056), 25 and 100% load points for PEMS 4.

For PM, the COV or precision of the measurements was generally below 10% for both the FRM and PEMS, with no consistent advantages in precision seen for the FRM. However, recall the disparity in the accuracy for the other PM methods over all ranges. THC measurements generally showed higher dispersion or COVs for the PEMS than the FRM. The COV for THC with the FRM ranged between 4 and 7 %, while the COV for PEMS1 was from 17-33%, the COV for PEMS2 was from 7-20%, and the COV for PEMS4 was from 23-37%. The COV for CO emissions measurements was generally below 10% for the FRM, PEMS1 and PEMS2. No statistically significant differences in the COVs were found for PEMS1 or 2 for CO, except for PEMS2 at the lowest load point. The CO COVs for PEMS 4 and PEMS3 at the low load points were larger than those for the FRM or the other PEMS.

The significant observation from the precision analyses is that precision and accuracy are independent measures. In fact, the data indicate that measurements for PM and THC were quite inaccurate but highly precise.

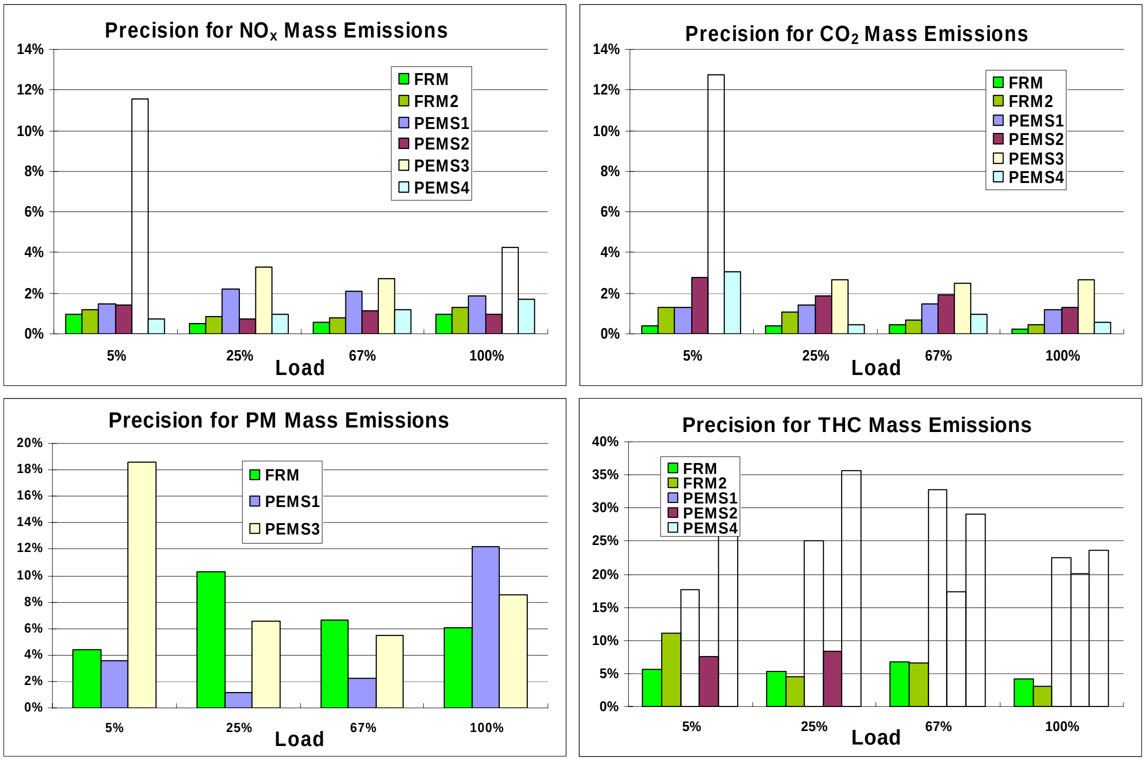


Figure 3-11 Precision of the FRM and PEMS for the Various Measurements. a) CO_2, b) NO_x, c) PM, and d) THC

4.0 Emissions Results – Mobile Source/Heavy-duty Truck Testing - Gas-Phase Emissions

The PEMS tested for on the chassis dynamometer for gas phase emissions were PEMS1 (Montana System), PEMS2 (Semtech D system), PEMS3 (the RAVEM system), and PEMS4 (the OBS-2200). In response to strong urging from both EPA and ARB management, Horiba submitted a prototype OBS-2200 instrument with unproven software for the chassis dynamometer test program at the ARB laboratory in Los Angeles. The product development team for this new instrument had not had the opportunity to test the prototype with a vehicle before shipping it to the ARB laboratory. During the week of testing several software related problems were discovered, which required on-site software revisions. The early runs in this program produced no viable data because of software bugs. The later data presented in this report is still prototype quality with incorrect software compensations applied. These results are preliminary to finishing the product cycle and should not be considered representative of the production model performance.

4.1 Primary Audit Bottle Check

The percent differences from the audit bottle for the FRM and PEMS during the chassis dynamometer testing are shown below in Figure 4-1, along with the raw and dilute audit bottle concentrations. Each PEMS was tested with either the raw or dilute audit bottle depending on whether the PEMS was configured to sample dilute or raw exhaust. The detailed results are provided in Appendix C. PEMS3 did not measure THC. It should be noted that the audit bottle concentrations were not provided to the PEMS manufacturers prior to the audit bottle check or before the engine testing, hence, the analyzer ranges were not necessarily optimized for the given concentration values during the engine testing.

The deviation from audit bottle concentration varied by PEMS and by pollutant. For the FRM all concentrations were within 2.5% of the audit bottle concentrations for both raw and dilute concentration levels. For PEMS2, the measured concentrations were within 2% of the audit bottle for NO_x and CO_2, with larger differences for THC (-7%) and CO (+13%). PEMS3 measured the same concentration as the audit bottle for NO_x, with differences of –11% and –8%, respectively, for CO and CO_2. PEMS4 showed the largest deviations from the audit bottle concentrations with differences of 26% and 17% for NO and CO_2, respectively, and differences of 20% and –9%, respectively, for THC and CO. The manufacturer of PEMS4 indicated that software bugs in their prototype unit caused reading and logging errors that contributed to the deviations from the audit bottle on Tuesday during this test period. The software was updated prior to conducting the emissions tests presented for PEMS4 later in the section. It should be noted that hydrocarbons for this section are denoted as THC, although one PEMS utilized NDIR for these measurements.

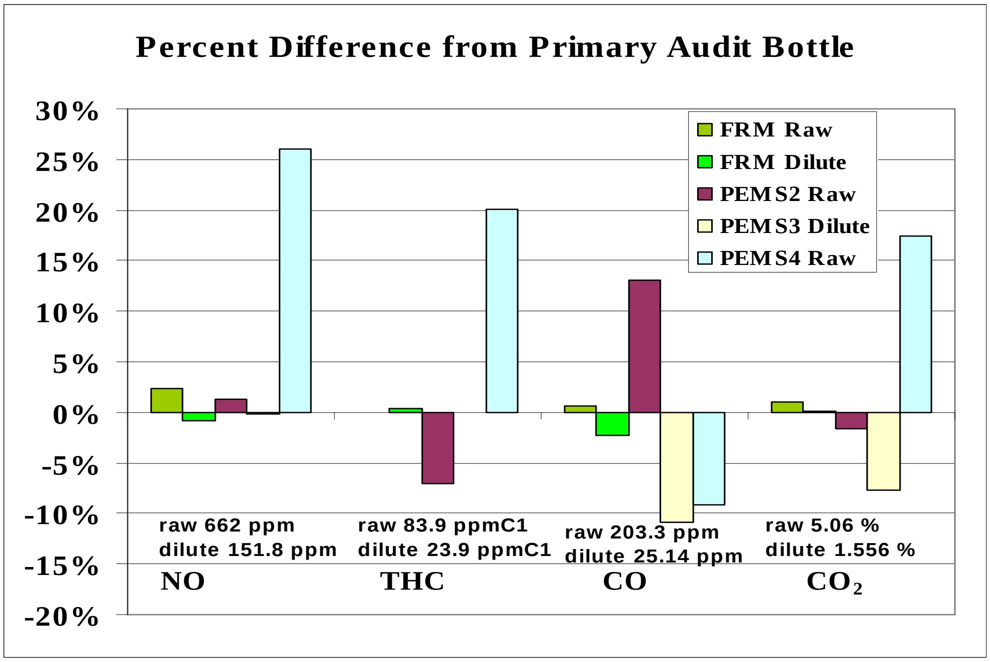


Figure 4-1 Percent Difference between PEMS/FRM and the Audit Bottle.

4.2 Integrated Cycle Emissions and Exhaust Flow Rates

Mass emission rates in grams per cycle and exhaust flow rates were determined for each of the cycles integrated over the entire duration of the cycle. This included the UDDS and 50 mph cruise cycles, the steady-state NTE cycle and the NTE stepped cycles. For the steady state and stepped NTE cycles, the integrated results were collected over all NTE events within a particular cycle and the transitions between NTE events. For the NTE steady-state cycles, this included all 7 values measured at the NTE events at the 40%, 70%, and 100% loads for one test iteration. The total number of complete cycles conducted during the testing program was as follows: seven UDDS cycles, seven 50 mph cruise cycles, six NTE stepped cycles and two each of the full NTE 1290, NTE 1500, and NTE 1770 cycles. Data for PEMS1 and PEMS4 are only available for one test for each of the NTE 1290, NTE 1500, NTE 1770. Only one test is also available for PEMS1 on the NTE stepped cycle and for PEMS4 on the 50 mph cruise cycle. There are no error bars in the Figures for PEMS/test cycle combinations where only a single test is available.

4.3 Integrated Exhaust Flow Rates

Both concentrations and flow rates must be accurately measured in order to obtain accurate emission rates. The average exhaust flow rates were determined for each of the integrated cycles. The FRM exhaust flow was determined by subtracting the measured flow of the dilution air from the total CVS tunnel flow, as explained in an earlier section.

The PEMS flow rates were obtained from their respective direct measurement of exhaust flow, except for the PEMS3 approach. PEMS3 does not require the direct measurement of flow rate as long as their partial dilution system maintains isokinetic, and therefore proportional, sampling of the main exhaust stream. For PEMS3 emission rates are determined using the ratio of the sampling probe diameter to the exhaust diameter.

Figure 4-2(a) below is a comparative plot of the flow rates measured by the FRM and PEMS 1, 2 and 4. The exhaust flow rates measured by the FRM ranged from 350 to 800 standard cubic feet per minute (SCFM). Exhaust flow rates for PEMS1 were approximately 10% different from those of the FRM. Exhaust flow rates for PEMS2 ranged from 0 to 4% with an average deviation of 2.7% as compared to those measured by the FRM. PEMS4 also showed good agreement with the FRM, with a range from 0 to 4% and an average deviation of less than 1%.

A different perspective of the correlation between the whole range of the exhaust flow rates for the FRM, PEMS2, and PEMS4 is provided in Figure 4-2(b). The curve fit or coefficient of determination over the whole range is excellent (>99%), although there are differences in the slopes and intercepts.

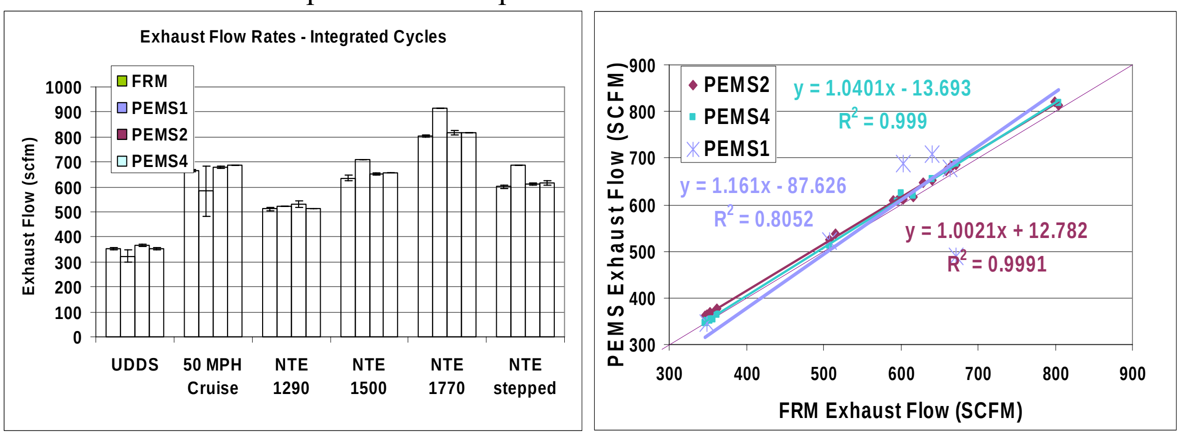


Figure 4-2 (a) Comparative FRM and PEMS Integrated Exhaust Flow Rates for and (b) Correlation Plot

4.4 Integrated Mass Emission Rates

Detailed mass emission rate results are provided in Appendix F, along with the average concentration measurements for the tests for each instrument. The statistical analysis results for the integrated comparisons are provided in Appendix G.

The integrated results for NO_x and CO_2, from the FRM and PEMS are presented in Figures 4-3 and 4-4. Error bars shown represent the 95% confidence limits based on results from multiple runs. For the NTE steady state and NTE stepped cycles, the integrated values represent the emissions collected over the entire duration of the cycle, including all speed and load points within the cycles (see earlier Figures 2-2 and 2-3). Except for PEMS1, the NO_x readings for the PEMS were higher than those obtained by the FRM. PEMS2 readings ranged from 5 to 12% higher than the FRM over the different cycles. For PEMS3, NO_x emissions ranged from 14 to 21% higher than the FRM. PEMS4 showed differences in NO_x emissions generally ranging from 19 to 40% higher than the FRM. It should be noted that some of these differences might be related to the calibration differences seen in the primary audit bottle concentrations and associated software problems. The manufacturer of PEMS4 indicated software issues in their prototype unit contributed to the observed differences. For PEMS1, NO_x values ranged from 13% lower to 25% higher than the FRM. A statistical analysis indicates that the differences between the FRM and PEMS for NO_x are statistically significant at a 95% confidence level for most cycles for the most PEMS. Exceptions include the results for the NTE 1290 which are not statistically different, the results for the NTE 1770 cycle that are statistically significant at only a 90% confidence level, and the results for PEMS1 on the UDDS and 50 mph cruise cycles.

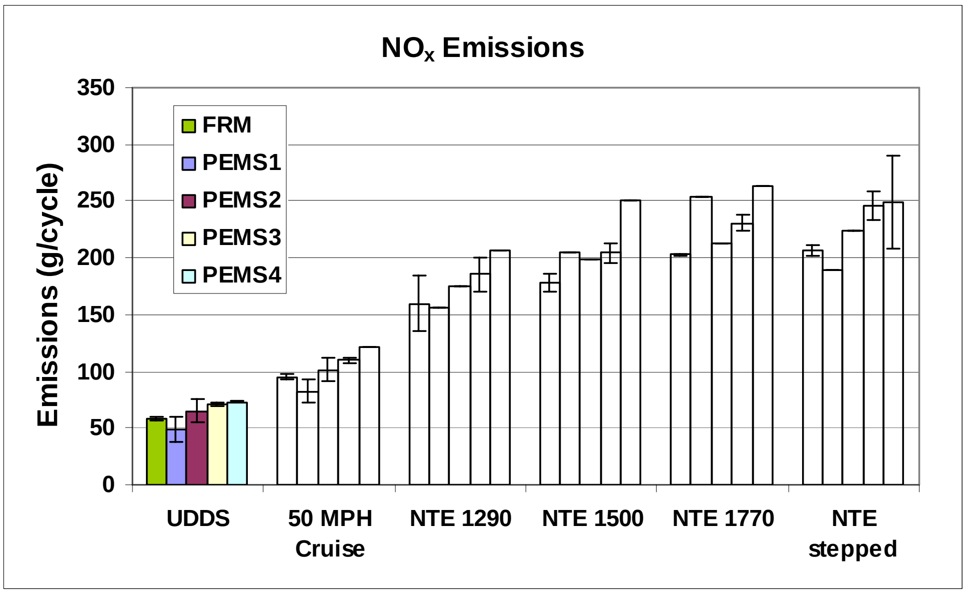


Figure 4-3. Mass Emissions (NO_x g/cycle) for PEMS Relative to FRM

CO_2 emissions also showed a trend with the PEMS having generally higher emissions than the FRM. The PEMS2 CO_2 emissions were within 5% of those measured by the FRM for most of the test runs, with no statistically significant differences for NTE 1290, 1500 and 1770 steady state cycles. These differences are comparable to those found between the exhaust flow rates for the FRM and PEMS2, as discussed below. The differences in CO_2 for PEMS3 were slightly higher ranging from 9 to 14% over the difference cycles. The CO_2 emissions for PEMS4 were between 11 and 26% higher than the FRM. For comparison, the calibration for PEMS4 was approximately 17% high on the audit bottle. The CO_2 emissions measurements for PEMS1 were below those of the FRM for all test cycles, with a range from 4 to 35% lower.

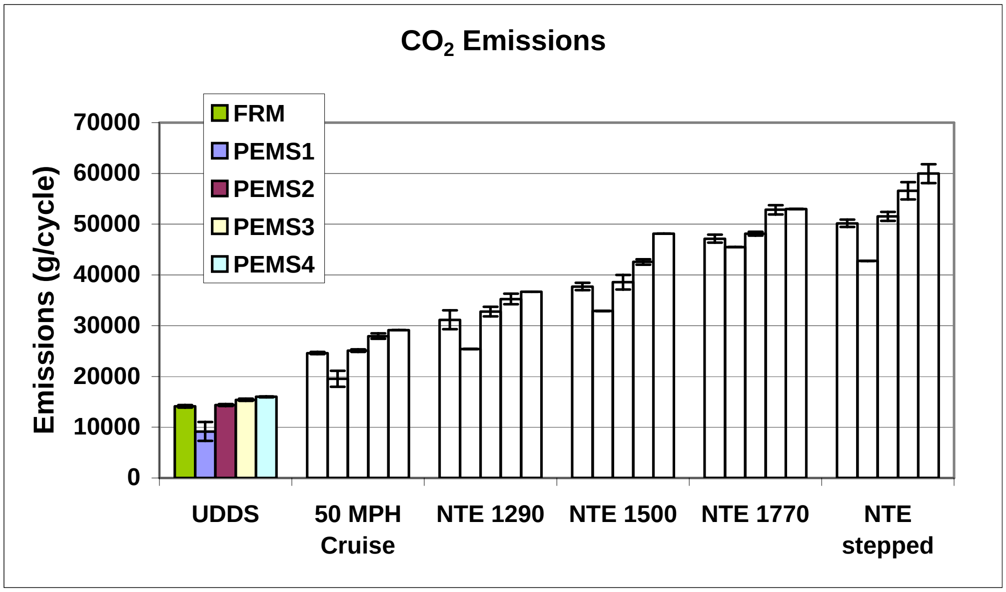


Figure 4-4 Mass Emissions (CO_2 g/cycle) for PEMS Relative to FRM.

The percentage differences for the integrated cycles are provided in Table 4-1 for all emissions.

	THC (g/cycle)			CO (g/cycle)			NO_x (g/cycle)				CO_2 (g/cycle)			
	PEMS 1	PEMS 2	PEMS 4	PEMS 1	PEMS 2	PEMS 3	PEMS 1	PEMS 2	PEMS 3	PEMS 4	PEMS 1	PEMS 2	PEMS 3	PEMS 4
UDDS	-103	57	76	-42	20	-29	-13	12	21	25	-35	1.7	9	13
50 mph cruise	-78	-3	-6	-16	21	-25	-9	7	16	38	-19	2.1	14	22
NTE 1290	-88	-36	-4	-10	51	-38	5	9	16	40	-16	5.3	13	21
NTE 1550	-46	-33	-29	-16	36	-29	13	11	15	37	-14	2.2	13	26
NTE 1770	-83	2	-61	-8	38	-25	25	5	14	30	-4	2.1	12	11
NTE Stepped	-4	-18	1	-25	43	-64	-8	8	18	19	-14	2.7	13	19

Table 4-1. Percentage Differences for Integrated Cycle Results (in percent)

To better understand the differences in the independent factors of concentration and exhaust flow, the mass emission rate of NO_x was divided by that of the CO_2 to provide a metric that is nearly independent of flow rate. The results are provided in Figure 4-5. The NO_x emissions normalized to CO_2 for PEMS2 show slightly closer agreement with the FRM, now ranging from 3 to 10%. For PEMS3, the agreement with the FRM improved considerably and was within 5% for most cycles, except the UDDS which was 10%. This indicates that differences in flow measurements could be a primary source of the differences between the FRM and PEMS3. The agreement between PEMS4 and the FRM also improved and now ranged from 0 to 17%. While part of the narrowing in deviation could be attributed to flow, the exhaust flow measurements for PEMS4 are similar to those of the FRM. It is more likely the fairly large differences found for PEMS4 for NO_x and CO_2 were simply normalized using this approach. For PEMS1, the NO_x/CO_2 values were all higher than those of the FRM, probably due in part to the lower CO_2 emissions reported by PEMS1.

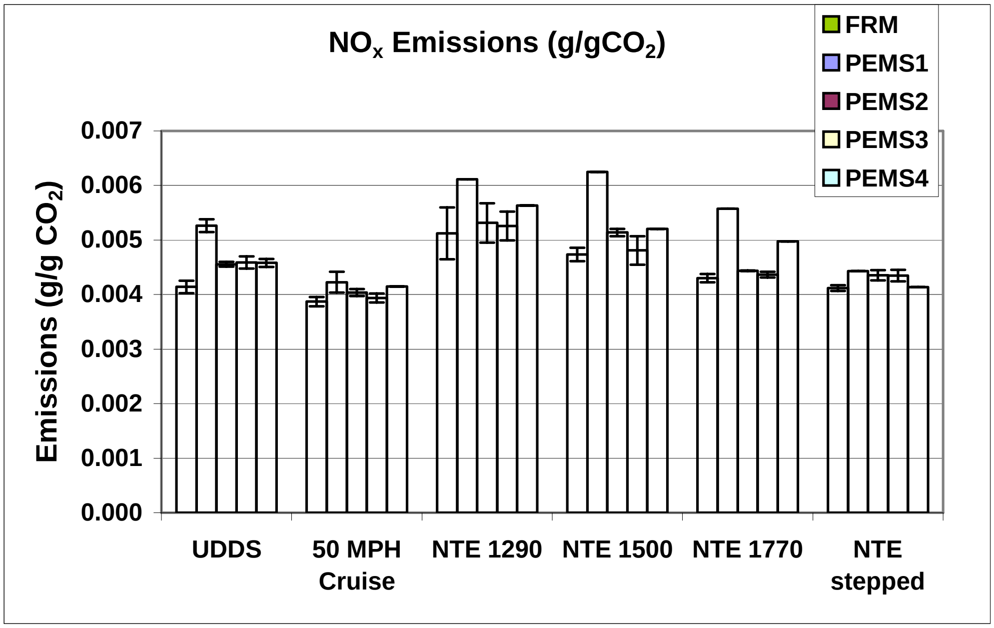


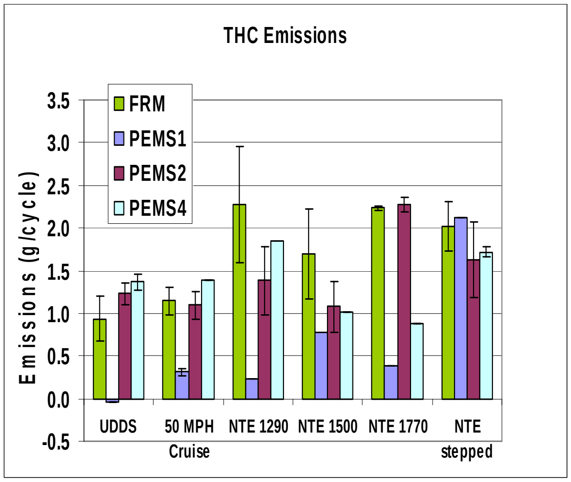
Figure 4-5 NO_x/CO_2 Emission Rates for the FRM and PEMS.

The integrated THC and CO measurements for the FRM and PEMS are shown in Figure 4-6a and 4-6b, respectively. PEMS3 did not measure THC and CO emissions were not available for PEMS4 due to software issues. As such, they are not included in those respective figures.

The measurement of THC emissions showed greater variability than measurements of other emissions components. Under the test conditions and with the equipment used for this program, the percentage differences between the FRM and PEMS were generally not statistically significant. Interestingly, the approximately 20% higher bias in the THC calibration gas for PEMS4 is not seen in the mass emission results which are lower than the FRM values for all but the UDDS and 50 mph cruise cycles. THC levels for PEMS1 were well below those of the FRM. The THC levels measured in this study were relatively low overall (~10 ppmv) and were below the NTE standard thresholds. Hence, the percentage differences relative to the NTE standards were generally less than 5%, as discussed below.

The CO emissions for PEMS2 and PEMS3 show opposite trends in comparison with the FRM. CO emissions for PEMS1 were generally lower than those for the FRM, ranging from 8 to 42% lower. PEMS2 CO emissions were higher compared with the FRM for all test cycles. CO emissions for PEMS2 ranged from 20 to 50% higher than the FRM. Some of the difference can be attributed to the ~13% higher readings on audit gas. The measured CO emissions for PEMS3 were all lower than those for the FRM with the differences ranging from 25 to 64%. Some of this difference could be attributed to the approximately 11% low audit bottle reading that was found for PEMS3 on CO. To keep the CO measurements in perspective, the levels measured in this research were

~100ppmv and well below the NTE standard. Hence, the percentage difference relative to the NTE standards were generally less than 2% as discussed below.



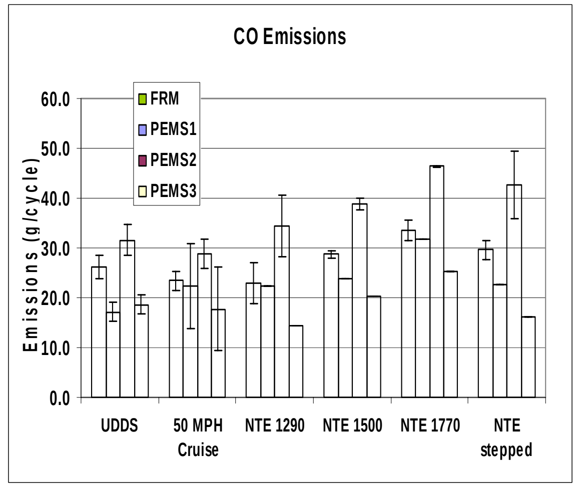


Figure 4-6 FRM and PEMS Mass Emissions Rates for Various Cycles (a) THC and (b) CO.

Correlation plots for CO_2, NO_x, PM, and THC between the PEMS and FRM were also developed for the integrated data. These plots are shown in Figures 4-7 (a) to (d).

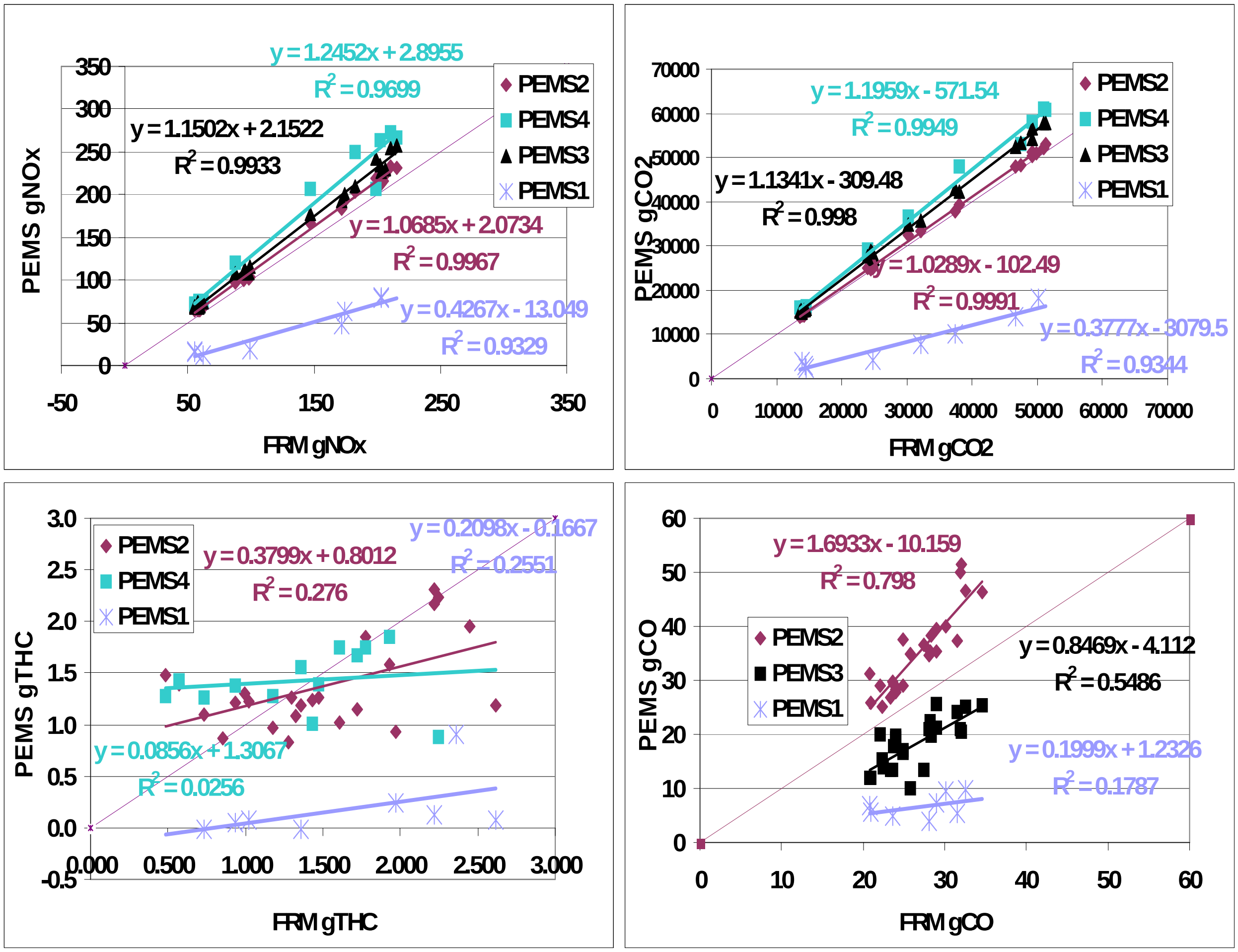


Figure 4-7 Correlation Plots of FRM and PEMS for the (a) NO_x (b)CO_2 (c)THC and (d) CO

4.5 Data Analysis Protocol within the NTE Zone

The characterization of emission measurements during NTE events was a critical component of the chassis dynamometer testing and analysis. For this task, two cycles were specifically designed to simulate operation in the NTE zone and transitions into and out of the NTE zone. These two were the NTE steady state cycles and the NTE stepped cycle. NTE events were also identified in the inventory cycles, namely the UDDS and the 50 mph cruise.

This section simply reports on comparisons between the PEMS2 and PEMS4 and the FRM for events in the NTE zone. The NTE analysis primarily focused on NTE events that were determined based on information obtained from the engine control module data and the J1939 signal. For PEMS4, the engine data connection did not work, so the NTE events for PEMS4 were determined based on the data collected by UCR. The FRM sampled the J1939 signal at 10 Hz and recorded every 10th point for a discrete 1 Hz signal (with no averaging) for NTE determination. PEMS2 sampled at the maximum J1939 broadcast data rate (up to 10 Hz depending on the parameter), averaged the data over 1/4 second intervals, and recorded data at that rate. The data were then interpolated between the 4 Hz averages to the precise 1 second reporting intervals. Since PEMS4 used the FRM data, subsequent comparisons of identified NTE events (e.g., Table 4-2 below) and bhp-hr (e.g., Figure 4-8) only include the FRM and PEMS2.

4.6 Measurements of Brake-Horsepower Hour

Emission certification standards are reported in emissions per unit or work, thus measurement of work is an important issue for compliance testing. The work recorded within the NTE zone was based on measurements obtained from the J1939 signal and integrated over the individual NTE events to determine the brake horsepower hour for each NTE event. Figure 4-8 shows the correlation between the bhp calculated by the FRM and PEMS2. The correlation plot represents a filtered set of data in which only NTE events that "matched" between the FRM and PEMS2 are included and for the entire set of NTE data. In this case, matching NTE events are ones where the identified NTE events has a similar start time between the FRM and PEMS2 and a duration that is the same within 4 seconds. Overall, bhp showed good correlation on an NTE event basis, with the outlier data primarily due to different identification of a specific NTE event. Differences in the identification of specific NTE events are discussed further below.

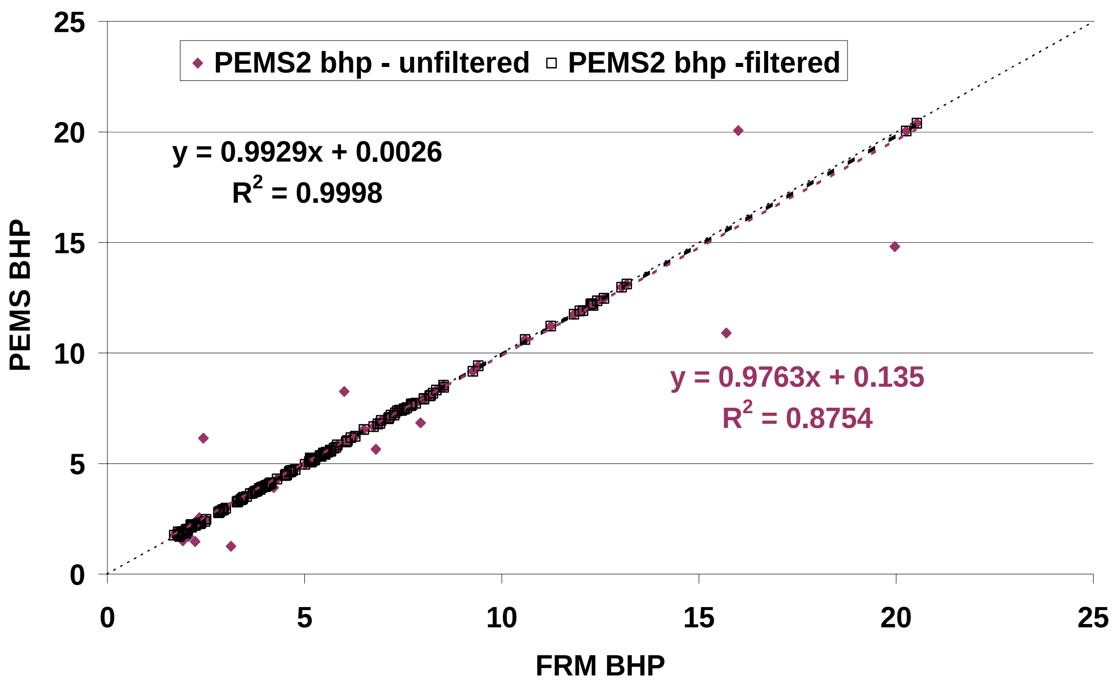


Figure 4-8 Correlation Plot for bhp for Individual NTE Events

4.7 Identifying the NTE Events in the Steady State Cycle

The NTE steady state cycles were designed to have steady state operation with transitions into and out of the NTE zone by changing load. Each test segment included seven replicates with identifiable NTE events. To help in the identification of the NTE event we created an ID number that included the engine speed, followed by the iteration, followed by the number of the NTE event as it was identified within the cycle. For example, the first event was identified as NTE_1290_1_1. The load is also presented in a separate column.

In general, the number and duration of NTE events was relatively consistent for the FRM and PEMS. There were typically 21 NTE events within a cycle at a particular engine speed, corresponding to 7 iterations at 3 engine load points. The 1290 engine speed/40% load was generally outside the NTE zone because the torque was below the threshold value for the NTE onset after subtracting the frictional torque.

A breakdown of the NTE events is shown in Figure 4-9 and a comparison of rpm and torque signals for the FRM and PEMS2 is provided in Figures 4-10. For PEMS4, emissions data were collected for only one of the two cycles run at the different speeds and the final NTE event was not identified in the PEMS4 analysis. The FRM also only collected two data points for NO_x for the first run at 1550 at the highest load point due to an electronic problem with the trigger to the PEMS instruments.

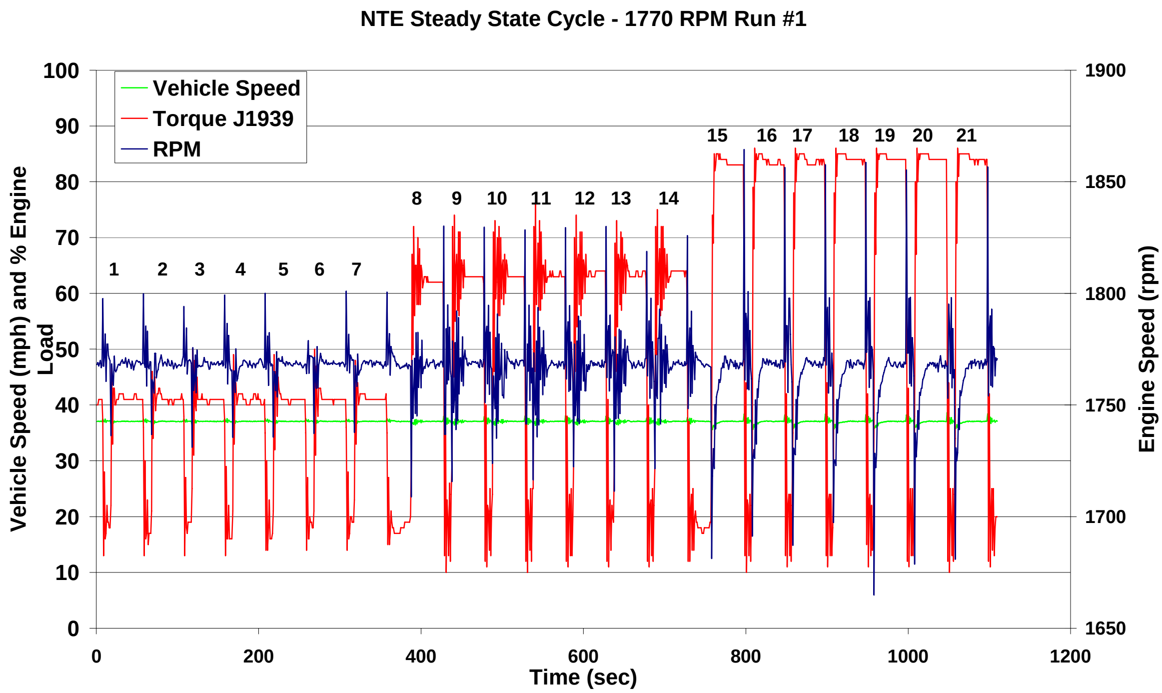


Figure 4-9. Summary of NTE Events identified during the NTE Steady State Cycle.

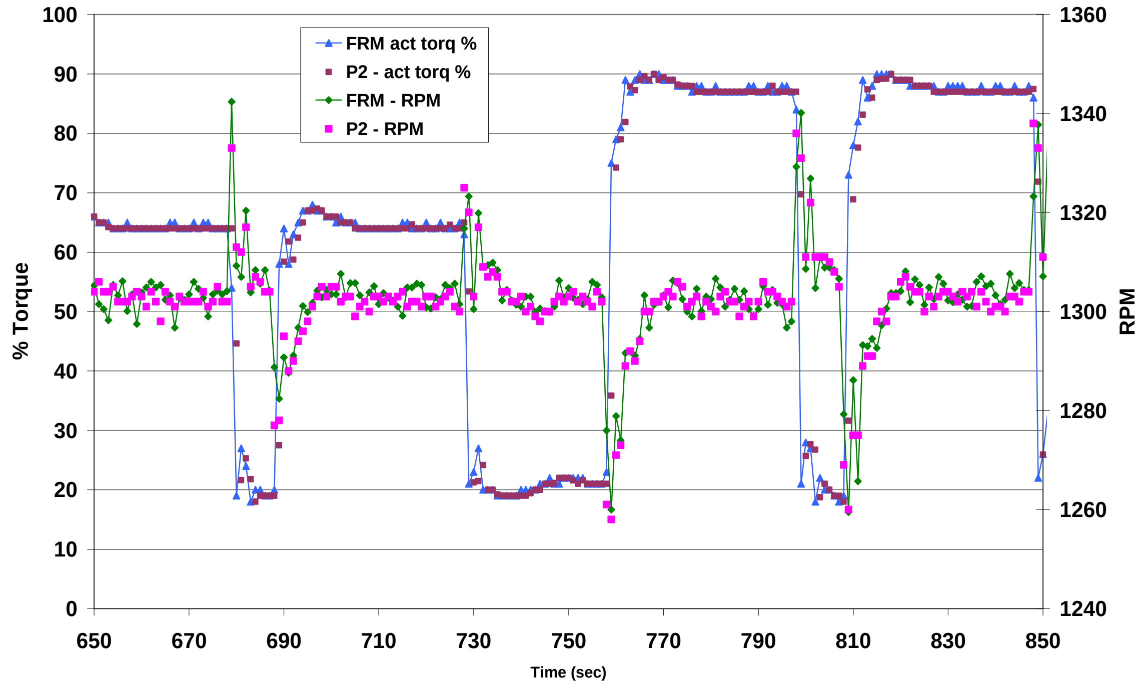


Figure 4-10. Comparison of Torque and RPM Signals for Typical NTE Event

A comparison of each identified NTE event is provided in Table 4-2, including the start time and the duration determined by the FRM and the PEMS.

Table 4-2. Identified NTE Events for the FRM and PEMS over the NTE Steady State Cycle

Unique ID for NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
NTE_1290_1_1	389	389	0	40	40	0
NTE_1290_1_2	439	439	0	40	40	0
NTE_1290_1_3	489	489	0	40	40	0
NTE_1290_1_4	539	539	0	40	40	0
NTE_1290_1_5	589	589	0	40	40	0
NTE_1290_1_6	639	639	0	41	41	0
NTE_1290_1_7	689	689	0	40	40	0
NTE_1290_1_8	759	759	0	40	40	0
NTE_1290_1_9	809	809	0	40	40	0
NTE_1290_1_10	859	859	0	40	40	0
NTE_1290_1_11	909	909	0	40	40	0
NTE_1290_1_12	959	959	0	40	40	0
NTE_1290_1_13	1009	1009	0	40	40	0
NTE_1290_1_14	1059	1059	0	40	40	0
NTE_1290_2_1	391	391	0	40	40	0
NTE_1290_2_2	441	441	0	40	40	0
NTE_1290_2_3	491	491	0	40	40	0
NTE_1290_2_4	541	541	0	40	40	0
NTE_1290_2_5	591	591	0	40	40	0

Unique ID for NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
NTE_1290_2_6	641	641	0	40	40	0
NTE_1290_2_7	691	691	0	40	40	0
NTE_1290_2_8	761	761	0	40	40	0
NTE_1290_2_9	811	811	0	40	40	0
NTE_1290_2_10	861	861	0	40	40	0
NTE_1290_2_11	911	911	0	40	40	0
NTE_1290_2_12	961	961	0	40	40	0
NTE_1290_2_13	1011	1011	0	40	40	0
NTE_1290_2_14	1061	1061	0	40	41	1
NTE_1500_1_1	19	19	0	40	40	0
NTE_1500_1_2	69	69	0	40	40	0
NTE_1500_1_3	119	119	0	40	40	0
NTE_1500_1_4	169	169	0	40	39	-1
NTE_1500_1_5	219	219	0	40	40	0
NTE_1500_1_6	272	270	-2	37	39	2
NTE_1500_1_7	319	319	0	40	39	-1
NTE_1500_1_8	389	389	0	40	40	0
NTE_1500_1_9	439	439	0	40	40	0
NTE_1500_1_10	489	489	0	40	40	0
NTE_1500_1_11	539	539	0	40	40	0
NTE_1500_1_12	589	589	0	40	40	0
NTE_1500_1_13	639	639	0	40	40	0
NTE_1500_1_14	689	689	0	40	40	0
NTE_1500_1_15	759	759	0	40	40	0
NTE_1500_1_16	809	809	0	40	40	0
NTE_1500_1_17	859	859	0	40	40	0
NTE_1500_1_18	909	909	0	40	40	0
NTE_1500_1_19	959	959	0	40	40	0
NTE_1500_1_20	1009	1009	0	40	40	0
NTE_1500_1_21	1059	1059	0	40	40	0
NTE_1500_2_1	20	21	1	39	38	-1
NTE_1500_2_2	69	70	1	40	40	0
NTE_1500_2_3	120	120	0	39	40	1
NTE_1500_2_4	170	170	0	39	39	0
NTE_1500_2_5	222	220	-2	37	40	3
NTE_1500_2_6	269	270	1	40	39	-1
NTE_1500_2_7	319	320	1	40	40	0
NTE_1500_2_8	389	390	1	40	40	0
NTE_1500_2_9	439	440	1	40	40	0
NTE_1500_2_10	489	490	1	40	40	0
NTE_1500_2_11	539	540	1	40	40	0
NTE_1500_2_12	589	590	1	40	40	0
NTE_1500_2_13	639	639	0	40	41	1
NTE_1500_2_14	689	690	1	40	40	0
NTE_1500_2_15	759	759	0	40	41	1
NTE_1500_2_16	809	809	0	40	41	1
NTE_1500_2_17	859	860	1	40	40	0
NTE_1500_2_18	909	909	0	40	41	1
NTE_1500_2_19	959	960	1	40	40	0

Unique ID for NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
NTE_1500_2_20	1009	1009	0	40	41	1
NTE_1500_2_21	1059	1059	0	41	41	0
NTE_1770_1_1	21	19	-2	38	40	2
NTE_1770_1_2	69	69	0	40	40	0
NTE_1770_1_3	121	119	-2	38	40	2
NTE_1770_1_4	171	169	-2	38	40	2
NTE_1770_1_5	221	219	-2	38	40	2
NTE_1770_1_6	271	269	-2	38	40	2
NTE_1770_1_7	321	319	-2	38	40	2
NTE_1770_1_8	389	389	0	40	40	0
NTE_1770_1_9	439	439	0	40	40	0
NTE_1770_1_10	489	489	0	40	40	0
NTE_1770_1_11	539	539	0	40	40	0
NTE_1770_1_12	589	589	0	40	40	0
NTE_1770_1_13	639	639	0	40	40	0
NTE_1770_1_14	689	689	0	40	40	0
NTE_1770_1_15	758	759	1	41	40	-1
NTE_1770_1_16	809	809	0	40	40	0
NTE_1770_1_17	858	859	1	41	40	-1
NTE_1770_1_18	909	909	0	40	40	0
NTE_1770_1_19	958	959	1	41	40	-1
NTE_1770_1_20	1008	1009	1	41	40	-1
NTE_1770_1_21	1058	1059	1	41	40	-1
NTE_1770_2_1	19	20	1	40	39	-1
NTE_1770_2_2	69	70	1	40	39	-1
NTE_1770_2_3	119	120	1	40	39	-1
NTE_1770_2_4	169	170	1	40	39	-1
NTE_1770_2_5	219	220	1	40	39	-1
NTE_1770_2_6	269	270	1	40	39	-1
NTE_1770_2_7	319	320	1	40	39	-1
NTE_1770_2_8	389	389	0	40	41	1
NTE_1770_2_9	439	439	0	40	41	1
NTE_1770_2_10	489	489	0	40	40	0
NTE_1770_2_11	539	539	0	40	41	1
NTE_1770_2_12	589	589	0	40	41	1
NTE_1770_2_13	639	639	0	40	41	1
NTE_1770_2_14	689	689	0	40	41	1
NTE_1770_2_15	759	759	0	40	41	1
NTE_1770_2_16	809	809	0	40	41	1
NTE_1770_2_17	859	859	0	40	41	1
NTE_1770_2_18	909	909	0	40	41	1
NTE_1770_2_19	959	959	0	40	41	1
NTE_1770_2_20	1009	1009	0	40	41	1
NTE_1770_2_21	1059	1059	0	40	41	1

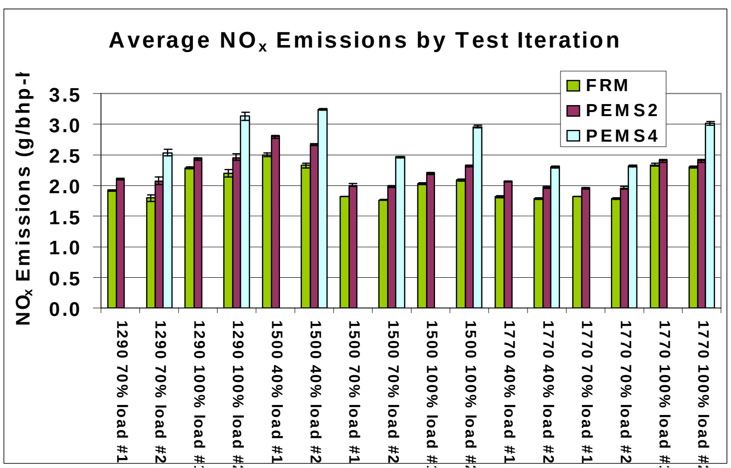
4.8 Analysis of the Data for the Steady-state NTE Cycle

Before discussing into the full analysis, the approach used needs to be explained.

1. Results are expressed as g/bhp-hr like certification standards and on a fuel specific (fs) basis. The fs calculations were based on fuel use determined from CO_2 emissions measurements so in part will normalize flow differences between the different instruments.
2. Results are expressed relative to the approximate NTE thresholds for 2007 model year engines since a determination of the error margin for PEMS units relative to the NTE standard is an important consideration.

The full results for the individual tests are provided in Appendix H on a g/bhp-hr and fuel specific (fs) basis. Statistical comparisons of the NTE steady state results are provided in Appendix I. The statistical analyses included a paired and unpaired t-test and an F-test for comparison of experimental variance. The statistical comparisons for the steady state cycle showed that in most cases the differences between the mass emission rates for the different instruments were statistically significant at greater than a 95% confidence level. The statistical significance of the F-test results depended on the specific test iteration and the specific emission component.

The average NTE results in g/bhp-hr and in fuel specific units for NO_x over the steady state cycles are provided in Figure 4-11a and 4-11b.



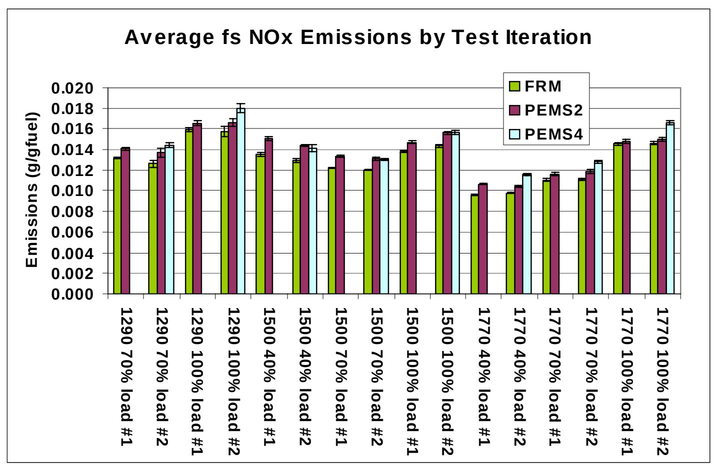


Figure 4-11 Comparison of NOx Emission Rates and 95% Confidence Limits. (a) g/bhp-hr, (b) fsNOx

A correlation plot for the g/bhp-hr is provided in Figure 4-12.

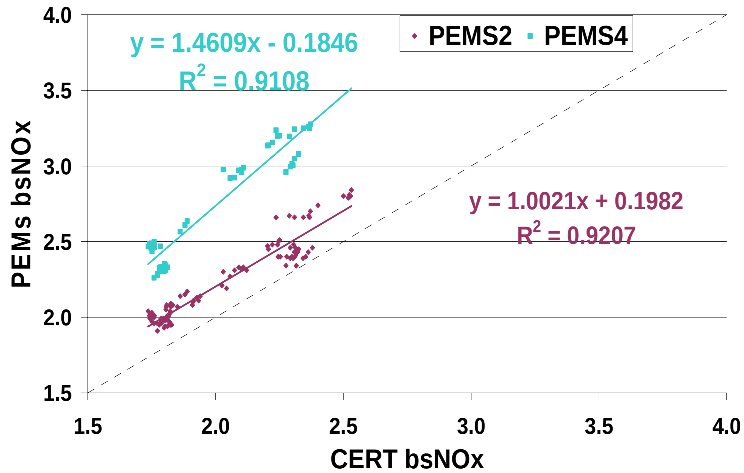


Figure 4-12. Correlation Plot for g/bhp-hr NO_x emissions over all NTE Steady State Cycle Events

As evident in Figure 4-12, the correlation plots show reasonable correlation between the FRM and PEMS (R^2 = 0.91 and 0.92), with each PEMS showing a bias from the FRM. Clearly, PEMS 2 is much closer to the values measured by the FRMs.

Separate plots of the percentage difference for the PEMS in comparison with the FRM are provided in Figure 4-13a and 4-13b, respectively, for g/bhp-hr relative to the NTE thresholds and fs units. The absolute values of the differences are provided in Table 4-3.

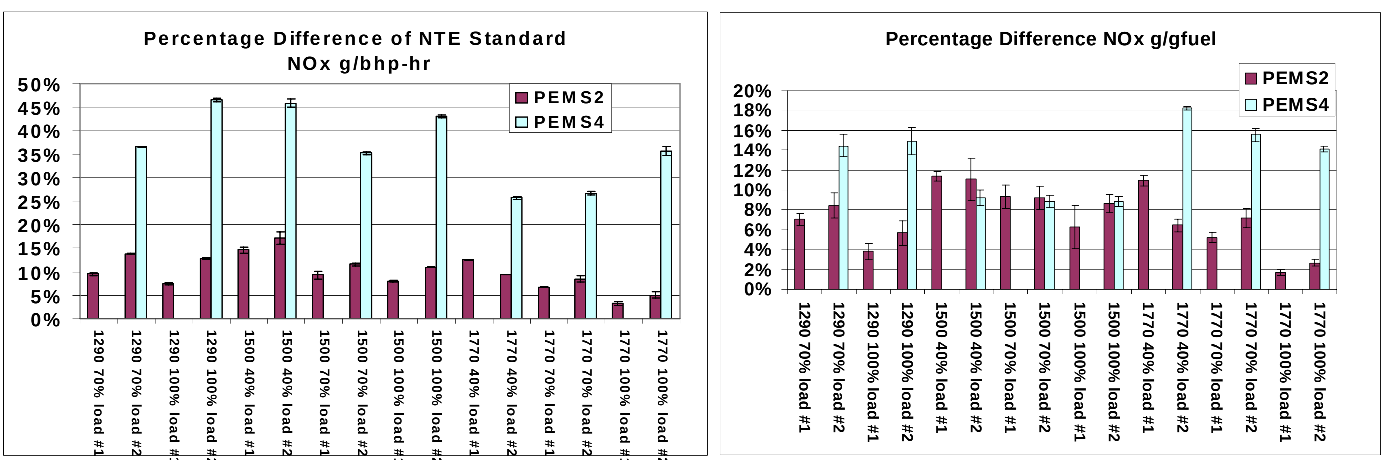
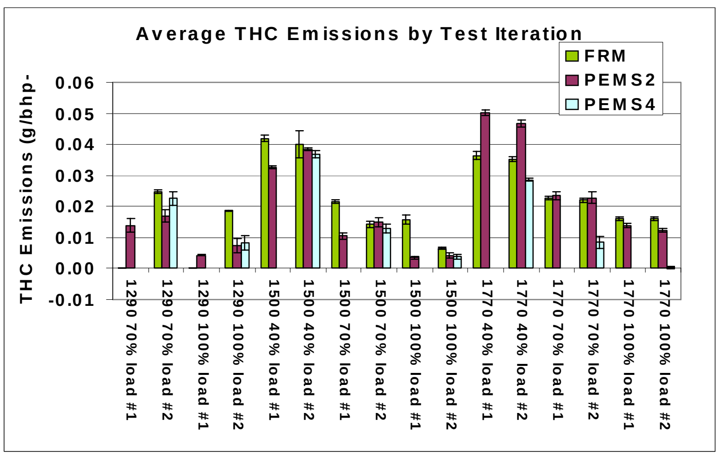


Figure 4-13. Comparison of Percentage Differences in NO_x Emission Rates for Different PEMS. a) g/bhp-hr, b) $fsNO_x$

The percentage differences for the NTE events were calculated relative to the NTE thresholds, since these are the differences most relevant for regulatory implementation. For NO_x, this was done by taking the absolute difference in the mass emission rates for the FRM and a particular PEMS, dividing by the NTE threshold (2.0 g/bhp-hr for NO_x), and presenting the value as a percent. The NO_x emission rates for PEMS2 was approximately 3 to 17% higher than those for the FRM in g/bhp-hr units relative to the NO_x NTE threshold. PEMS 4 showed larger differences compared to the FRM, with percent differences ranging from 26 to 47%. These larger differences could be due in part to the calibration offset and associated software issues for PEMS4, as noted above. On a fs basis, PEMS2 showed slightly lower differences with the FRM ranging from 2-11%. The comparison of fs NO_x emissions improved for PEMS4, with differences ranging from 9-18%. This is probably due to the fact that both the NO_x and CO_2 calibrations for PEMS4 were relatively high, which would be offset when the emissions are ratioed.

The average THC NTE results in g/bhp-hr and the percentage difference relative to the NTE threshold for the PEMS in comparison with the FRM are provided in Figure 4-14a and 4-14b, respectively. THC was generally lower for both PEMS2 and PEMS4 compared with the FRM. THC emissions were below the NTE threshold standards for these measurements. Relative to the approximate NTE threshold for THC of 0.21 g/bhp-hr, the percentage differences were all within 10%, with most being within 5%.



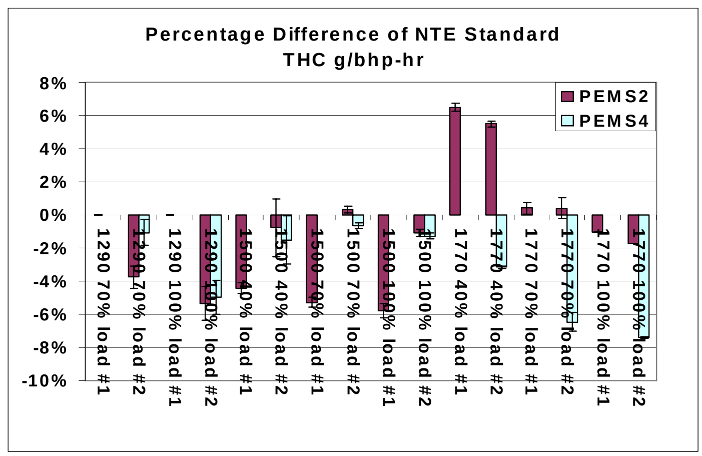


Figure 4-14. (a) Comparison of Mass Emission Rates for THC in g/bhp-hr (b) Percentage Difference of NTE Standard between PEMS and FRM for THC in g/bhp-hr

The correlation plot for THC g/bhp-hr emissions is provided in Figure 4-15. The correlation coefficient for THC emissions was not as good as for NO_x emissions as R^2 = 0.78 and 0.74, respectively, for PEMS2 and PEMS4.

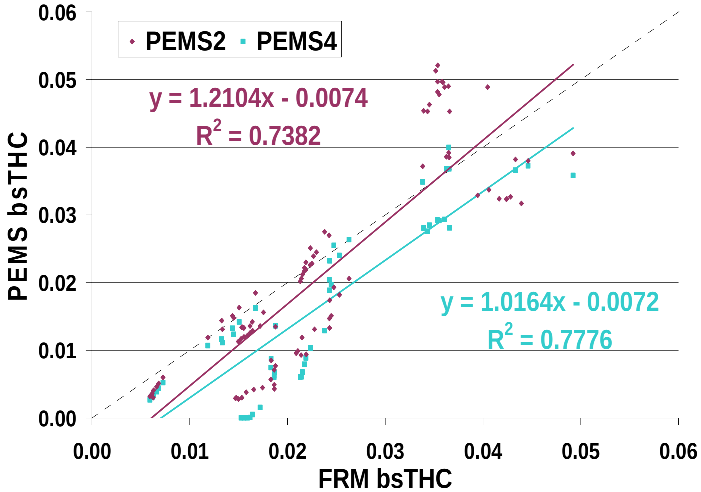


Figure 4-15. Correlation Plot for g/bhp-hr THC Emissions over all NTE Steady State Cycle Events

The average CO NTE results in g/bhp-hr and the percentage difference for the PEMS in comparison with the FRM are provided in Figure 4-16a and 4-16b, respectively. CO emissions for PEMS2 were consistently higher than those for the FRM. However, the CO emissions were well below the NTE threshold of 19.4 g/bhp-hr, and the percentage differences between the FRM and PEMS2 were all within 2% relative to the NTE CO threshold.

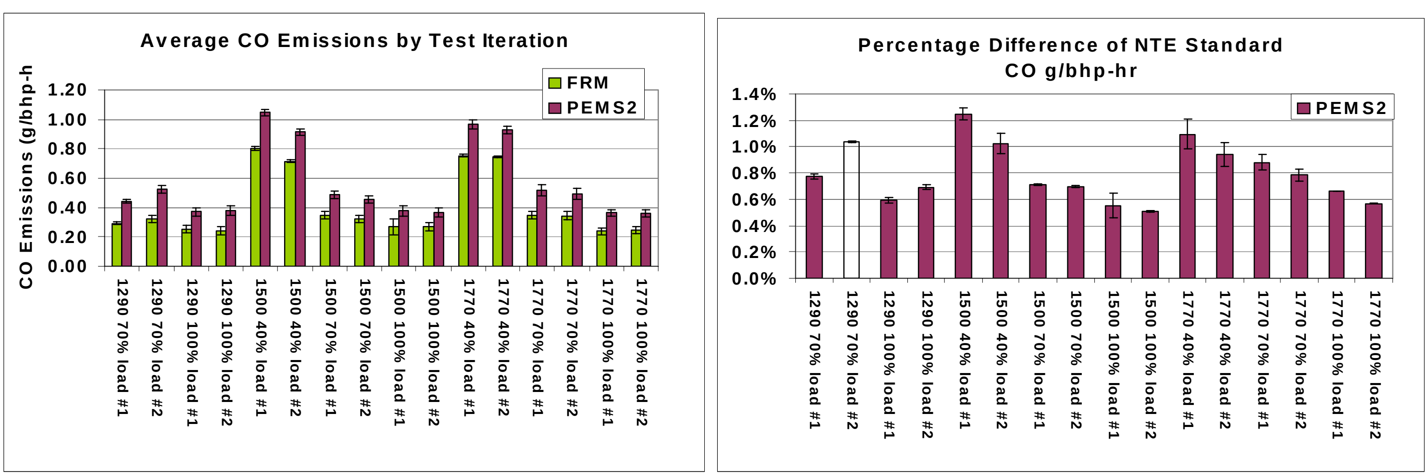


Figure 4-16. (a) Comparison of Mass Emission Rates for CO in g/bhp-hr (b) Percentage Difference of NTE Standard between PEMS and FRM for CO in g/bhp-hr

The correlation plot over the whole range of measured values is depicted in Figure 4-17 and shows an R^2=0.99, with a definitive bias; PEMS 2 is always higher than the FRM values.

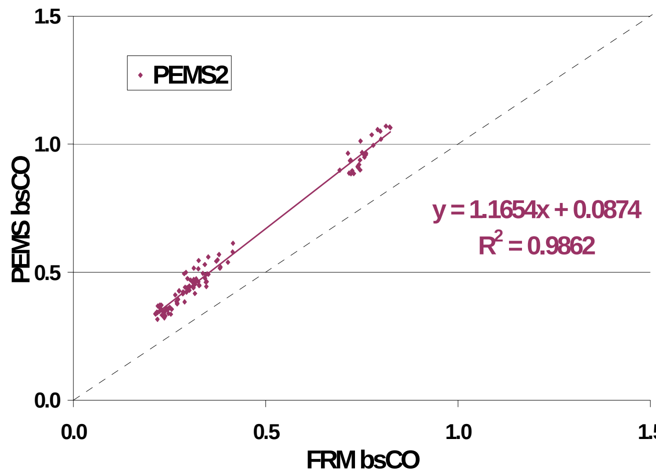


Figure 4-17 Correlation Plot for CO g/bhp-hr Emissions over all NTE Steady State Cycle Events

The average CO_2 NTE results in g/bhp-hr and the percentage difference for the PEMS in comparison with the FRM are provided in Figure 4-18a and 4-18b, respectively. Results depended on the PEMS unit. Results from PEMS2 were generally 5% higher than the FRM while results from PEMS4 varied from 10 to 30% higher.

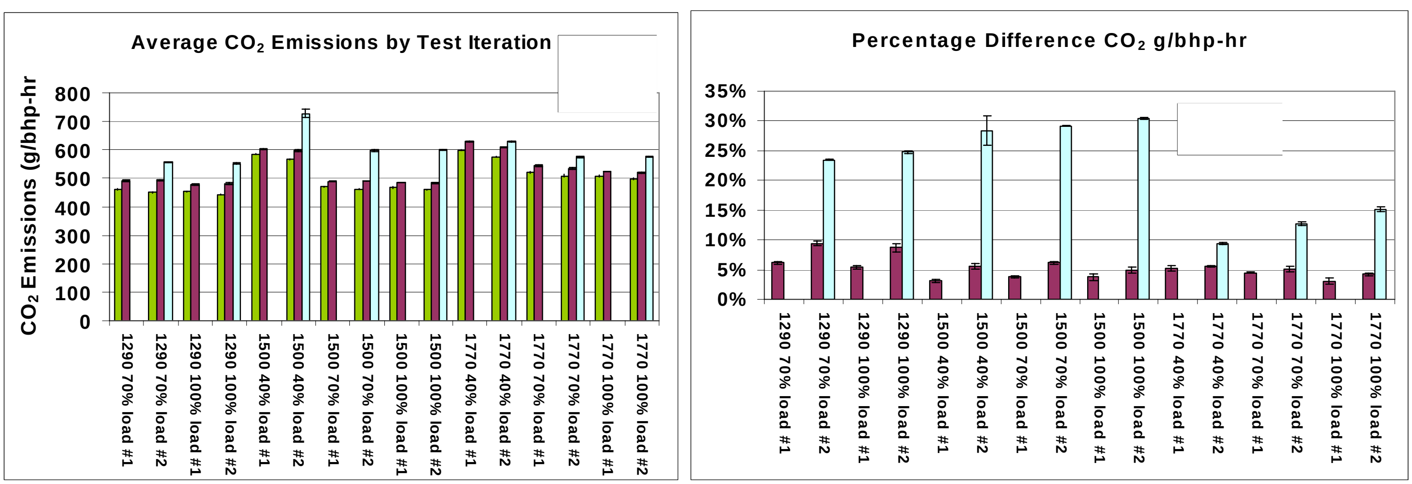


Figure 4-18. (a) Comparison of Mass Emission Rates for CO_2 in g/bhp-hr (b) Percentage Difference between PEMS and FRM for CO_2 in g/bhp-hr

The correlation plot for CO_2 is shown in Figure 4-19. PEMS2 showed good correlation with the FRM (R^2 = 0.99), but a slight bias. PEMS4 CO_2 emissions were 9 to 30% higher than those the FRM, with a relatively poor correlation coefficient (R^2 = 0.57). The magnitude of the bias for PEMS4 is in the range of the calibration offset for PEMS4, although the poor correlation indicates that other factors also contribute to this difference.

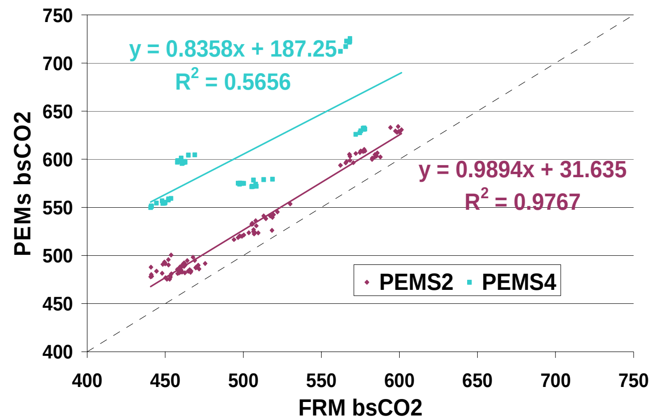


Figure 4-19. Correlation Plot for CO_2 g/bhp-hr Emissions over all NTE Steady State Cycle Events

Table 4-3 below provides the total stream used in the charts and analysis that were just reviewed and included for completeness.

	NO_x					CO_2					THC					CO		
	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	FRM	P2	P2 vs. FRM
				absol. Diff					absol. Diff					absol. Diff				absol. Diff
	g/bhp-hr					g/bhp-hr					g/bhp-hr					g/bhp-hr		
1290 70% load #1	1.92	2.11	NA	0.19	NA	462	490	NA	28.39	NA	NA	0.014	NA	NA	NA	0.29	0.44	0.15
1290 70% load #2	1.80	2.08	2.53	0.28	0.73	451	493	556	42.63	105.52	0.025	0.017	0.02	-0.01	0.00	0.32	0.52	0.20
1290 100% load #1	2.29	2.43	NA	0.15	NA	454	478	NA	24.51	NA	NA	0.004	NA	NA	NA	0.26	0.37	0.11
1290 100% load #2	2.20	2.46	3.13	0.26	0.93	442	481	552	38.61	109.98	0.019	0.007	0.01	-0.01	-0.01	0.24	0.38	0.13
1500 40% load #1	2.50	2.80	NA	0.29	NA	585	603	NA	18.26	NA	0.042	0.033	NA	-0.01	NA	0.8	1.05	0.24
1500 40% load #2	2.33	2.67	3.24	0.34	0.92	567	599	728	31.65	160.92	0.04	0.038	0.04	0.00	0.00	0.72	0.91	0.20
1500 70% load #1	1.82	2.00	NA	0.19	NA	471	489	NA	17.70	NA	0.021	0.01	NA	-0.01	NA	0.35	0.48	0.14
1500 70% load #2	1.76	1.99	2.46	0.23	0.70	463	491	598	28.42	134.92	0.014	0.015	0.01	0.00	0.00	0.32	0.46	0.14
1500 100% load #1	2.03	2.19	NA	0.16	NA	467	484	NA	17.64	NA	0.016	0.003	NA	-0.01	NA	0.27	0.38	0.11
1500 100% load #2	2.09	2.31	2.96	0.22	0.86	460	483	600	22.81	139.32	0.006	0.004	0	0.00	0.00	0.27	0.37	0.10
1770 40% load #1	1.82	2.07	NA	0.25	NA	599	630	NA	31.67	NA	0.036	0.05	NA	0.01	NA	0.75	0.97	0.21
1770 40% load #2	1.79	1.98	2.30	0.19	0.51	576	608	630	32.35	54.10	0.035	0.047	0.03	0.01	-0.01	0.75	0.93	0.18
1770 70% load #1	1.82	1.95	NA	0.13	NA	520	543	NA	23.40	NA	0.023	0.023	NA	0.00	NA	0.35	0.52	0.17
1770 70% load #2	1.79	1.96	2.32	0.17	0.53	509	535	574	25.87	64.84	0.022	0.023	0.01	0.00	-0.01	0.34	0.5	0.15
1770 100% load #1	2.34	2.40	NA	0.06	NA	508	524	NA	15.73	NA	0.016	0.014	NA	0.00	NA	0.24	0.37	0.13
1770 100% load #2	2.30	2.40	3.02	0.10	0.71	499	520	575	21.32	76.53	0.016	0.012	0	0.00	-0.02	0.25	0.36	0.11

Table 4-3. Absolute Differences in g/bhp-hr Emissions for the Steady State Cycle NTE Events

4.9 Analysis of the Data for the NTE Stepped Cycle

This cycle consisted of a series of speeds/loads that were stepwise increased and then decreased. The number of NTE events identified for this varied from 12 to 15, depending on the test iteration and the measurement device. Figure 4-20 shows graphically when the NTE events occurred within the cycle. Twelve primary events were built into the experimental design and are the focus of the subsequent analysis. These are labeled 1-12 in Figure 4-20. Some "miscellaneous" NTE events were also identified intermittently for a subset of tests by one or more of the instruments. These additional miscellaneous NTE events are labeled "m1-m3" in the Figure. A summary of the NTE events for all tests is provided in Table 4-4. It must be noted that the data for PEMS4 was only available for the final three stepped cycles. PEMS4 also did not identify any NTE events that occurred after 1,000 seconds into the cycle.

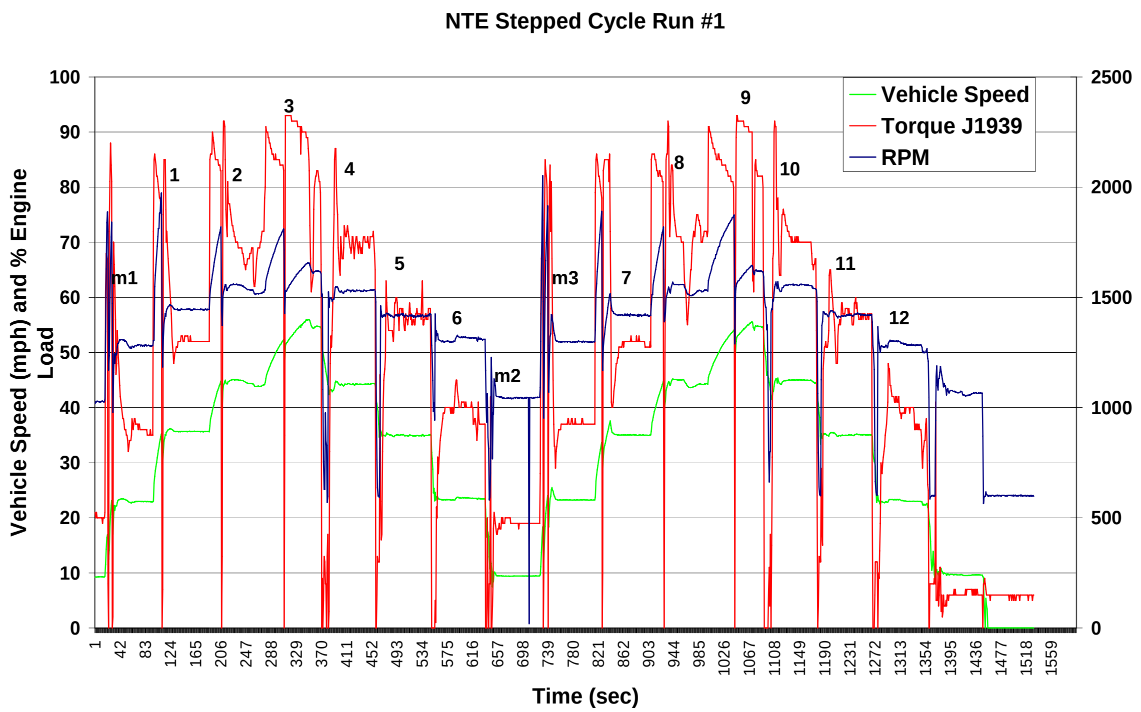


Figure 4-20. Summary of NTE Events for the NTE Stepped Cycle

Table 4-4. NTE Event Summary for NTE Stepped Cycle

NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
#1						
NTE_Stepped_1_1	112	113	1	95	95	0
NTE_Stepped_2_1	102	#N/A	#N/A	100	#N/A	#N/A
NTE_Stepped_3_1	106	106	0	96	97	1
NTE_Stepped_4_1	124	124	0	97	97	0
NTE_Stepped_5_2	105	105	0	101	102	1
NTE_Stepped_6_1	106	106	0	99	99	0
#2						
NTE_Stepped_1_2	209	209	0	100	101	1
NTE_Stepped_2_2	204	204	0	114	114	0
NTE_Stepped_3_2	204	205	1	110	110	0
NTE_Stepped_4_2	224	224	0	112	112	0
NTE_Stepped_5_3	209	209	0	105	105	0
NTE_Stepped_6_2	207	207	0	117	117	0
#3						
NTE_Stepped_1_3	311	311	0	59	60	1
NTE_Stepped_2_3	319	319	0	44	44	0
NTE_Stepped_3_3	318	316	-2	42	44	2
NTE_Stepped_4_3	338	338	0	47	47	0
NTE_Stepped_5_4	316	317	1	43	43	0
NTE_Stepped_6_3	#N/A	326	#N/A	#N/A	40	#N/A
#4						
NTE_Stepped_1_4	384	385	1	74	74	0
NTE_Stepped_2_4	377	377	0	75	74	-1
NTE_Stepped_3_4	372	373	1	80	79	-1
NTE_Stepped_4_4	399	399	0	72	72	0
NTE_Stepped_5_5	373	373	0	76	76	0
NTE_Stepped_6_4	374	374	0	78	78	0
#5						
NTE_Stepped_1_5	470	471	1	79	78	-1
NTE_Stepped_2_5	461	461	0	80	80	0
NTE_Stepped_3_5	460	461	1	81	81	0
NTE_Stepped_4_5	481	482	1	81	80	-1
NTE_Stepped_5_6	458	458	0	82	82	0
NTE_Stepped_6_5	462	462	0	80	80	0
#6						
NTE_Stepped_1_6	567	568	1	50	51	1
NTE_Stepped_2_6	557	557	0	53	53	0
NTE_Stepped_3_6	556	557	1	54	54	0
NTE_Stepped_4_6	580	580	0	51	51	0
NTE_Stepped_5_7	557	558	1	53	36	-17
NTE_Stepped_6_6	560	560	0	66	66	0
#7						
NTE_Stepped_1_7	829	829	0	99	99	0

Unique ID for NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
NTE_Stepped_2_8	828	829	1	97	97	0
NTE_Stepped_3_7	822	823	1	102	101	-1
NTE_Stepped_4_8	848	848	0	97	97	0
NTE_Stepped_5_10	824	825	1	101	100	-1
NTE_Stepped_6_8	829	830	1	97	96	-1
#8						
NTE_Stepped_1_8	929	931	2	114	112	-2
NTE_Stepped_2_9	927	927	0	113	113	0
NTE_Stepped_3_8	926	927	1	102	102	0
NTE_Stepped_4_9	947	947	0	110	110	0
NTE_Stepped_5_11	927	928	1	113	112	-1
NTE_Stepped_6_9	929	929	0	116	116	0
#9						
NTE_Stepped_1_9	1044	1045	1	47	46	-1
NTE_Stepped_2_10	1041	1041	0	41	41	0
NTE_Stepped_3_9	1031	1031	0	52	53	1
NTE_Stepped_4_10	1059	1059	0	45	45	0
NTE_Stepped_5_12	1042	1042	0	38	38	0
NTE_Stepped_6_10	1047	1047	0	36	36	0
#10						
NTE_Stepped_1_10	1105	1105	0	72	73	1
NTE_Stepped_2_11	1095	1095	0	78	78	0
NTE_Stepped_3_10	1096	1096	0	75	75	0
NTE_Stepped_4_11	1115	1115	0	76	75	-1
NTE_Stepped_5_13	1092	1092	0	76	77	1
NTE_Stepped_6_11	1093	1093	0	79	79	0
#11						
NTE_Stepped_1_11	1187	1188	1	80	80	0
NTE_Stepped_2_12	1182	1182	0	79	79	0
NTE_Stepped_3_11	1180	1181	1	80	79	-1
NTE_Stepped_4_12	1200	1200	0	82	81	-1
NTE_Stepped_5_14	1177	1177	0	82	83	1
NTE_Stepped_6_12	1182	1182	0	79	79	0
#12						
NTE_Stepped_1_12	1291	1292	1	45	45	0
NTE_Stepped_2_13	1295	1295	0	46	36	-10
NTE_Stepped_3_12	1286	1283	-3	43	47	4
NTE_Stepped_4_13	#N/A	1314	#N/A	#N/A	36	#N/A
NTE_Stepped_5_15	1272	1272	0	76	76	0
NTE_Stepped_6_13	1277	1278	1	75	30	-45
miscellaneous						
NTE_Step_5_1 “m1”	48	48	0	55	55	0
NTE_Step_2_7 “m2”	#N/A	665	#N/A	#N/A	48	#N/A
NTE_Step_6_7 “m3”	748	750	2	79	78	-1
Stp_5_8 “m3-P2”	#N/A	735	#N/A	#N/A	30	#N/A
Step_5_9 “m3-FRM”	768	#N/A	#N/A	54	#N/A	#N/A
Step_4_7“before #7”	#N/A	812	#N/A	#N/A	33	#N/A
6_14 split 6_13	#N/A	1309	#N/A	#N/A	43	#N/A

Note: 114 seconds added to NTE Start for PEMS2 on test iteration #2 because the PEMS2 sampler was started late for this cycle, due to the late start NTE event #1 is also missing for PEMS2 for this test iteration.

The average results for the NTE stepped cycle are presented in Table 4-5 on a g/bhp-hr and fuel specific basis. The results are presented in chronological order for the 12 major NTE events within the cycle. The average values are derived based on the results of the 6 test iterations for the specific NTE event. The statistical comparisons of the differences in emissions between the FRM and PEMS are provided in Appendix J. Generally, most differences observed between the FRM and PEMS were statistically significant at greater than the 95% confidence limit.

The general trends for emissions for the stepped cycle are similar to those found for the NTE steady state cycle and the integrated results. On a g/bhp-hr basis, NO_x emissions for PEMS2 ranged from 6 to 11% higher than the FRM relative to the NTE threshold, while NO_x emissions for PEMS4 were from 17 to 48% higher than the FRM relative to the NTE threshold.

For CO_2, PEMS2 ranged from 3.2% to 6.5% higher than the FRM, while PEMS4 was 19 to 25% higher than the FRM. For PEMS4, some of these differences can be attributed to the offset for the calibration. CO also showed a consistent positive bias for PEMS2 relative to the FRM for CO, but this represented less than a 1% difference relative to the NTE threshold. THC emissions as a whole were relatively low. THC emissions for PEMS2 tended to the lower than those for the FRM, while THC emissions for PEMS4 were mixed relative to the FRM. For both PEMS, the percentage differences represented less than 5% of the NTE standard for all NTE events.

	NOx							CO_2							THC							CO			
	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	P2	P4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	P2	P2 vs. FRM	P2
	g/bhp-hr			absol. Diff		% diff of NTE vs. FRM		g/bhp-hr			absol. Diff		% diff vs. FRM		g/bhp-hr			absol. Diff		% diff of NTE vs. FRM		g/bhp-hr		absol. Diff	% diff of NTE vs. FRM
NTE_Stepped_1	2.1	2.27	2.8	0.17	0.7	8.70%	35.30%	549	565	656	16.3	107.8	3.50%	21.10%	0.02	0.03	0.03	0.009	0.009	4.30%	4.60%	0.4	0.5	0.14	0.70%
NTE_Stepped_2	2.07	2.19	2.6	0.12	0.53	6.10%	26.90%	490	506	597	15.9	107.7	3.20%	22.10%	0.01	0.02	0.02	1E-03	1E-03	0.20%	0.20%	0.3	0.4	0.13	0.60%
NTE_Stepped_3	2.34	2.56	3.31	0.22	0.97	10.90%	48.40%	460	485	571	24.8	110.6	5.30%	24.70%	0.01	0.01	0.01	-0.003	-0.002	1.60%	1.30%	0.3	0.4	0.11	0.60%
NTE_Stepped_4	1.83	2	2.18	0.17	0.35	8.20%	17.30%	464	487	564	23.5	100	5.10%	22.80%	0.02	0.01	0.01	-0.004	-0.004	2.00%	2.10%	0.2	0.3	0.13	0.70%
NTE_Stepped_5	1.84	2.04	2.3	0.2	0.46	9.80%	22.80%	481	512	574	31	92.8	6.40%	21.80%	0.02	0.01	0.01	-0.005	-0.006	2.70%	3.00%	0.2	0.4	0.16	0.80%
NTE_Stepped_6	2.05	2.26	2.61	0.21	0.56	10.50%	27.80%	523	553	622	29.9	98.7	5.70%	18.80%	0.03	0.02	0.02	-0.007	-0.007	3.40%	3.60%	0.4	0.6	0.19	1.00%
NTE_Stepped_7	2.11	2.29	2.79	0.18	0.68	8.50%	33.50%	549	570	660	20.4	110.1	3.70%	21.40%	0.02	0.02	0.02	-1E-03	-1E-03	0.80%	0.50%	0.3	0.5	0.15	0.80%
NTE_Stepped_8	2.09	2.23	2.85	0.14	0.76	6.70%	37.80%	488	505	593	16.4	104.8	3.40%	22.40%	0.01	0.01	0.01	-0.003	-0.002	1.50%	1.20%	0.2	0.4	0.13	0.60%
NTE_Stepped_9	2.39	2.59	NA	0.2	NA	9.60%	NA	455	480	NA	25.3	NA	5.60%	NA	0.01	0.01	NA	-0.004	NA	1.90%	NA	0.3	0.4	0.12	0.60%
NTE_Stepped_10	1.85	2.02	NA	0.17	NA	8.40%	NA	460	481	NA	21.9	NA	4.80%	NA	0.01	0.01	NA	-0.004	NA	1.90%	NA	0.2	0.3	0.13	0.70%
NTE_Stepped_11	1.85	2.05	NA	0.2	NA	9.80%	NA	479	510	NA	31	NA	6.50%	NA	0.02	0.01	NA	-0.005	NA	2.80%	NA	0.2	0.3	0.14	0.70%
NTE_Stepped_12	2.05	2.26	NA	0.21	NA	10.70%	NA	535	556	NA	20.7	NA	3.40%	NA	0.03	0.02	NA	-0.009	NA	3.90%	NA	0.4	0.5	0.16	0.90%

	NOx					THC					CO				
	FRM	P2	P4	P2	P4	FRM	P2	P4	P2	P4	FRM	P2	P4	P2	P4
	fs			% diff vs. FRM		fs			% diff vs. FRM		fs			% diff vs. FRM	
NTE_Stepped_1	0.0121	0.0128	0.0136	4.8%	9.7%	0.00011	0.00016	0.00014	53%	48%	0.0022	0.0029	NA	34%	NA
NTE_Stepped_2	0.0133	0.0138	0.0138	3.5%	3.1%	0.00009	0.00009	0.00008	1%	-3%	0.0016	0.0024	NA	46%	NA
NTE_Stepped_3	0.0161	0.0170	0.0184	4.8%	15.3%	0.00009	0.00006	0.00005	-35%	-27%	0.0019	0.0026	NA	41%	NA
NTE_Stepped_4	0.0125	0.0132	0.0122	5.3%	-2.4%	0.00010	0.00007	0.00006	-32%	-32%	0.0013	0.0021	NA	64%	NA
NTE_Stepped_5	0.0121	0.0128	0.0127	5.8%	5.8%	0.00013	0.00008	0.00007	-35%	-31%	0.0014	0.0023	NA	63%	NA
NTE_Stepped_6	0.0124	0.0131	0.0133	5.9%	9.1%	0.00018	0.00013	0.00011	-29%	-22%	0.0023	0.0032	NA	43%	NA
NTE_Stepped_7	0.0122	0.0128	0.0134	5.2%	10.9%	0.00010	0.00010	0.00008	-9%	-6%	0.0019	0.0027	NA	44%	NA
NTE_Stepped_8	0.0135	0.0141	0.0152	3.9%	11.4%	0.00009	0.00007	0.00006	-25%	-23%	0.0014	0.0022	NA	52%	NA
NTE_Stepped_9	0.0166	0.0173	NA	3.7%	NA	0.00008	0.00005	NA	-37%	NA	0.0017	0.0025	NA	43%	NA
NTE_Stepped_10	0.0127	0.0135	NA	6.3%	NA	0.00010	0.00007	NA	-31%	NA	0.0012	0.0020	NA	70%	NA
NTE_Stepped_11	0.0122	0.0129	NA	5.9%	NA	0.00012	0.00008	NA	-35%	NA	0.0013	0.0022	NA	65%	NA
NTE_Stepped_12	0.0121	0.0132	NA	10.7%	NA	0.00018	0.00012	NA	-25%	NA	0.0022	0.0031	NA	35%	NA

Table 4-5 Comparison of Average g/bhp-hr and fs Emissions for FRM and PEMS for the NTE Stepped Cycle

4.10 Analysis of the Data for the 50 mph cruise

The 50 mph cruise had between 3 to 6 NTE events over the 7 replicate runs. Four primary NTE events were consistently identified over the replicate test runs. The NTE events are labeled 1-4 in Figure 4-21. Other NTE events varied throughout the course of the cruise portion of the cycle. These additional NTE events that were identified for at least one of the test iterations are labeled “m” in Figure 4-21. As an example, Figure 4-22 shows the torque, RPM and engine load for one test iteration where differences in identified NTE events were observed between the FRM and PEMS2.

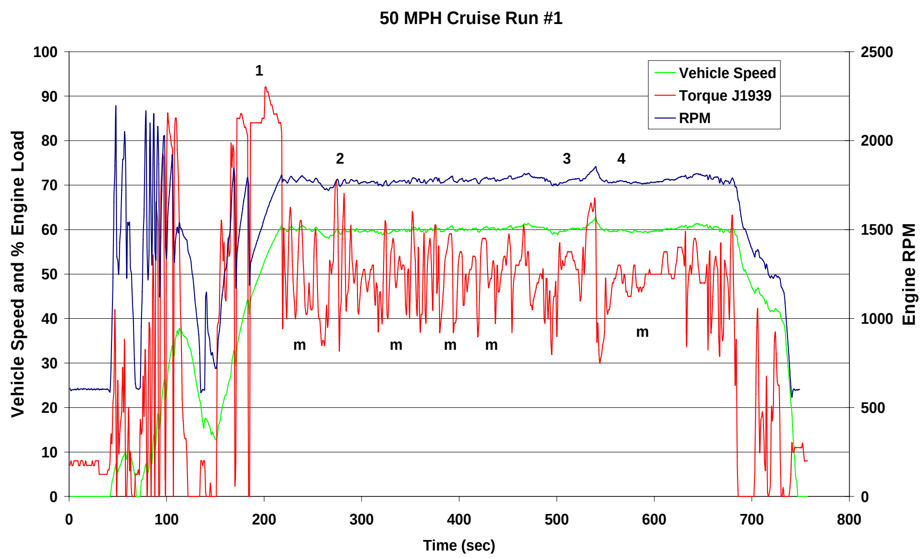


Figure 4-21. Summary of the NTE Events Identified During the 50 mph Cruise Cycle

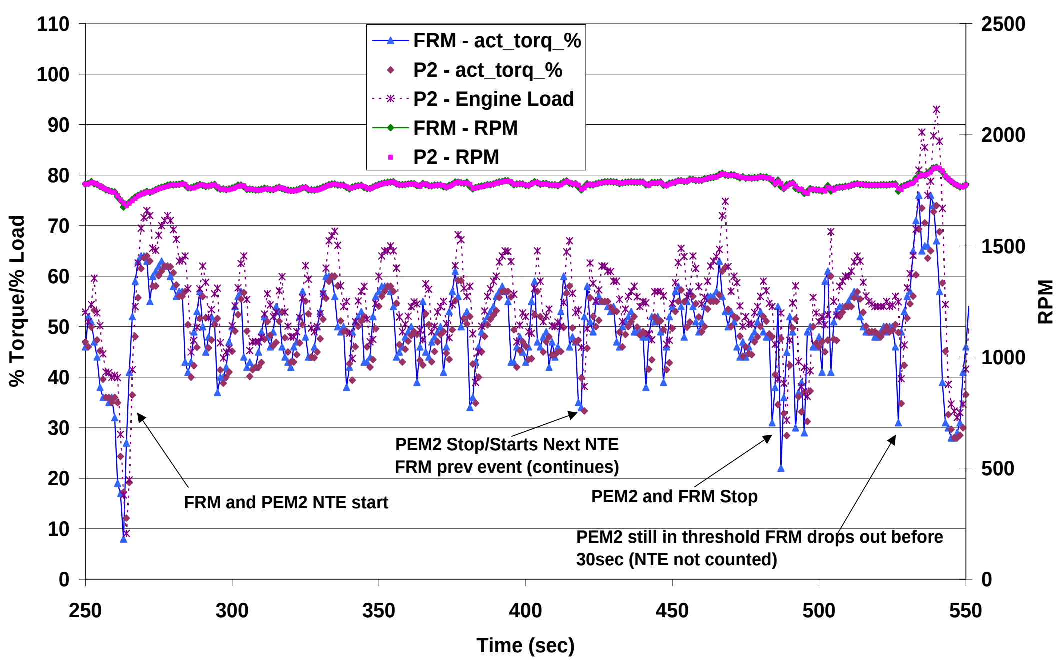


Figure 4-22. Comparison of Torque and RPM Signals for Unmatched NTE Events

Table 4-6 shows the number of NTE events identified by the FRM and PEMS2 for each test run.

Table 4-6. NTE Event Summary for the 50 mph Cruise

NTE event	FRM NTEstart	PEMS2 NTEstart	PEMS2 difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 difference
#1						
50CRUISE_1_1	186	186	0	91	309	218
50CRUISE_2_1	223	192	-31	34	65	31
50CRUISE_3_1	187	188	1	38	34	-4
50CRUISE_4_1	192	126	-66	66	66	0
50CRUISE_5_1	193	194	1	68	67	-1
50CRUISE_6_1	194	195	1	65	64	-1
50CRUISE_7_1	191	192	1	66	65	-1
#2						
50CRUISE_1_2	278	#N/A	#N/A	217	#N/A	#N/A
50CRUISE_2_2	263	263	0	225	282	57
50CRUISE_3_3	265	265	0	219	154	-65
50CRUISE_4_2	262	197	-65	283	282	-1
50CRUISE_5_2	266	267	1	54	54	0
50CRUISE_6_2	265	265	0	283	284	1
50CRUISE_7_2	260	262	2	283	211	-72
#3						
50CRUISE_1_3	496	496	0	47	48	1
50CRUISE_2_3	489	#N/A	#N/A	56	#N/A	#N/A
50CRUISE_3_5	#N/A	496	#N/A	#N/A	47	#N/A
50CRUISE_5_5	496	497	1	78	78	0
50CRUISE_7_3	#N/A	474	#N/A	#N/A	70	#N/A
#4						
50CRUISE_1_4	547	548	1	86	119	33
50CRUISE_2_4	550	550	0	134	134	0
50CRUISE_3_6	549	549	0	120	121	1
50CRUISE_4_3	547	482	-65	123	123	0
50CRUISE_6_3	550	550	0	134	136	2
50CRUISE_7_4	548	549	1	120	120	0
misc.						
50CRUISE_3_2	226	223	-3	34	38	4
50CRUISE_5_3	322	322	0	60	61	1
50CRUISE_5_4	383	384	1	106	106	0
50CRUISE_3_4	#N/A	420	#N/A	#N/A	67	#N/A
50CRUISE_5_6	575	592	17	94	78	-16

The results for the g/bhp-hr and fuel-specific emissions for the 50 mph Cruise cycle are presented in Table 4-7 and 4-8. The percentage differences for the brake specific NO_x, CO, and THC are given relative to the applicable NTE threshold. The Tables include only PEMS2, since data for PEMS4 are available for only a single test cycle iteration. The results are generally consistent with the other cycles. The percentage difference from the FRM relative to the NTE standard for NO_x was between –1 to 12% for PEMS2 and 36-

72% for PEMS4. For THC, the percentage differences represented 5% or less of the NTE threshold, while CO measurement differed by 1% or less of the NTE threshold. CO_2 measurements for PEMS2 were within 7% of the FRM for all NTE events, while PEMS4 showed larger differences of 22-39%. The differences between the PEMS and the FRM were generally statistically significant over the data set.

Table 4-7. g/bhp-hr NTE Results for the 50 mph Cruise Cycle

NTE event	FRM bsNOx	PEMS2 bsNOx	PEMS2 vs. FRM absol. Diff	PEMS2 % diff vs. NTE	FRM bsTHC	PEMS2 bsTHC	PEMS2 vs. FRM absol. Diff	PEMS2 % diff vs. NTE	FRM bsCO	PEMS2 bsCO	PEMS2 vs. FRM absol. Diff	PEMS2 % diff vs. NTE	FRM bsCO2	PEMS2 bsCO2	PEMS2 vs. FRM absol. Diff	PEMS2 % diff vs. FRM
50CRUISE_1_1	2.27	2.25	-0.02	-1%	0.020	0.023	0.00	2%	0.46	0.61	0.15	0.8%	538	573	34.83	6%
50CRUISE_1_2	2.08	#N/A	#N/A	#N/A	0.024	#N/A	#N/A	#N/A	0.56	#N/A	#N/A	#N/A	570	#N/A	#N/A	#N/A
50CRUISE_1_3	2.08	2.19	0.11	5%	0.024	0.022	0.00	-1%	0.53	0.59	0.06	0.3%	561	582	20.41	4%
50CRUISE_1_4	2.07	2.19	0.12	6%	0.026	0.024	0.00	-1%	0.54	0.61	0.07	0.4%	563	589	25.98	5%
50CRUISE_2_1	2.15	2.43	0.28	14%	0.016	0.014	0.00	-1%	0.49	0.53	0.04	0.2%	571	529	-41.88	-7%
50CRUISE_2_2	2.11	2.25	0.14	7%	0.016	0.018	0.00	1%	0.51	0.64	0.13	0.7%	572	583	11.07	2%
50CRUISE_2_3	2.10	#N/A	#N/A	#N/A	0.015	#N/A	#N/A	#N/A	0.49	#N/A	#N/A	#N/A	567	#N/A	#N/A	#N/A
50CRUISE_2_4	2.13	2.28	0.15	8%	0.016	0.018	0.00	1%	0.48	0.65	0.17	0.9%	570	586	15.55	3%
50CRUISE_3_1	2.33	2.44	0.11	5%	0.017	0.015	0.00	-1%	0.38	0.45	0.07	0.4%	528	518	-10.45	-2%
50CRUISE_3_2	2.22	2.37	0.15	7%	0.026	0.030	0.00	2%	0.50	0.68	0.19	1.0%	582	585	3.37	1%
50CRUISE_3_3	2.15	2.27	0.12	6%	0.025	0.019	-0.01	-3%	0.49	0.66	0.18	0.9%	571	576	4.89	1%
50CRUISE_3_4	#N/A	2.27	#N/A	#N/A	#N/A	0.017	#N/A	#N/A	#N/A	0.63	#N/A	#N/A	#N/A	594	#N/A	#N/A
50CRUISE_3_5	#N/A	2.25	#N/A	#N/A	#N/A	0.014	#N/A	#N/A	#N/A	0.61	#N/A	#N/A	#N/A	572	#N/A	#N/A
50CRUISE_3_6	2.20	2.35	0.15	8%	0.026	0.016	-0.01	-5%	0.45	0.61	0.16	0.8%	574	587	13.56	2%
50CRUISE_4_1	2.31	2.51	0.20	10%	0.018	0.012	-0.01	-3%	0.44	0.56	0.12	0.6%	535	534	-0.60	0%
50CRUISE_4_2	2.17	2.35	0.18	9%	0.022	0.016	-0.01	-3%	0.45	0.62	0.17	0.9%	572	586	14.19	2%
50CRUISE_4_3	2.19	2.34	0.15	7%	0.022	0.016	-0.01	-3%	0.44	0.60	0.16	0.8%	572	588	15.73	3%
50CRUISE_5_1	2.31	2.40	0.09	4%	0.017	0.022	0.01	3%	0.43	0.46	0.03	0.2%	544	554	9.51	2%
50CRUISE_5_2	2.19	2.29	0.10	5%	0.018	0.027	0.01	4%	0.46	0.53	0.07	0.4%	543	576	32.59	6%
50CRUISE_5_3	2.19	2.30	0.11	6%	0.019	0.028	0.01	4%	0.47	0.53	0.07	0.3%	554	583	28.92	5%
50CRUISE_5_4	2.18	2.27	0.09	4%	0.019	0.029	0.01	5%	0.43	0.51	0.08	0.4%	567	595	28.17	5%
50CRUISE_5_5	2.18	2.26	0.08	4%	0.019	0.029	0.01	5%	0.44	0.52	0.08	0.4%	565	592	27.16	5%
50CRUISE_5_6	2.21	2.29	0.08	4%	0.020	0.028	0.01	4%	0.42	0.48	0.07	0.3%	564	591	27.12	5%
50CRUISE_6_1	2.34	2.47	0.13	7%	0.017	0.020	0.00	2%	0.43	0.52	0.09	0.5%	532	537	5.45	1%
50CRUISE_6_2	2.21	2.29	0.08	4%	0.020	0.028	0.01	4%	0.43	0.54	0.11	0.6%	564	590	25.96	5%
50CRUISE_6_3	2.22	2.30	0.08	4%	0.020	0.028	0.01	4%	0.42	0.55	0.12	0.6%	560	590	29.70	5%
50CRUISE_7_1	2.24	2.48	0.24	12%	0.023	0.021	0.00	-1%	0.53	0.64	0.10	0.5%	514	543	28.70	6%
50CRUISE_7_2	1.95	2.16	0.21	11%	0.028	0.028	0.00	0%	0.65	0.80	0.15	0.8%	560	589	28.60	5%
50CRUISE_7_3	#N/A	2.15	#N/A	#N/A	#N/A	0.027	#N/A	#N/A	#N/A	0.78	#N/A	#N/A	#N/A	597	#N/A	#N/A
50CRUISE_7_4	1.94	2.16	0.22	11%	0.028	0.027	0.00	0%	0.64	0.81	0.17	0.9%	557	591	33.96	6%

Table 4-8. Fuel-Specific NTE Results for the 50 mph Cruise Cycle

Unique ID for NTE event	FRM fsNOx	PEMS2 fsNOx	PEMS2 % diff	FRM fsTHC	PEMS2 fsTHC	PEMS2 % diff	FRM fsCO	PEMS2 fsCO	PEMS2 % diff
50CRUISE_1_1	0.0133	0.0124	-7%	0.000117	0.000133	14%	0.0027	0.0035	28%
50CRUISE_1_2	0.0115	#N/A	#N/A	0.000135	#N/A	#N/A	0.0031	#N/A	#N/A
50CRUISE_1_3	0.0117	0.0120	2%	0.000132	0.000122	-8%	0.0030	0.0033	11%
50CRUISE_1_4	0.0116	0.0119	3%	0.000143	0.000131	-9%	0.0030	0.0033	10%
50CRUISE_2_1	0.0119	0.0144	21%	0.000088	0.000086	-2%	0.0027	0.0032	20%
50CRUISE_2_2	0.0117	0.0124	6%	0.000088	0.000099	13%	0.0028	0.0035	26%
50CRUISE_2_3	0.0117	#N/A	#N/A	0.000084	#N/A	#N/A	0.0027	#N/A	#N/A
50CRUISE_2_4	0.0118	0.0125	6%	0.000086	0.000097	12%	0.0027	0.0036	34%
50CRUISE_3_1	0.0140	0.0150	8%	0.000103	0.000096	-6%	0.0023	0.0028	23%
50CRUISE_3_2	0.0121	0.0130	8%	0.000141	0.000164	16%	0.0027	0.0038	40%
50CRUISE_3_3	0.0119	0.0126	6%	0.000139	0.000107	-23%	0.0027	0.0037	38%
50CRUISE_3_4		0.0122	#N/A	#N/A	0.000093	#N/A	#N/A	0.0034	#N/A
50CRUISE_3_5		0.0126	#N/A	#N/A	0.000082	#N/A	#N/A	0.0035	#N/A
50CRUISE_3_6 #N/A	0.0121	0.0128	6%	0.000142	0.000086	-39%	0.0025	0.0033	35%
50CRUISE_4_1 #N/A	0.0136	0.0148	9%	0.000104	0.000074	-29%	0.0026	0.0033	30%
50CRUISE_4_2	0.0120	0.0128	7%	0.000120	0.000087	-28%	0.0025	0.0034	36%
50CRUISE_4_3	0.0121	0.0128	6%	0.000121	0.000086	-29%	0.0024	0.0033	36%
50CRUISE_5_1	0.0134	0.0137	2%	0.000096	0.000135	41%	0.0025	0.0027	9%
50CRUISE_5_2	0.0127	0.0127	0%	0.000107	0.000149	39%	0.0026	0.0030	11%
50CRUISE_5_3	0.0125	0.0127	2%	0.000109	0.000156	43%	0.0027	0.0030	12%
50CRUISE_5_4	0.0122	0.0122	0%	0.000108	0.000156	45%	0.0024	0.0028	14%
50CRUISE_5_5	0.0122	0.0123	1%	0.000109	0.000158	45%	0.0025	0.0029	15%
50CRUISE_5_6	0.0124	0.0124	0%	0.000111	0.000154	39%	0.0023	0.0026	12%
50CRUISE_6_1	0.0139	0.0145	4%	0.000098	0.000123	25%	0.0026	0.0031	21%
50CRUISE_6_2	0.0124	0.0125	1%	0.000112	0.000150	34%	0.0024	0.0029	23%
50CRUISE_6_3	0.0125	0.0125	0%	0.000113	0.000152	35%	0.0024	0.0030	25%
50CRUISE_7_1	0.0137	0.0142	3%	0.000139	0.000131	-6%	0.0033	0.0038	17%
50CRUISE_7_2	0.0110	0.0117	7%	0.000159	0.000155	-3%	0.0037	0.0044	20%
50CRUISE_7_3		0.0115	#N/A	#N/A	0.000148	#N/A	#N/A	0.0042	#N/A
50CRUISE_7_4	0.0110	0.0117	6%	0.000156	0.000144	-8%	0.0036	0.0044	21%

#N/A

4.11 Analysis of the Data for the Urban Dynamometer Driving Schedule (UDDS)

Between one and three NTE events were identified for the UDDS over the 7 test iterations. The primary NTE event for this cycle occurred approximately 632 seconds into the cycle as the vehicle is approaching its highest speed point, as shown in Figure 4-23. This NTE event typically lasted between 30-35 seconds. One or two other NTE events were identified for most of the UDDS cycles, but these were not uniformly identified by all PEMS/FRM. A summary of the identified NTE events identified by the FRM and both PEMS for each test run is provided in Table 4-9. For all identified NTE events, the duration of the event was essentially the same for all PEMS/FRM.

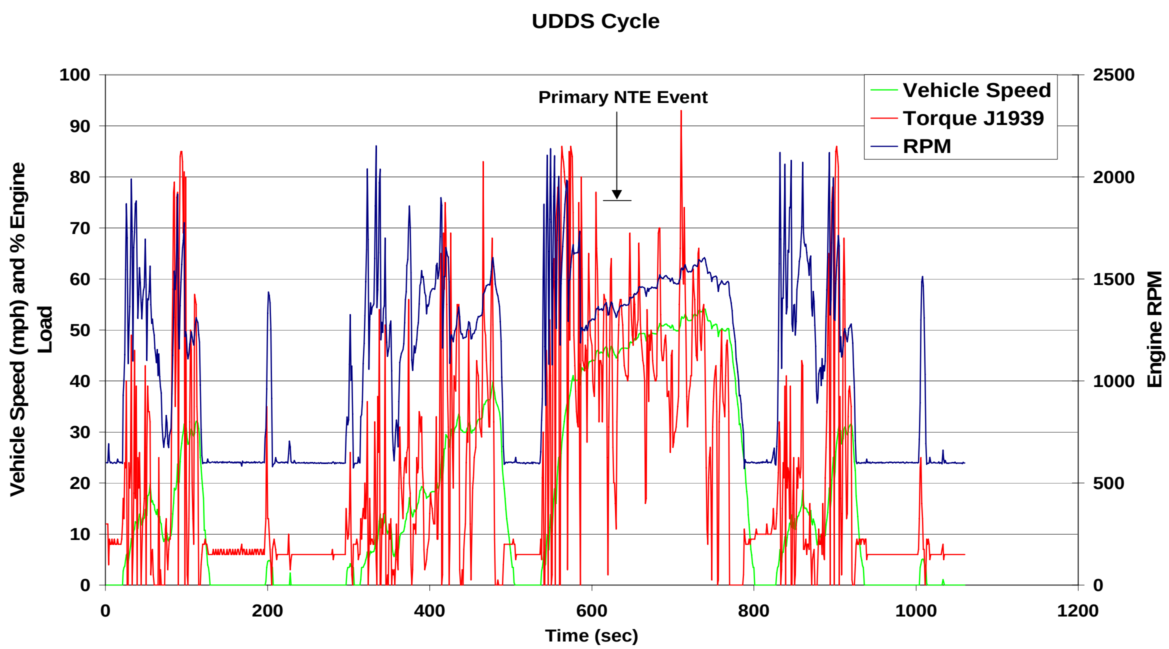


Figure 4-23. Summary of the NTE Events Identified during the UDDS Cycle

Table 4-9. NTE Event Comparison for UDDS Cycle

	FRM NTEstart	PEMS2 NTEstart	PEMS2 %difference	FRM NTEdur	PEMS2 NTEdur	PEMS2 %difference
UDDS_MTA_1_1	632	632	0	34	34	0
UDDS_MTA_2_1	632	632	0	33	33	0
UDDS_MTA_2_2	667	668	-1	32	32	0
UDDS_MTA_2_3	702	703	-1	38	38	0
UDDS_MTA_3_1	632	632	0	34	33	1
UDDS_MTA_3_2	705	707	-2	37	35	2
UDDS_MTA_4_1	NA	594	NA	NA	34	NA
UDDS_MTA_4_2	634	633	1	35	30	5
UDDS_MTA_4_3	NA	NA	NA	NA	NA	NA
UDDS_MTA_5_1	633	633	0	34	34	0
UDDS_MTA_5_2	NA	669	NA	NA	32	NA
UDDS_MTA_6_1	635	634	1	33	34	-1
UDDS_MTA_7_1	635	636	-1	34	33	1
UDDS_MTA_7_2	NA	672	NA	NA	31	NA

Tables 4-10 and 4-11 show emissions for each individual NTE event in g/bhp-hr and g/grams of fuel, respectively, along with the associated percentage differences with the FRM. The comparisons between the FRM and PEMS for the different NTE events are similar to those found for the other cycles and were statistically significant in most cases.

Table 4-10. Comparison of Average g/bhp-hr Emissions for FRM and PEMS for the UDDS Cycle

NTE event	NOx							CO_2							THC							CO			
	FRM	PEMS2	PEMS4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	PEMS2	PEMS4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	PEMS2	PEMS4	P2 vs. FRM	P4 vs. FRM	P2	P4	FRM	PEMS2	P2 vs. FRM	P2 vs. FRM
	g/bhp-hr			absol. Diff		% diff vs. NTE		g/bhp-hr			absol. Diff		% diff vs. NTE		g/bhp-hr			absol. Diff		% diff vs. NTE		g/bhp-hr		absol. Diff	% diff vs. NTE
UDDS_MTA_1_1	2.14	2.34	2.66	0.20	0.52	10%	26%	480	512	590	31.86	110.23	6.6%	23%	0.023	0.026	0.389	0.00	0.37	1%	174%	0.54	0.77	0.23	1.2%
UDDS_MTA_2_1	2.14	2.30	2.68	0.16	0.54	8%	27%	476	514	584	37.99	108.05	8.0%	23%	0.013	0.023	0.025	0.01	0.01	5%	6%	0.51	0.66	0.15	0.8%
UDDS_MTA_2_2	2.42	2.67	3.16	0.25	0.74	13%	37%	506	542	608	35.95	102.29	7.1%	20%	0.014	0.025	0.028	0.01	0.01	5%	7%	0.56	0.75	0.19	1.0%
UDDS_MTA_2_3	2.32	2.47	2.86	0.15	0.53	7%	27%	496	529	589	32.74	93.14	6.6%	19%	0.013	0.022	0.025	0.01	0.01	5%	6%	0.58	0.70	0.12	0.6%
UDDS_MTA_3_1	2.14	2.34	2.77	0.20	0.63	10%	31%	486	510	570	23.82	84.08	4.9%	17%	0.022	0.018	0.024	0.00	0.00	-2%	1%	0.47	0.61	0.13	0.7%
UDDS_MTA_3_2	2.36	2.49	3.03	0.13	0.67	7%	34%	504	522	590	17.93	85.64	3.6%	17%	0.020	0.016	0.023	0.00	0.00	-2%	1%	0.53	0.67	0.15	0.7%
UDDS_MTA_4_1	#N/A	2.33	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	510	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.030	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.64	#N/A	#N/A
UDDS_MTA_4_2	2.16	2.72	2.69	0.56	0.54	28%	27%	483	540	567	57.17	84.06	12%	17%	0.011	0.033	0.028	0.02	0.02	10%	8%	0.47	0.69	0.22	1.1%
UDDS_MTA_4_3	#N/A	#N/A	3.08	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	588	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.030	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
UDDS_MTA_5_1	2.21	2.37	2.74	0.16	0.54	8%	27%	484	505	563	21.23	79.89	4.4%	17%	0.013	0.022	0.024	0.01	0.01	4%	5%	0.47	0.66	0.19	1.0%
UDDS_MTA_5_2	#N/A	2.68	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	532	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.023	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.73	#N/A	#N/A
UDDS_MTA_6_1	2.07	2.30	2.55	0.23	0.48	11%	24%	480	509	556	28.87	75.73	6.0%	16%	0.022	0.020	0.027	0.00	0.01	-1%	3%	0.57	0.75	0.19	1.0%
UDDS_MTA_7_1	2.05	2.31	4.56	0.26	2.51	13%	125%	480	508	990	28.81	510.34	6.0%	106%	0.018	0.026	0.047	0.01	0.03	4%	14%	0.60	0.79	0.20	1.0%
UDDS_MTA_7_2	#N/A	2.54	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	543	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.028	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.88	#N/A	#N/A

Table 4-11 Comparison of Average fs Emissions for FRM and PEMS for the UDDS Cycle

	NOx fs					THC					CO				
	FRM	P2	P4	P2 % diff vs. FRM	P4 % diff vs. FRM	FRM Fs	P2 Fs	P4 Fs	P2 % diff vs. FRM	P4 % diff vs. FRM	FRM fs	P2 fs	P4 fs	P2 % diff vs. FRM	P4 % diff vs. FRM
UDDS_MTA_1_1	0.0141	0.0147	0.0143	4%	1%	0.00015	0.00016	0.00208	4%	1249%	0.0035	0.0048	NA	36%	NA
UDDS_MTA_2_1	0.0142	0.0144	0.0146	1%	3%	0.00009	0.00015	0.00013	68%	57%	0.0034	0.0041	NA	21%	NA
UDDS_MTA_2_2	0.0151	0.0158	0.0165	5%	9%	0.00009	0.00015	0.00015	70%	69%	0.0035	0.0045	NA	26%	NA
UDDS_MTA_2_3	0.0148	0.0150	0.0154	1%	4%	0.00008	0.00014	0.00014	71%	71%	0.0037	0.0042	NA	15%	NA
UDDS_MTA_3_1	0.0139	0.0148	0.0154	6%	11%	0.00014	0.00011	0.00013	-19%	-6%	0.0031	0.0038	NA	24%	NA
UDDS_MTA_3_2	0.0148	0.0153	0.0163	4%	10%	0.00012	0.00010	0.00012	-20%	-2%	0.0033	0.0041	NA	25%	NA
UDDS_MTA_4_1	NA	0.0147	NA	NA	NA	NA	0.00019	NA	NA	NA	NA	0.0040	NA	NA	NA
UDDS_MTA_4_2	0.0141	0.0162	0.0150	15%	7%	0.00007	0.00019	0.00016	175%	124%	0.0031	0.0041	NA	33%	NA
UDDS_MTA_4_3	NA	NA	0.0166	NA	NA	NA	NA	0.00016	NA	NA	NA	NA	NA	NA	NA
UDDS_MTA_5_1	0.0144	0.0152	0.0154	5%	7%	0.00009	0.00014	0.00013	57%	51%	0.0031	0.0042	NA	36%	NA
UDDS_MTA_5_2	NA	0.0163	NA	NA	NA	NA	0.00014	NA	NA	NA	NA	0.0044	NA	NA	NA
UDDS_MTA_6_1	0.0136	0.0146	0.0146	7%	7%	0.00014	0.00013	0.00016	-10%	8%	0.0037	0.0047	NA	27%	NA
UDDS_MTA_7_1	0.0135	0.0149	0.0146	10%	8%	0.00012	0.00017	0.00015	45%	31%	0.0039	0.0050	NA	28%	NA
UDDS_MTA_7_2	NA	0.0150	NA	NA	NA	NA	0.00017	NA	NA	NA	NA	0.0052	NA	NA	NA

5.0 Exploratory Survey of PM-Capable PEMS for Mobile Sources

5.1 Experimental Procedures

The earlier section on measuring emissions from stationary sources presented some comparative data for PEMS and the FRM. By the time of the mobile source testing many more PM-capable PEMS were available so the thrust of this section is to describe the comparison between the FRM and four different PM-capable PEMS during the chassis dynamometer testing portion of this research. One PEMS used conventional filter methods and three used real-time second-by-second mass concentration methods. Table 5-1 and 5-2 lists the principle of operation and specifications for each of the PM measurement techniques. Additionally, PEMS6 for measuring PM was included in the study for the chassis dynamometer testing. After the testing, it was determined that the instrument had not been operating within manufacturers' specifications, so these data were not reported. Note that the PM-capable PEMS are an evolving product, like the gaseous PEMS, so there is little standardization. Diversity in manufacturer approach is expected.

UCR's MEL took PM mass samples with conventional Gelman Teflo® 47 mm filters and the elemental and organic carbon (EC/OC) samples on specially prepared quartz media. Following the CFR protocol, all filter media were sampled using secondary dilution, a 47°C filter temperature and an inlet classifier as per CFR for 2007. The secondary dilution tunnel was operated at a dilution ratio of 2.5/1, and a filter sample flow rate of 19 standard liters per minute (slpm), giving filter face velocities of around 37 cm/s for both the quartz and Teflon filters. The NIOSH method was used to measure the EC and OC and to estimate the mass. PEMS 5, 7, and 8 all sampled from the FRM primary dilution tunnel. PEMS 3 sampled from its own dilution tunnel connected to the raw exhaust.

PEMS 3, 7, 8 and MEL were operated by CE-CERT staff following manufacturer procedures for details on leak checks, zero checks and zero adjustments. PEMS 3 and 5 were operated by the manufacturer. Note that PEMS 8 was part of the MEL lab, calibrated against diesel exhaust and used regularly to indicate the expected concentration range. These values have helped to set dilution ratios and sampling times when measuring diesel sources of unknown PM concentration. However, it is more common for PEMS 8 to be calibrated with Arizona dust and used for ambient monitoring. For the purposes of this study, all figures and tables show the PEMS 8 values with the manufacturer calibration and uncorrected for the UCR correlation.

CE-CERT staff analyzed mass based PM emissions calculations using the FRM exhaust volume and PEMS mass concentration for PEMS 5, 7 and 8. Only PEMS 3 performed independent PM mass-based calculations. The FRM mass calculations used the same CVS volume and secondary dilution-ratio as the PEMS, but in addition required filter sample flows and filter mass.

Table 5-1. Specifications for the Different PEMS Used During the Mobile Source Testing.

ID	Output	Mfg Max Sample Rate	Mfg Dynamic Range	Mfg Maximum Range	Mfg LDL	Mfg Size Range
FRM	Teflon_ug	1/cycle	100	1mg	10 ug	< 2500 nm
EC/OC	Quartz_ug	1/cycle	1000	< 10mg	10 ug	< 2500 nm
PEMS3	Teflon_ug	1/cycle	250	2.5mg	10 ug	n/a
PEMS5	ug/m3	20Hz	1000000	10000 mg/m3	<1ug/m3	n/a
PEMS7	mg/m3	20Hz	>5000	50mg/mg3	~5ug/m3	n/a
PEMS8	mg/m3	1Hz	100000	100mg/m3	1 ug/m3	100-2500 nm

Table 5-2. Principles of Operation for Particulate Matter (PM) Measurement System and Possible Limitations.

ID	Measurement Principal	Known Limitations	Description
FRM CE-CERT	gravimetric	EPA standard possible OC artifact	Secondary dilution of 47 mm 2.0 um min efficiency teflo membrane filter media. Sample flow conditions were 47C, 37 cm/s with a 2.5 um classifier [1, 2]. Filter media is 99.99 % efficient. Net filter weights based on difference from pre and post weights measured in duplicate. Filter weights range from 450 to 1000 ug.
EC/OC CE-CERT	thermal optical analysis	mass varies with EC/OC content, filter distribution, See [NIOSH].	47 mm quartz oven fired filters (same specs as FRM Teflon). The NIOSH method involves taking a 1.5 cm^2 punch of the filter and heat following the NIOSH program (amb to 850 °C in Helium then cool. Then heat to 950 °C in presences of oxygen/helium blend). While heating/cooling measure transmittance. A specific change in transmittance corresponds to the OC/EC split. The mass before is OC and mass after is EC. All mass is inferred using a FID [5].
PEMS3 RAVEM	gravimetric	EPA standard (same as FRM)	47 mm Pallflex T60A20 Teflon-coated borosilicate glass filters. Single dilution system with dilution ratio between 22:1 through 68:1.
PEMS5 ARTIUM	laser induced incandescence	response to only dry soot carbon (only EC)	A laser heats particles that give off incandescence light as a result of the heating. The amount of incandescence is proportional to only dry soot (typically referred to as EC) and no response for the OC particles. The incandescence is detected by photo detectors and used to estimate PM volume fraction. The mass concentration is calculated by assuming the soot has a density of 1.9 g/cm^3. Manufacture states method has measured particles below 5 nm and does not know of any lower particle size limitation.
PEMS7 AVL	photo acoustic	response to only dry soot carbon (only EC)	A modulating laser light is absorbed by particles in the sample. EC particles absorb the modulated laster light where OC particles absorb only a negligable amount. The absorbed light leads to periodic heating and cooling of the particles which leads to periodic pressure waves. The pressure waves are measured by a microphone. The microphone acustic signal is coorelated to PM mass concentration. The manufacture does not know of any particle size limitation.
PEMS8 DUSTRAK	90° laser light scattering	response varies for EC/OC, shape, 100 nm size minimum	Measures the scattering of light from a laser using photo detectors located at 90° to the laser. The scattering is limited to particles of sufficient size to scatter light (typically greater than 100 nm). The amount of scattered light is different for EC vs OC particles and possibly varies by particle shape.

5.2 Results

The PM was sampled concurrently with the gaseous emission tests and the PM instruments were only evaluated over a complete integrated cycle. Table 5-3 shows the complete test results for each of the PEMS and FRM. Additional details of the results are provided in Appendix K. The blank spaces are invalid test points removed due to things such as lost filter flow, air compressor failure, serial port buffer overruns, instrument voltage dropping below manufacturer recommended levels, PEMS not operating properly as identified by PEMS technician, and frozen serial data from serial communication errors. The quartz filters for EC mass were sampled on only a few tests, which accounts for most of the blank EC mass values.

After a review of the FRM data, the manufacturer of PEMS 5 was concerned that their data was not representative of instrument design. They concluded that the signal recorded by CE-CERT was in error compared to their duplicate copy of the same signal. PEMS 5 output a volt signal to the CE-CERT for ease of post processing and time alignment. It appears there was a problem with the output signal that made the CE-CERT PEMS 5 data to be in error. PEMS 5 post processed all their own mass integrated numbers and second by second numbers and submitted them back to CE-CERT. After a review and discussion between ARB, the manufacturer and CE-CERT, it was decided to replace the CE-CERT PEMS 5 data by data processed from PEMS 5 manufacture. All figures and tables show PEMS 5 data processed by PEMS 5 manufacture.

Table 5-3. Emissions of Total and EC Mass for PEMS and FRM Tested Over Various Cycles.

	PM g/cycle					
Trace	FRM	PEMS 5	PEMS 7	PEMS 8	PEMS 3	EC
UDDS	3.55	5.65	3.09	5.16	3.14	2.45
UDDS	3.61	6.39	3.08	5.26	3.03	2.55
UDDS	3.77	6.77	3.26	5.54	3.24	
UDDS	3.81	5.86	3.34	5.41	3.24	
UDDS	4.00	6.10	3.48	5.73	3.43	
UDDS	4.07	5.60		5.16	3.02	
UDDS	3.87	5.34		4.99	2.87	
50CRUISE	4.30	6.74	3.53	5.64	4.14	3.08
50CRUISE	4.20	6.45	3.46	5.55	3.82	3.03
50CRUISE	3.98	6.31	3.33	5.32	3.95	2.86
50CRUISE	4.16	6.29	3.38	5.51	3.76	2.84
50CRUISE	4.29	6.30	3.44	5.60	3.87	2.97
50CRUISE	4.95	6.10		5.40	3.66	2.74
50CRUISE	3.42	6.74	3.51	5.60	3.80	2.42
NTE_1290	4.12	6.02			4.18	
NTE_1290	3.44	5.52	2.90	4.88	3.25	2.42
NTE_1500	4.49	6.43			6.26	
NTE_1500				6.52	4.44	
NTE_1770	7.81	8.25		9.69	11.67	
NTE_1770		10.15		10.53	8.28	
NTE_Stepped				6.62	4.76	
NTE_Stepped	5.58	6.23	4.20	7.70		
NTE_Stepped	5.38	6.00	4.18	7.41		
NTE_Stepped	5.75	7.42	4.40	8.33	4.84	3.61
NTE_Stepped	6.59	8.65	5.28	10.42	5.15	
NTE_Stepped	7.52	7.11	6.01	10.35	6.44	

The PM mass emission results are presented in Figure 5-1, with error bars representing 95% confidence intervals for multiple measurements. In comparison with the FRM filter measurements, PEMS 3 and 7 agree within 15% to 25%; and PEMS 5 and 8 were within 10% to 70%.

It should be noted that the NTE cycles generally had a larger standard deviation than the UDDS and 50 mph cruise. The larger standard deviation is partly due to the NTE cycles being performed twice as compared with the seven repeats for the time-velocity traces. The NTE cycles were also not designed as strict speed versus time traces so there can be some variability in how the driver approaches the NTE events with different test iterations. The NTE cycles are included in the analysis since each point has significance for correlation comparisons.

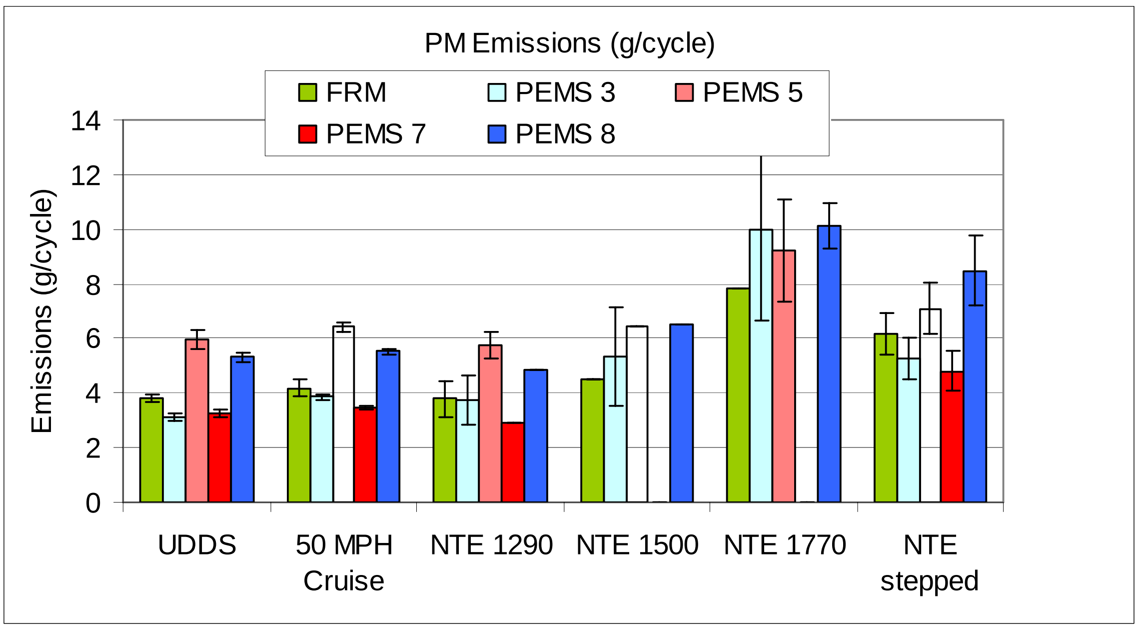


Figure 5-1. Mass Emissions for PEMS 3, 5, 7, 8 and FRM.

The correlation plot between the FRM and the PEMS is provided in Figure 5-2. Looking at the plot, the linear regression for PEMS 3 was closest to the parity line, but showed a correlation coefficient of 0.68. PEMS 3 response was typically 5% to 20% lower then the FRM except for two points that were around 40% higher then the FRM. PEMS 7 results were consistently below the FRM, but showed a high correlation coefficient of 0.95. PEMS 8 also had a high correlation coefficient of 0.9, but was consistently higher then the FRM. The good correlation for PEMS 7 and 8 indicate that the agreement for these instruments might be improved if calibrated against the gravimetric filter weights. PEMS 5 regression coefficient was greater than the FRM and had the lowest correlation of 0.53 compared to the FRM.

There are some sources of systematic error or bias that should be considered when comparing the PEMS and the FRM. Of the PEMS only 8 and the FRM sampled through an inlet classifier prescribed by the 2007 standards. The inlet classifier would remove a small fraction of the total mass (~ 5%) attributed to the particles >2.5µ. As a consequence PEMS 3, 5, and 7 would be biased slightly higher when compared with 8 and the FRM. Another bias results from the filter face temperature. The FRM measures PM with filters at 47 °C where all the PEMS inlets are maintained at near ambient temperatures of 25 °C. Previous studies have shown the PM mass is increased by approximately 11% when the filter face temperature is reduced from 47°C to 25°C. This effect would bias the FRM low as compared to the PEMS. The classifier and temperature biases should have both lowered the FRM mass compared to the PEMS. Only PEMS 8 was consistently higher than the FRM, but the difference was considerably greater than the 15% bias that could have been attributed to the combined classifier and temperature effects. The work suggests that other sources of error need to be investigated.

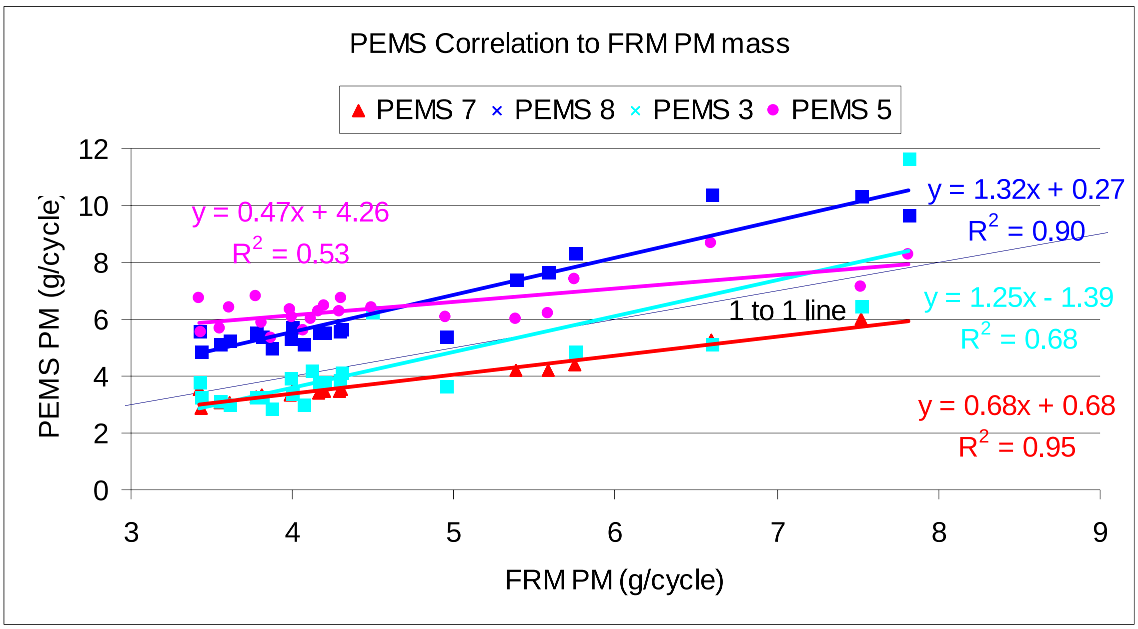


Figure 5-2. Plot of FRM PM Mass Correlation with PEMS PM Mass.

Statistical comparisons of the test cycles results are provided in Appendix L. The statistical analyses included a paired and unpaired t-test and an F-test for comparison of experimental variance. The statistical comparisons for the cycles showed that in all cases the differences between the mass emission rates for the different instruments were statistically significant at greater than a 95% confidence level. The statistical significance of the F-test results differed depending on the specific test iteration and the specific emissions component.

The measurement principles incorporated into the design of PEMS 5, 7, and 8 are such that the instruments are expected to better predict the PM when the EC is a high percentage of the PM mass. The other techniques, including the FRM, are designed to measure the total PM. Based on the data in Table 5-3, the EC represented approximately 80% of the total carbon (TC) mass and did not vary significantly for the different cycles.

For this calculation, the TC mass was determined by the sum of EC and 1.2*OC, the later factor added to account for oxygen, hydrogen and other elements related to the carbonaceous material. The high EC/TC ratio was as expected based on the previous studies that showed a high conversion over a diesel oxidation catalyst such as included on the exhaust system of the test vehicle.

Figure 5-3 shows the EC/TC ratios and a comparison of FRM total and EC masses to the total mass determined by PEMS 5, 7, and 8. From Figure 5-3, the mass measured by PEMS 7 shows a PM mass that was between that of the FRM gravimetric and FRM EC mass while PEMS 5 and 8 was always higher.

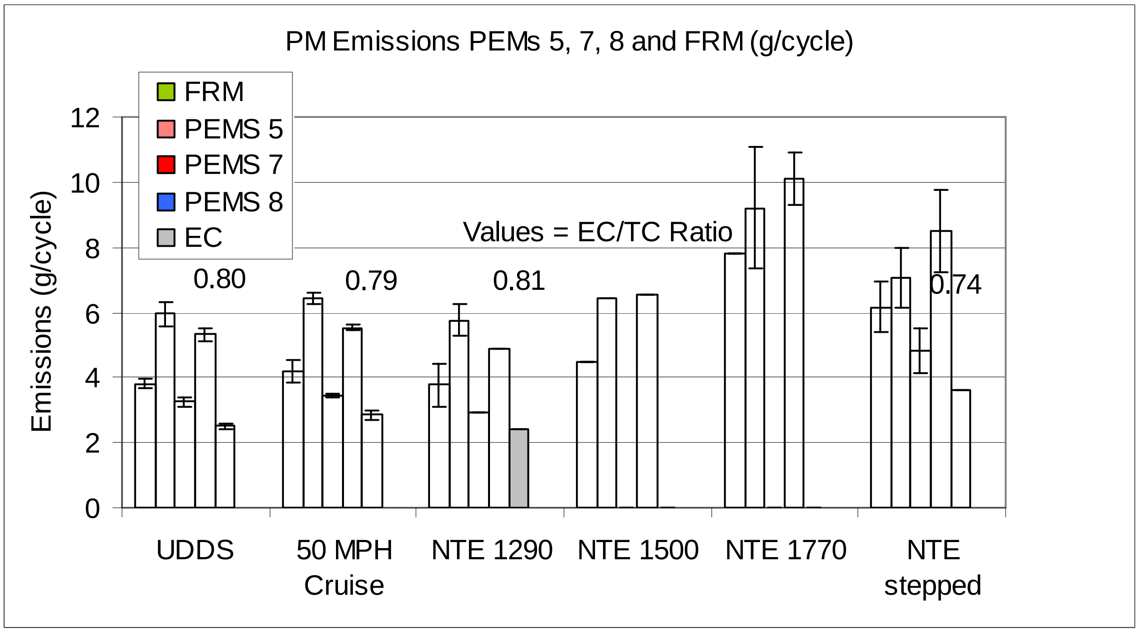


Figure 5-3. PM Mass Emissions for PEMS 5, 7, 8 and FRM. FRM Includes EC mass. Values Represent the EC/TC Average Ratio for Each Cycle.

Figure 5-4 presents the same data as a correlation plot of the EC mass and the total mass measured by PEMS 5, 7, and 8. The correlation coefficient between the EC mass and PEMS 5, 7, and 8 mass was less than the correlation with gravimetric FRM mass. The correlation between EC mass and the FRM gravimetric mass was 0.76. The low correlations could be due to smaller data cluster in the subset of tests where EC measurements were made.

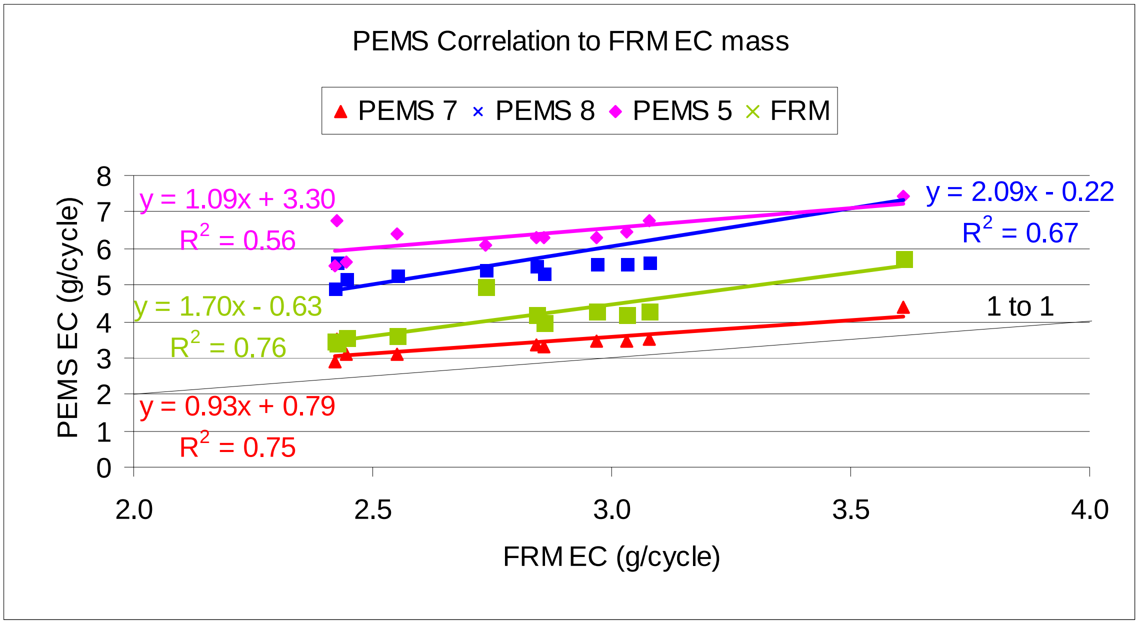


Figure 5-4. PEMS correlation to FRM by PM EC mass.

Figures 5-5 and 5-6 are plots of second-by-second data for one of the NTE steady state cycles and one of the UDDS cycles. These figures represent a significant advance over the current FRM and PEMS 3 that can collect only integrated data and miss the transitions in diesel operation when the air fuel ratio is varied considerably during the driving schedule. A good example of the highly transient nature of real world driving and PM emissions can be viewed during the transitions. Further note that the real-time data shows similarities between the instruments with respect to when peak PM emissions are formed as well as differences in the magnitudes of the PM instruments. Similar trends to the bar charts and correlation plots can be seen in comparison to PEMS 7 where PEMS 5 and 8 were higher. Notice that PEMS 5, 7 and 8 all show relatively the same transient spike with a change in engine torque. Also notice how transient the torque is on the UDDS large hill and all the PM oscillations during this transient torque condition.

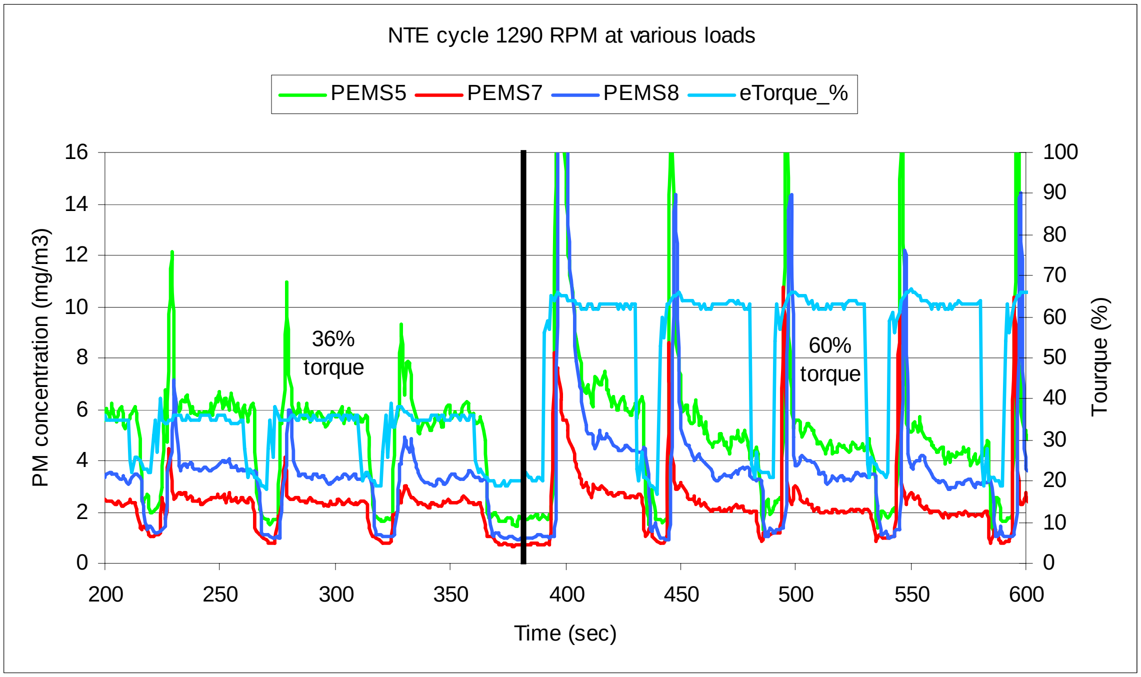


Figure 5-5. Primary Diluted PM Concentration for PEMS 5, 7, and 8 for the NTE 1290 RPM Cycle at 36% and 60% Rated Torque. Note: e-Torque is an ECM Broadcast Measurement.

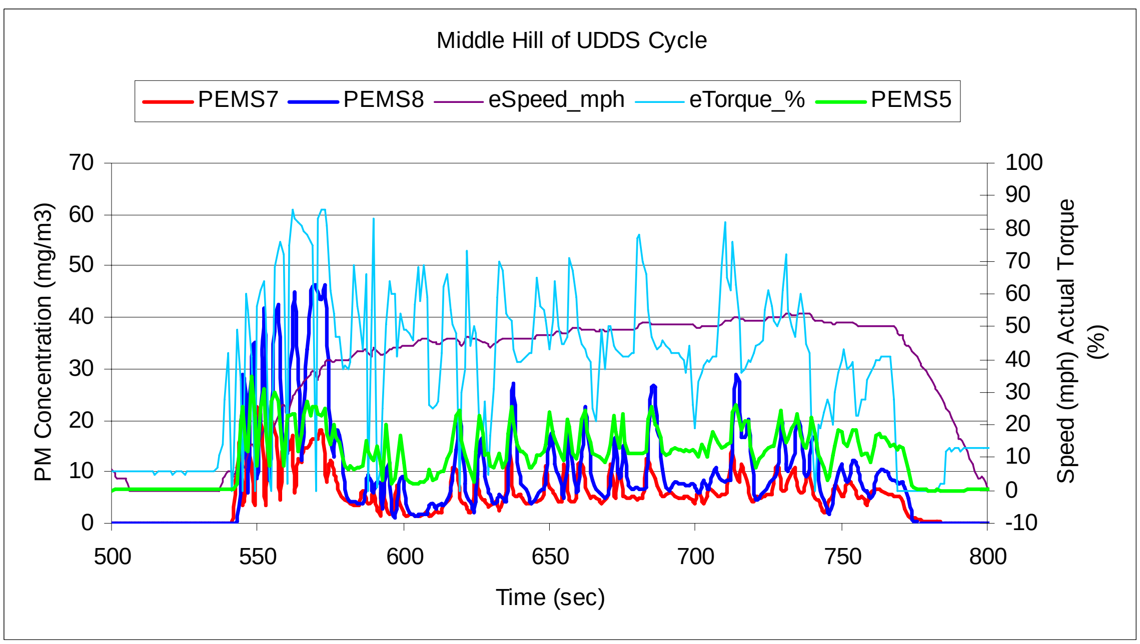


Figure 5-6. Primary Diluted PM Concentration for PEMS 5, 7 and 8 for the Middle Hill of the UDDS Cycle. Note: e-Speed and e-Torque are ECM Broadcast Measurements.

6.0 Discussion of Overall Results

The goal of this project was to provide data on the performance of PEMS as alternatives to EPA reference methods for measuring real-world, on-board, in-use emissions from diesel engines. Comparative measurements were made for the concentrations of audit gases (‘true values”) and emissions from both a stationary source (backup generator) with true steady state engine operation and a mobile source (heavy-duty diesel truck) on a chassis dynamometer with quasi-steady-state and transient engine operation. These measurements were intended to provide quantitative insight concerning the use of PEMS for regulatory applications, such as the Not-To-Exceed (NTE) regulations and emission inventories.

A total of seven PEMS manufacturers were represented in this research program and as one manufacturer provided two instruments, a total of eight instruments were tested. Three instruments measured solely particulate matter (PM), three measured solely gaseous emissions and the last two units measured both PM and gaseous emissions. Several points need to be made. First, the highest priority was establishing the data for the gaseous instruments and second, not all the PEMS systems were used for both the stationary and the mobile source tests.

Manufacturer	**Unit/Model**	**Gases**	**PM**	**Gas/PM**
Artium	Laser Induced Incandescence (LII)		X	
AVL	Photoacoustic Microsoot Sensor		X	
Clean Air Technology	Montana system			X
RPI	DustTrak		X	
Engine, Fuels and Emissions Engineering	RAVEM system			X
Horiba	OBS-1300	X		
Horiba	OBS-2200 (prototype)	X		
Sensors	Semtech D system	X		

Emission Measurement Tests –Stationary Source/Backup Generator

The first phase measured emissions from a diesel backup generator and was intended to represent true steady-state engine operation. Flow rates and emission measurements were measured with four PEMS and compared with the values from the FRMs while the BUG operated at four load points. Results for NO_x showed the deviation range depends strongly on the PEMS and the load. PEMS #2 and #3 show the best agreement with the FRM, ranging from about 1 to 10% of the FRM. Reasons for deviations observed with the other PEMS were discussed in the report. Deviations for THC and PM were quite high suggesting that more development is needed.

Emission Measurement Tests –Mobile Source/Heavy, Heavy-duty Diesel Truck

The second phase measured emissions from a heavy-duty tractor operated on ARB's chassis dynamometer and was intended to represent quasi steady-state and transient engine operation. Flow rates and emissions were measured from a 475 hp Caterpillar C-15 ACERT engine certified to the 2.5 g/bhp-hr NO_x + NMHC and 0.1 g/bhp-hr PM standards with eight PEMS and compared with values from FRMs. Three of the PEMS measured only PM, three PEMS measured only gases and the remaining PEMS measured both gases and PM.

Testing during this phase was carried out following a carefully planned series of quasi steady state and transient driving schedules. These four driving schedules included:

1) Three-mode steady-state NTE test cycle run.
2) Stepped NTE test cycle
3) The Urban Dynamometer Driving Schedule (UDDS)
4) The 50-mph Cruise mode from the ARB 5-mode HHDDT test cycle

While data were collected for four driving schedules the discussion focuses on the emissions results for only the 3-Mode steady state NTE cycle as the results for other cycles were generally comparable. Results depended strongly on the PEMS. For PEMS2 the NO_x emission rates were approximately 3 to 17% higher than those for the FRM in g/bhp-hr units relative to an NTE threshold of 2.0 g/bhp-hr. PEMS 4 showed larger differences compared to the FRM, with percent differences ranging from 26 to 47%.

The CO_2 emissions were used to determine fuel specific (fs) emissions and results indicated that during steady state NTE events, CO_2 emissions for PEMS2 were generally about 5% higher than those of the FRM and PEMS4 values were 9 to 30% higher than those the FRM. Further analysis is offered in the main report.

Emission Measurement Tests –Mobile Source & PM-capable PEMS

One of the most interesting results from the research was the exploratory survey of the commercial PM-capable PEMS applied to a mobile source following transient driving schedules. The strong point of the results was the clarity which the PEMS can follow transitions in a diesel driving schedule and the magnitude of the PM releases while the engine dramatically changes the air/fuel ratio. However, these results must be mitigated with the observation that more work is needed to better understand the mismatch between the total mass measured by the FRM and PEMS when integrated over a number of cycles.

Next Steps

The original scope for this project included four main emissions testing tasks: 1) backup generator testing of all participating PEMS, 2) heavy-duty truck chassis dynamometer testing of all participating PEMS, 3) On-vehicle, over-the-road testing of all participating PEMS using pre-selected test routes, and 4) on-board, over-the-road testing of "the most suitable" PEMS under conditions meant to mimic the actual in-use compliance program (i.e., real vehicles in actual revenue service). However, since this project began, the ARB, US EPA and heavy-duty engine companies (as represented by the Engine Manufacturers Association) agreed to a measurement allowance program to determine exactly what numerical values should be assigned, as referenced in the Memorandum of Agreement (MoA) signed by the above parties in June, 2005. The original scope of this project is being revised so that the resources originally allocated for this project can reallocated to support this measurement allowance program. The measurement allowance program will be examining topics and issues similar to those studied in this project - how PEMS compare against the reference methods, but will do so in a more focused and extensive manner. Specifically, all factors expected or suspected to influence PEMS emissions measurements such as vibration, ambient conditions (such as changes and variations in pressure, temperature. and humidity, ambient background HC concentrations), radio frequency and electromagnetic interference, etc. will be studied with the goal of developing actual, pollutant-specific, numerical measurement allowances for NO_x, THC, and CO. In addition, the measurement allowance program will also quantify variability between engine dynamometer measurements of engine torque and speed. The current project scope is being revised to support this measurement allowance program. Specifically, CE-CERT will: 1) perform a Code of Federal Regulations Part 1065 audit of the CE-CERT mobile emissions laboratory, 2) perform side-by-side testing at SwRI, and 3) perform a validation of the Monte Carlo model used to develop the measurement allowance by collecting over-the-road emissions data using the MEL.

7.0 Conclusions and Recommendations

This project was borne out a need to identify the accuracy and precision of PEMS as such systems were being used to accumulate in-use data on emissions from buses, trucks and locomotives and other equipment for inventory purposes. Furthermore, new regulations requiring on-board, in-use measurement and compliance with the NTE rules were being issued and these parties also needed the information on accuracy and precision. Finally there is the realization that the measurement from large fixed laboratories and PEMS are both needed to advance and improve data used for preparing SIPs. Thus a broad stakeholder group was easily formed to serve as advisers for the research on a project destined to help improve the understanding of the comparative performance of traditional FRMs with PEMS.

An important perspective when viewing these findings is that PEMS are evolving products that use a wide range of different measurement principles and operating practices. Thus as expected, different PEMS show varying degrees of agreement with standard products and practices specified for FRMs; for example, a NO_x analyzer, whose specifications and operation are outlines in great detail in the CFR. Further, the results from this program represent the best equipment and best operator. Thus it is best to state that results from this research represent a snapshot in time since the technology and capability of PEMS will continue to evolve as the product moves towards standardization.

Given these caveats, a number of conclusions can be reached based on the results of this study:

- Measured flow rates were in good agreement with the FRM, except for one PEMS unit with a failed part. One of the more creative approaches PEMS#1 who calculated the flow rate based on engine operation and gas law principles. Their results best matched the FRM for the stationary source.

- For NO_x emissions, the best performing PEMS unit was within 5-10% of the FRM. This represented 5-25% of the 2.0 g/bhp-hr NO_x standard depending on the specific test and operating condition. The other PEMS showed larger differences for NO_x with some showing significantly larger deviations from FRM.

- For CO_2 emissions, the best performing PEMS were able to measure within 5% of the FRM. In some cases, considerably larger deviations were found in CO_2 when there were errors in the measurement of exhaust flow rate, calibration or software.

- On an absolute basis, THC emissions showed considerably larger deviation than other emissions components due to the low concentrations of THC emissions. From an NTE perspective, the deviations between the PEMS and FRM were less than 5% of the NTE threshold standard for THC for the chassis dynamometer testing, with larger deviations seen for the stationary source tests. Results suggest that additional development is needed for accurate in-use THC emission values.

- The deviations between the PEMS and FRM varied for CO. One PEMS was within 5% of the FRM during the stationary source testing. For most other test scenarios, the differences between the FRM and PEMS ranged from 10-50% or higher. From an NTE perspective, the deviations represented less than 2% of the NTE CO threshold for nearly all test conditions. Additional accuracy may be needed to obtain in-use emissions measurements for CO for use in emissions inventories.

- A wide range of exciting new technologies were investigated for measuring PM-capable PEMS. Several of the instruments based their design on elemental carbon. As such, not all instruments were directly comparable with the FRM PM mass. The best PEMS for measuring PM were within 15-25% of the PM mass emissions measured by the FRM, with considerably larger deviations seem for some other instruments. It is expected that further development of PM PEMS will be needed to meet the regulatory challenges of measuring the low PM levels that will be found for engines equipped with after treatment devices.

- Results suggest that more comprehensive QA/QC procedures for in-field operation are needed to ensure reliable operation from a range of PEMS instruments. In the present program, issues such as problems measuring calibration gases were identified, suggesting the need for improved procedures for in-field units.

Recommendations

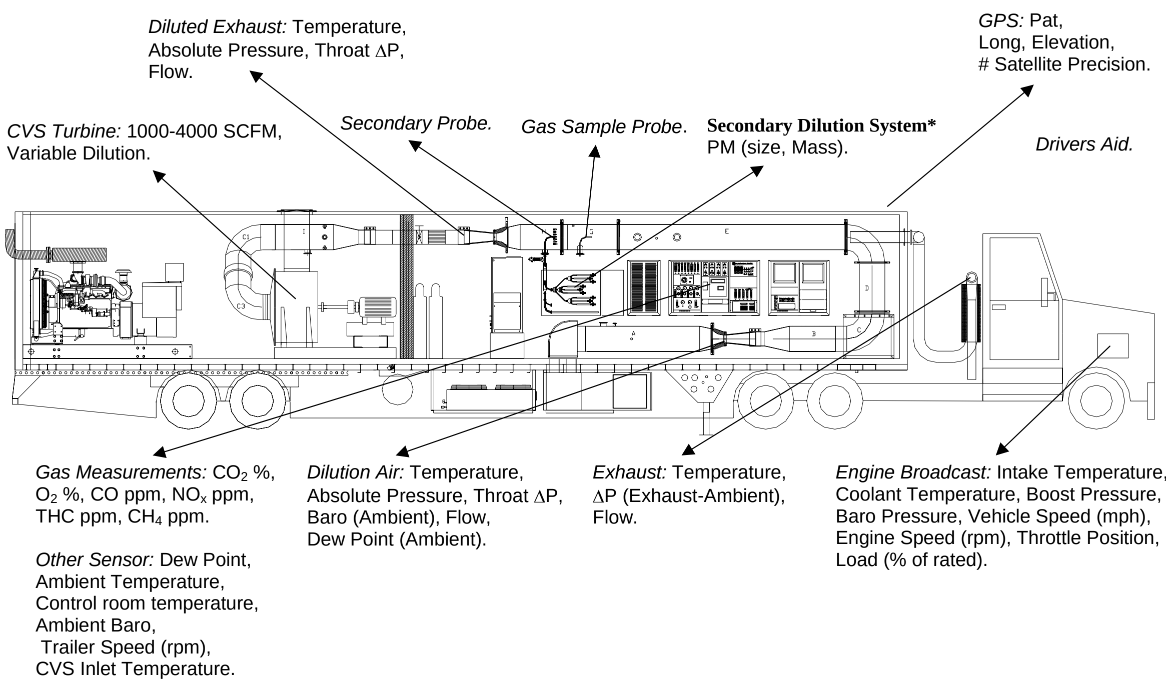
The results of this research show that of the four gaseous PEMS that PEMS2 compared better with the FRM for NO_x and CO_2 than other units. An exploratory trial of PM-capable PEMS showed great promise for real-time PM measurements but more development is needed. The following recommendations are made based on the observations in this research:

- More attention is needed to establish detailed use protocols and performance limits as specified for a CFR method. For example, the CFR specifies a particular type of analyzer for NO_x as well as the specifications.
- Even the best PEMS with an experienced operator had problems so PEMS require experienced operators.
- It is suggested that more frequent calibrations are needed to establish confidence intervals and ensure reliable operation of the PEMS during sampling in the field.
- For the best progress, measurement programs must be collaborative in design and analysis between the PEMS manufacturer, ARB, EPA, EMA and the contract lab making measurements.

Looking ahead, we expect PEMS confidence limits to improve from that observed in this research as a result of the ARB/EPA/EMA's Measurement Allowance Program.

Appendix A – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in Reference 2; so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.



Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600kW. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH4	30/100/300/1000 (ppmC)	FID

Summary of gas-phase instrumentation in MEL

Quality Assurance and Quality Control Requirements

Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL staff as part of the data quality assurance/quality control program is listed in the table below. The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1 %, are obtained from Scott-Marrin Inc. (Riverside, CA). By using precision blending, the number of calibration gas cylinders in the lab was reduced to 5 and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) and produces the required calibration gas concentrations within the required ± 1.5 percent accuracy.

In addition to weekly propane recovery checks which yield >98% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield >98% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling bias.

An example shown below is for propane mass injected into the exhaust transfer line while sampling from raw and dilute ports (three repeats) to evaluate exhaust flow measurement on steady state basis (duration = 60 sec, Date completed January 2005).

Tests	Raw C3H8 g	Dil C3H8 g	CVS DF	Raw C3H8 est	Diff
1	2522	608	4.11	2499	-0.9%
2	2485	598	4.10	2454	-1.2%
3	2462	601	4.13	2484	0.9%
ave	2490	602	4.12	2479	-0.4%
stdev	30	5	0.01	23	
COV	1.2%	0.8%	0.3%	0.9%	

Recent example of propane quality control check

EQUIPMENT	FREQUENCY	**VERIFICATION PERFORMED**	**CALIBRATION PERFORMED**
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ±5 inH_20	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test		Zero Span
	Daily	Zero span drifts	
	Monthly	Linearity Check	
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Tunnel Banks	
	Monthly	Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Sample of Verification and Calibration Quality Control Activities

Appendix B – Descriptions of PEMS Instruments

PEMS1 – CATI Montana System

1. The CATI OEM 2100 PEMS measures second-by-second mass emissions from vehicle tailpipes with electronically controlled sparked ignition and compression ignition engines. The unit provides HC, CO, CO2, NOx and O2 readings for gasoline-powered vehicles and NOx, CO, CO2, O2, PM readings for diesel vehicles.

The unit provides second by second emissions, fuel consumption, vehicle speed, engine rpm and temperature, throttle position, and other parameters.

The CATI PEMS includes: Touch-screen computer (256MB RAM, USB, Serial, Parallel, Network Ports) · Dual Gas Analyzer -HC (gasoline only), NOx, CO, CO2, O2 · Light-Duty Engine Scanner · Heavy-Duty Engine Scanner · Sensor Array (for non-electronically controlled vehicles) · Particulate Matter (PM) Monitor (diesel only);· Weatherproof Case · Keyboard · Back-up Battery.

The unit is weighs 44lbs. The system uses power directly from a vehicle's 12V or 24V electrical system, consuming 8 A at 12V DC, or can be powered by AC in the case of stationary testing.
Engine data can be sensed directly using an array of analytical sensors. This method involves attaching several analog sensors to the engine itself.

For vehicles with a supported computer diagnostic port, engine and vehicle data is acquired using this interface. The unit is equipped with ECU scanners that will communicate with the ECU and obtain any needed engine parameters. The two most common engine scanners that can be incorporated are the heavy duty scanner and a light duty scanner.

The diagnostic port interface cable is routed directly to the unit from the port connector. For sensor array installations, sensors are installed on the applicable engine systems and are then routed to the unit.

2. Instrument Range

The concentrations of HC, CO, CO_2, O_2, NO_x and PM in the exhaust gas are determined by following methods and have the following ranges:

- Non-Dispersive Infrared (NDIR) analyzer for hydrocarbon (HC), carbon monoxide (CO) and carbon dioxide (CO_2) measurement of 0 – 2000 ppm hexane (C_6) with an accuracy of ±4 ppm abs. or ±3 % rel., 0 – 10.00 % CO with an accuracy of ±0.02 % abs. or ±3 % rel., and 0 – 16.00 % CO_2 with an accuracy of ±0.3 % abs. or ±3 % rel.

- Electrochemical sensors for oxides of nitrogen (NO_x) and oxygen (O_2) measurement of 0 – 4000 ppm NO with an accuracy of ±25 ppm abs. or ±4 % rel. and 0- 25.00 % O_2 with an accuracy of ±0.1 % abs. or ±3 % rel.
- Particulate matter (PM) concentration is measured using laser light scattering.

The PM range is from ambient levels to low double digit opacity levels. The accuracy of PM measurement has not be quantified at this point. Response is dependent on size and composition of the particles. As a result, there may be a systematic measurement bias associated with each individual vehicle. This bias is minimized by the use of virtual impactors which eliminate course mode particles (1-2 microns). The sampling system allows for small nuclei-mode particles (< 100 mm) to conglomerate or condense onto soot particles. This narrows the particle size distribution, allowing for a more accurate conversion of the reading to particulate mass concentration and PM mass emissions

3. The CATI PEMS measures ppm/second emission data. Theoretical exhaust flow is calculated using engine parameters read from the vehicle's engine control unit or the sensor array. Emission results are calculated by combining the theoretical exhaust flow and the collected ppm/second emission data. Results are reported in grams/second format.

From the intake air mass flow, known composition of intake air, measured composition of exhaust, and user supplied composition of fuel, a second by second exhaust mass flow is calculated. This calculation is proprietary, but involves a mass balance equation, whereby matter coming into the engine must equal that matter coming out of the engine. Multiplying the exhaust mass flow by the concentrations of different pollutants yields grams per second emission data.

Engine power output can be estimated based on ECU torque readings and/or using the fuel consumption and engine rpm data, and the manufacturer's *brake specific* fuel consumption charts. All measured pollutants can then be calculated on a *brake specific* basis. This information can be used for NTE analysis.

PEMS2 – Semtech D

SEMTECH-D is a complete, fully integrated portable emissions measurement system (PEMS) for testing all classes of diesel-powered vehicles and equipment under real-world operating conditions. SEMTECH-D measures diesel emissions at the tailpipe, engine-out, or at any stage of after-treatment. A data logger records the vehicle emissions, environmental conditions, and the output of a vehicle's on-board electronic control system to compact flash removable storage while the vehicle is in operation. The optional exhaust mass flowmeter and GPS are also fully integrated with the SEMTECH-D data logger and post-processing software. Engine and vehicle-related parameters are combined with gaseous emissions on a real-time basis to determine in-use emissions levels in g/sec, g/g-fuel, g/Bhp-hr, and g/mile. Not to Exceed (NTE) vehicle operation and emissions results are also determined on a real-time basis. Test results can also be viewed subsequently with the user-configurable post-processor application.

Access to the central processor is provided through LabView™ PC host software. The user interface is designed to provide immediate feedback to the user. There are over 150 different fault codes that the SEMTECH will automatically report to the user if a problem occurs. In addition, there are 24 warning codes that will also automatically be reported when potential problems exist. They indicate to the user when to change filters, when to change the FID fuel bottle, when to zero the instrument. In addition, many of the routine tasks that are required to operate the system are fully automated, requiring minimal effort for the user.

The SEMTECH-D system comprises of eight individual analyzers, all integrated into a single package and controlled from a central processor/data logger. The following table describes the subcomponents and system features.

SEMTECH-D Subsystem	Specifications
Sample Line & Filter	Heated (191 ^{o}C)
THC	Heated FID (191 ^{o}C), Wet sample measurement, autoranging, max 4 Hz data rate
NO_2	NDUV resonant absorption spectroscopy
NO	NDUV resonant absorption spectroscopy
CO and CO_2	CO and CO2 through NDIR spectroscopy
O_2	Electrochemical Cell
Methane	Unheated FID with cutter, external to SEMTECH
Exhaust flow rate and temperature	Sensors Exhaust Flow Meter (averaging Pitot tube)
Vehicle speed and position	Garmin 16-HVS GPS, WAAS supported
Ambient temperature, relative humidity, barometric pressure	Vaisla remote temperature and humidity monitor; on-board barometric pressure sensor, max 4 Hz data rate
Vehicle Interface (VI) Protocols	Heavy-Duty: SAE-J1708, SAE-J1939 Light-Duty: SAE-J1850 VPW, SAE-J1850 PWM, ISO-9141-2, ISO-14230-4, ISO-11898, ISO-15765
Engine torque	VI (if available from equipment's CAN/ECM)
Engine RPM	VI (if available from equipment's CAN/ECM), or through use of an optical tachometer probe on mechanically-controlled equipment
Air-fuel ratio	Determined per ISO 16183 carbon balance method
Size	14"H x 17"W x 22"D
Weight	approximately 75 lbs
Communications	Wired and wireless Ethernet, 8.0211g
Host Software	Sensor Tech suite using Labview™
Analog output	8-channels, 0 – 5V

SEMTECH-D Subsystem	Specifications
Analog input	3-channels, ±5V, ±10V, ±10V with programmable transform functions
Digital input	2-channel
Digital output	1-channel
Data Storage	Up to 1 Gb Compact Flash cards. Adequate to hold one full week of data.
Data rate	Configurable 1 – 4 Hz for most channels

PEMS3 – RAVEM System

The Ride-Along Vehicle Emissions Measurement (RAVEM) is capable of measuring PM as well as NOx, CO, and CO_2. Optional capabilities also allow the measurement and quantification of total hydrocarbons (THC), sulfur dioxide (SO_2), ammonia (NH_3), and nitrous oxide (N_2O), as well as individual species of volatile organic compounds (VOC) and carbonyls such as formaldehyde, acetaldehyde, and acrolein.

Principals of Operation

The RAVEM system is described in two published papers (1,2). As Reference **Error! Bookmark not defined.** explains in more detail, the RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the air dilution and total flow arrangements are such that the pollutant *concentration* in the CVS dilution tunnel is proportional to the pollutant *mass flow rate* in the vehicle exhaust.

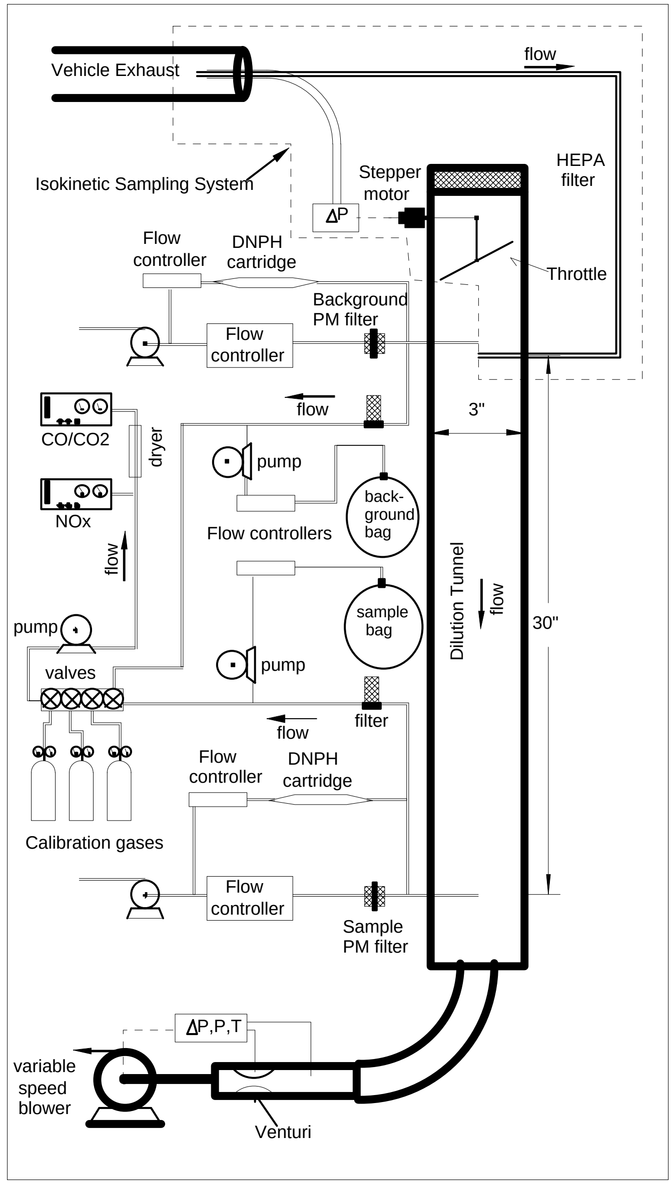
The total pollutant mass emissions over a given driving cycle are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone. The CVS flow rate enters into the calculation as a constant multiplier. The integration of pollutant concentration can be accomplished either numerically or physically. For gases, the RAVEM system uses both numerical and physical integration. Concentrations of NOx, CO_2, and CO in the dilute exhaust gas are measured and recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in Tedlar® bags during the test, and analyzed afterward for NOx, CO_2, CO and (optionally) other pollutants.

In CVS sampling for particulate matter, sample integration is accomplished physically -- by passing dilute exhaust mixture through a pre-weighed filter at a constant, controlled flow rate. The weight gain by the filter is then divided by the volume of mixture passed through it to yield the average particulate concentration over the test cycle.

A schematic diagram of the RAVEM system is shown below. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

Conventional emission laboratory methods defined by the U.S. EPA (4) and California ARB (5) utilize full-flow CVS, in which the entire exhaust flow is extracted and diluted with air. However, the large amounts of dilution air required make full-flow CVS impractical for portable systems.

The principle of the RAVEM sampling system is as follows: the RAVEM's sampling system extracts and dilutes only a small, constant fraction of the total exhaust flow. The dilution air requirements and dilution tunnel size can thus be reduced to levels compatible with portable operation. The patented isokinetic proportional sampling system[5] continuously adjusts the sample flow rate so that the flow velocity in the sample probe is equal to that of the surrounding exhaust. Since the velocities are equal ("isokinetic"), the ratio of the flow rates in the exhaust pipe and the sample probe is equal to the ratio of their cross-sectional areas.



Pollutant concentration measurements in the RAVEM system follow the methods specified by the U.S. EPA (US CFR Vol 40 Part 86) and ISO standard 8178. The pollutants measured are:

- Oxides of Nitrogen (NOx) by chemilumenescent analysis of the dilute exhaust sample. The zero-100 ppm range is normally used, but ranges from 0-10 to 0-3000 ppm are available;
- Carbon monoxide (CO) and carbon dioxide (CO_2) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample. The 0-200 ppm range is normally used for CO, but a 0-500 ppm range is available. For CO_2, the 0-6000 ppm range is normally used, 0-2000 and 0-10,000 ppm ranges are also available;
- Particulate matter (PM) is measured by passing the dilute exhaust sample through pre-weighed 47 mm filters of Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing. The minimum detectable PM filter mass is approximately 10 micrograms, the maximum practical mass on the filter is more than 3000 micrograms. Filter and CVS flow rates can also be adjusted to increase PM sensitivity or avoid PM overloading.

References

[1] C.S. Weaver and L.E. Petty “Reproducibility and Accuracy of On-Board Emission Measurements Using the RAVEM™ System “, SAE Paper No. 2004-01-0965, March, 2004.

[2] Weaver, C.S. and M.V. Balam-Almanza, “Development of the ‘RAVEM’ Ride-Along Vehicle Emission Measurement System for Gaseous and Particulate Emissions”, SAE Paper No. 2001-01-3644.

[3] 40 CFR 86, Subpart N “Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures”

[4] "California Exhaust Emission Standards and Test Procedures for 1985 and Subsequent Model Heavy-Duty Diesel Engines and Vehicles" as amended on February 26, 1999, California Air Resources Board

[5] U.S. Patent No. 6,062,092. "System for Extracting Samples from a Stream", May 16, 2000.

PEMS4 – Horiba OBS-2200

The HORIBA OBS-2200 is an on-board emission measurement system capable of analyzing vehicle emissions during in-use operation. The OBS 2200 consists of vibration-proof gas analyzers, a laptop PC with software for system controlling and data logging, accessory sensors, and a Pitot tube tailpipe flowmeter. All gases are analyzed wet, without drying. CO, CO_2 and water vapor concentrations are measured by a heated NDIR analyzer. The water measurement compensates for water vapor interferences. THC concentrations are measured by a heated FID analyzer (190ºC), and NOx concentrations are similarly measured by a heated CLD analyzer. The PC data logging software saves analyzer data, OBD ECU data, GPS data, tailpipe flow, and other external signals, as well as outputs from accessory sensors. The software provides time-trend profiles and integrated values for both mass emissions and fuel consumption. Software identifies NTE events and reports results.

Software Calculations:

The following data can be displayed in real time and logged to file:

- Concentration of CO, CO_2, THC, and NOx;
- Exh. flow rate [m^3/min]; Exh. temp. [ºC]; Exh. press. [kPa]
- Amb. temp. [ºC]; Atm. press. [kPa]; Amb. humidity (relative humidity) [%]
- GPS velocity [km/h]; Altitude [m]; Position (latitude/ longitude)
- External inputs (optional)
- OBD inputs (optional)

The following items can be calculated and displayed in real time and logged to file using input data:

- Mass emission of CO, CO_2, THC, and NOx [g/s, g/h]
- Fuel consumption [g/s]; Fuel economy [km/L, mile/L, L/100km, g/kWh or g/bhph]
- A/F (calculated by carbon balance method)
- Power [kW] (calculated from engine speed and torque/%torque)

Setting values to be used in calculation are as follows:

- Time alignment delay of CO, CO_2, THC, NOx analyzer response, (Time aligned with exhaust flow rate)
- H/C, O/C and density of fuel
- H/C ratio of hydrocarbon in exhaust emission

The following Calculated Data (as integrated values) can be calculated, displayed, and logged to file using input data:

- Mass emission of CO, CO_2, THC and NOx [g]
- Fuel consumption [g]; Fuel economy [km/L, g/mile, L/100km, g/kWh or g/bhph]
- Running distance [km]
- Work [kWh]

A Maximum of 8 items from the following list can be displayed in real time in chart/graphical format:

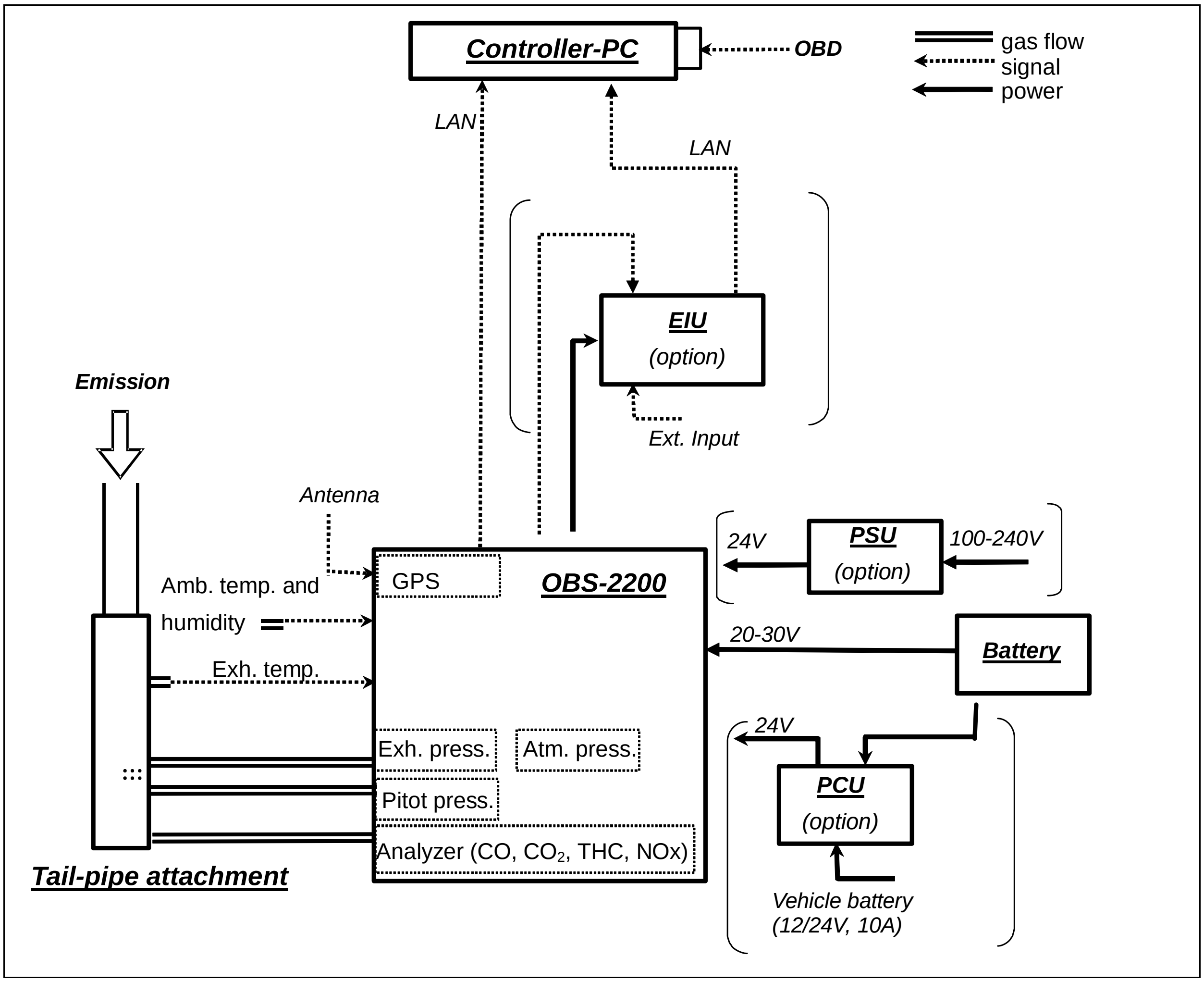
- Concentration of CO, CO_2, THC, and NOx
- Exh. flow rate [L/min]; Exh. temp. [ºC]; Exh. press. [kPa]
- Amb. temp. [ºC]; Atm. press. [kPa]; Amb. humidity (relative humidity)[%]
- GPS velocity [km/h]
- AFR (calculated value)
- External inputs (optional)

- OBD inputs (optional)

OBS-2200 EMISSIONS MEASUREMENT SYSTEM

	COMPONENTS	ANALYZER/INPUT	RANGE
Measuring components / Input signals	CO	HNDIR (wet)	0-0.5 to 0-10 vol%
	CO_2	HNDIR (wet)	0-5 to 0-20 vol%
	THC	HFID (wet)	0-100 to 0-10,000 ppmC
	NOx	HCLD (wet)	0-100 to 0-3,000 ppmC
	Exhaust flow	Pitot flow meter	8 Ranges available, 0-2.0 to 0-65 m^3/min
	Standard input	From accessory sensors	Exhaust pressure 0-115 kPa Exhaust temperature 0-800 deg. C Atmos. Pressure 0-115 kPa Ambient Temp. -40 to 85 deg.C. Ambient Humidity 0-100%RH GPS longitude, latitude, altitude, velocity
	External input	Max. 16 channels (optional)	Standard: 8 Analog: 0-10 VDC 2 Type J Thermocouple 2 Type K Thermocouple Optional modules: Analog 0-1 to 0-10 VDC RTD - PT100 Thermocouple – J/K Frequency - 0.1 to 100 kHz
	OBD data	Max. 16 items (optional)	J1939 or J1708/J1587
System specification	Power supply	20 to 30 V DC	PCU: optional power control to draw limited power from vehicle PSU: optional power converter for AC voltage inputs
	Power consumption (at stable state)	Approx. 0.5 kW	
	Dimension	Approx. 350 (W) x 330 (H) x 500 (D) mm	
	Mass	Approx. 29 kg	Main unit only
	Recommended Battery	Deep cycle battery, 24 V DC, 100 Ah (5 h rate), approx. 64 kg	
Application	Diesel vehicles	√	
	Gasoline, LPG and CNG vehicles	√	
	CFR 1065 subpart J Conformity	√	July 2005 amendment

OBS 2200 SYSTEM CONFIGURATION



PEMS5 The Artium Technologies, Inc. *LII 200*

The Artium Technologies, Inc. *LII 200* instrument used in these investigations consisted of a self-contained rugged optics enclosure which includes the laser and all components needed for operation of the instrument. The optical system consists of a computer-controlled automated laser beam energy generation, detection and adjustment system that maintains the laser light fluence at the sampling volume at optimum conditions. Optics are provided to transform the laser beam intensity into a near top-hat light intensity profile which facilitates uniform heating of the soot in the probe volume. Laser-induced incandescence (LII) employs a high-energy pulsed laser beam to rapidly (10 to 20 nanoseconds) heat the soot particles from the local ambient temperature to below 4000 K as they flow through the sample cell. The laser heating is independent of particle size, and the emitted light is nominally volumetric. Thermal emission, i.e., incandescence, from the particles is then recorded, using collection optics and photodetectors, as the particles slowly (1 to 2 microseconds) cool to the ambient temperature. Using appropriate calibration and analysis of the incandescence signal, the particle volume fraction and active surface area/primary particle diameter are estimated, where the former is obtained from the amplitude of the signal and the latter from the signals' rate of decay. The laser is typically pulsed at 20 Hz and a measurement is obtained for each laser pulse.

Prior to making measurements, calibration measurements are made using a known traceable radiance source at a known temperature, which provides calibration factors to relate the measured signals to absolute intensities. Auto-compensating LII (AC-LII), which is incorporated into the Artium LII 200, is based upon measurements of the particulate surface temperature determined by optical pyrometry. Incandescence at two or more independent wavelengths, λ, is recorded, and an average soot particle surface temperature in the probe volume is calculated by using the ratio of the observed signals (corrected for detection sensitivity) and the known soot particle absorption cross sections. This has the added advantage of permitting the laser light heating of the soot to be kept below the sublimation (vaporization) temperature so no significant soot volume is lost as a result of the measurement.

Soot (elemental carbon based particles emitted from combustion sources) absorbs and emits light predominantly on the scale of the primary particles. LII measurements are insensitive to liquid particles, because they absorb a negligible amount of laser energy compared to carbon and do not produce any incandescence signal. For carbon particles coated with volatile material, the latter will vaporize very early in the LII laser-heating period and AC-LII automatically compensates for the energy lost to evaporating the volatile fraction by measuring the particle temperature in real time, such that the measure of the soot particle is not affected. In general, it is reasonable to state that LII measures the volume fraction of solid carbonaceous material in the exhaust. Other constituents may include trace metals and ash. Although trace metals may contribute to the incandescence if they survive the peak temperatures, their concentration is typically so low that the contribution will be negligible.

The LII instrument measures the soot volume fraction (SVF) that is a volume concentration. The additional measurement of the exhaust flow rate leads to the time-integrated emissions results.

Measurement Range:

Using a density for soot of 1.9 g/cm^3, we have demonstrated a mass concentration minimum detection level of 10 μg/std m^3 and a maximum mass concentration level of 10 g/std m^3. This system can be extended to reach a minimum detection level of 1 μg/std m^3. These results can be obtained at the exhaust exit since dilution and conditioning of the exhaust are not needed when using LII. In these investigations the LII sample was drawn from the CVS dilution tunnel.

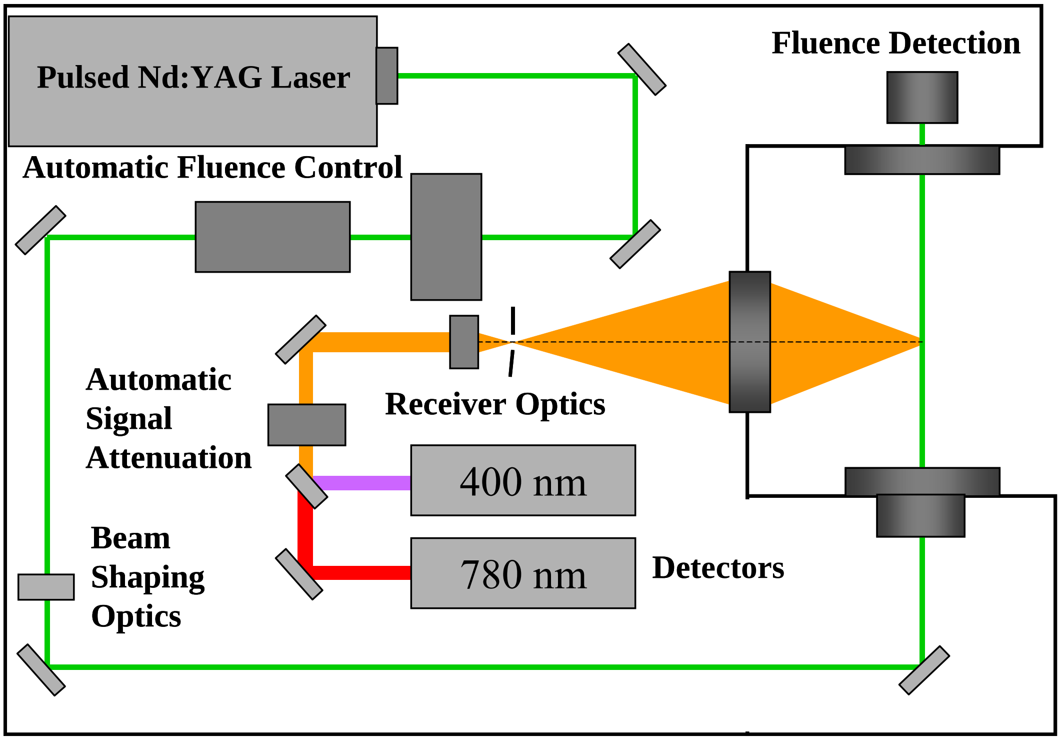
Transient measurements for a range of 2000:1 have been demonstrated to date. Using the LII 200 dynamic PMT (photomultiplier tube detectors) gain control, the instrument can reach 10,000:1. Larger measurement loading ranges requires a change of optical filters in the system which is done automatically when the software logic senses that it is required. This typically requires 0.5 to 2 seconds. It does not require operator intervention to do this. The instrument range is 10,000,000:1 but this cannot be achieved for a single transient that is shorter than the 0.5 to 2 seconds time specified because of the need to change the filters. A range of 2000:1 in concentration can be achieved on a measurement to measurement basis at 20 Hz.

Primary particle diameters of 5 nm to 100 nm have been measured with the LII 200, and do not represent the limits of the instrument.

Emissions Measurements:

The cycle integrated soot mass emissions were calculated as follows:

1. The 20 Hz LII soot volume fraction (SVF) data was multiplied by the density of soot (1.9 g/cm^3), to provide a 20 Hz mass concentration of soot in the exhaust.
2. A 20 point average of the 20 Hz mass concentration data was calculated, to provide a 1 Hz mass concentration data rate.
3. The 1 Hz mass concentration data was multiplied by the CVS flow rate on a second by second basis to determine the total mass flux of soot particulates from the engine, again on a 1 Hz basis.
4. The 1 Hz mass flux of soot emitted by the engine was integrated over the relevant portion of driving cycle (relevant times provided by CE-CERT) to produce an integrated mass of soot particulates over the test cycle.



Schematic of the LII 200 Optical system

PEMS7 – AVL 483 Micro Soot Sensor

PRODUCT INFORMATION

Emissions Test Instruments

AVL 483
Micro Soot Sensor
&
Conditioning Unit

Continuously Measurement of Soot Concentration

The AVL 483 Micro Soot Sensor (Photo Acoustic Soot Sensor PASS) is a system for continuous measurement of lowest soot concentration in diluted exhaust from IC engines. The device is sensitive for soot. In contrast to an Opacimeter the soot concentration will be determined directly from primary measurement quantity.
The AVL 483 Micro Soot Sensor works works on a photo-acoustic principle and the cell design we have chosen (called the "resonant measuring cell") allows a detection limit of typically ~ 5 µg/m³.

With the additional option "Conditioning Unit" measurements upstream a Diesel Particulate Filter (DPF) are also possible to evaluate e.g. the efficiency of the DPF.

Your benefits at a glance

- Transient measurement of soot concentration [mg/m³]
- Sensitive to soot (no interference to other components)
- Soot concentration determined directly from primary measurement quantity
- High sensitivity (resolution 1µg/m³, detection limit typically ~ 5µg/m³)
- High measuring range (0 – 50 mg/m³)
- Simple calibration
- Low maintenance effort
- Measurements upstream and downstream of DPF
  (back pressures up to 2000 mbar, temperatures up to 1000°C)

Application:

- For Diesel- and Gasoline Engines
- On Engine – and Chassis dyno testbeds (directly from CVS tunnel or with option Conditioning Unit)
- Measurement upstream and downstream of particulate filters
- Research & Development
- With Conditioning Unit also applicable for „On board measurement"

Last Update: 20.04.2006

PRODUCT INFORMATION

AVL 483 Micro Soot Sensor

Specifications:

Measuring Unit	
Measured value:	Concentration of soot (mg/m^3, $\mu g/m^3$) in the diluted exhaust gas
Measuring range:	0 – 50 mg/m^3
Display resolution:	0,001 mg/m^3
Detection limit:	~ 5 $\mu g/m^3$
Turndown ratio:	1 : 5.000
Data rate:	Digital: 10Hz Analog: 100 Hz
Rise time:	$\leq$ 1 sec
Operation temperature:	5°C to 43°C
Probe / Bypass flow:	~ 2 + 2 l/min
Interfaces:	RS232, Digital I/O, Analog I/O, Ethernet
Laser class:	Class 1 laser product
CONDITIONING UNIT	
Dilution ratio (DR) :	Adjustable from 2 – 10 and from 10 - 20 The actual DR will be displayed with the accuracy noted below.
Data rate:	Digital: max. 5 Hz Analog: 50 Hz
Accuracy (DR display):	Max. +/- 3% in the range of DR [2..10] , max. +/- 10% in the range of DR [10..20]
Power supply :	90...230V, 50/60Hz
Pressurized air:	Input pressure 1±0,2bar over pressure Flow: > 4l/min
Exhaust gas temperature :	Up to 1000°C
Exhaust gas back pressure (intermediate pressure)	Up to 2000 mbar
Pressure pulsation :	± 1000 mbar, but max. 50% of exhaust gas back pressure (intermediate pressure)
Blow by amount	Dep. on pressure, ~ 20 l/min at 1000 mbar
Power supply:	90...240 V AC, 50/60Hz, 500VA
Unit dimensions	Measuring unit: W x H x D ~ 19" x 5HE x 530 mm
	Conditioning unit: W x H x D ~ 19" x 4HE x 530 mm
Unit weight:	Measuring unit: ~ 20 kg
	Conditioning unit: ~ 12 kg

Calculating the emission when a diluter with a known, constant or slightly varying dilution ratio is used.

For these calculations, *the time-resolved exhaust gas mass flow q_{mew} in [kg/h] must be known.(1)*

$$M_{PM\_test} = \sum_{i=1}^{n} \frac{c_i \bullet r_{d,i} \bullet q_{mew,i} \bullet \Delta t_i}{3600 \bullet \rho_0}$$

ρ_0 being the density of the exhaust gas under standard conditions (0 °C, 1013 mbar).
It can be equated to the density of air, ρ_0 (air) =1.293 kg/m^3, within approx. 1 %.

If the dilution factor r_d = const., then with Δt_i = T/n = const the result is (2):

$$M_{PM\_test} = \frac{T \bullet r_d}{3600 \bullet n \bullet \rho_0} \sum_{i=1}^{n} c_i \bullet q_{mew,i}$$

If If the dilution factor r_d is not constant, then the result is (3a):

$$M_{PM\_test} = \frac{T}{3600 \bullet n \bullet \rho_0} \sum_{i=1}^{n} c_i \bullet r_{d,i} \bullet q_{mew,i}$$

Or, if a dilution-corrected value of the soot concentration is available (as in AVL 483 plus diluter), then the result is (3b):

$$M_{PM\_test} = \frac{T}{3600 \bullet n \bullet \rho_0} \sum_{i=1}^{n} c_{i,dil-corr} \bullet q_{mew,i}$$

The sum has to be calculated point by point online or offline. Separating the sum

$$\sum_{i=1}^{n} c_{i,dil-corr} \bullet \sum q_{mew,i}$$

into :
is not admissible.

Exposure Monitoring

DustTrak™ Aerosol Monitor

The DustTrak™ Aerosol Monitor measures aerosols in a wide variety of environments, from offices and industrial workplaces to outdoor environmental and construction sites. TSI's DustTrak provides reliable exposure assessment by measuring particle concentrations corresponding to PM10, PM2.5, PM1.0 or respirable size fractions.

The DustTrak is a portable, battery-operated laser photometer which gives you a real-time digital readout with the added benefits of a built-in data logger. Suitable for clean office settings as well as harsh industrial workplaces and outdoor applications, the DustTrak detects potential problems with airborne contaminants such as dust, smokes, fumes and mists.

The DustTrak is easy to use, too. You can perform quick spot checks or you can program the advanced logging modes for long-term sampling. You can program the start/stop times, recording intervals and other parameters. You can even set up the instrument for continuous unattended operation.

The DustTrak's new continuous analog output and adjustable alarm output allow remote access to real-time particle concentration data. Applications include site perimeter monitoring, ambient monitoring, process area monitoring and other remote uses. The alarm output with user-defined setpoint alerts you when upset or changing conditions occur. This feature allows you to program a switch closure at a concentration value of your choosing.

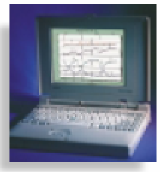
The DustTrak provides a real-time measurement based on 90° light scattering. A pump draws the sample aerosol through an optics chamber where it is measured. A sheath air system isolates the aerosol in the chamber to keep the optics clean for improved reliability and low maintenance.

TSI

Specifications

Model 8520 DustTrak Aerosol Monitor

Sensor Type	90° light scattering
Range	0.001 to 100 mg/m³ (Calibrated to ISO 12103-1, A1 test dust)
Resolution	±0.1% of reading or ±0.001 mg/m³, whichever is greater
Zero Stability	±0.001 mg/m³ over 24 hours using 10-second time-constant
Particle Size Range	0.1 to approximately 10 micrometers
Flow Rate	Adjustable 1.4 to 2.4 l/min (1.7 nominally)
Temperature Coefficient	+0.001 mg/m³ per °C (for variations from temperature at which the DustTrak was zeroed)
Operating Temperature	32° F to 120° F (0°C to 50°C)
Storage Temperature	-4° F to 140° F (-20°C to 60°C)
Operating Humidity	0 to 95% rh (non-condensing)
Time Constant	Adjustable from 1 to 60 seconds
Data Logging	31,000 data points (21 days of logging once/minute)
Logging Interval	Adjustable from 1 second to 1 hour
Physical	
External Dimensions	8.7 in. × 5.9 in. × 3.4 in. (221 mm × 150 mm × 87 mm)
Instrument Weight	3.3 pounds with batteries (1.5 kg)
Serial Interface	RS-232 1200 baud
Power	
AC	AC adapter (included)
Battery	Four C-size alkaline batteries (included)
Battery Run-time	Alkaline 16 hours
Analog Output Specifications	
Analog Output Voltage	0 to 5 VDC
Analog Output Scaling[1]	0 to 100 mg/m³ 0 to 10.0 mg/m³ 0 to 1.00 mg/m³ 0 to 0.100 mg/m³
Output Impedance	0.01 ohm
Maximum Output Current	15 mA



The DustTrak comes complete with TSI's TrakPro™ Data Analysis Software to allow you to perform a more comprehensive analysis of your measurement results. This exclusive Windows®-based program helps you generate the detailed graphs and reports needed to effectively communicate your findings.

Specifications are subject to change without notice.
Windows is a registered trademark of the Microsoft Corporation.

Alarm Output Specifications	
Type	Non-latching, MOSFET solid state (polarized)[2] analog switch
Setpoint Range[1]	0.010 to 100 mg/m³
Maximum Voltage	15 VDC
Maximum Current	1 Amp
Deadband	-5% of alarm setpoint
Connector	4-Pin, Mini-DIN connector

[1] User selectable through TrakPro™ Data Analysis Software.
[2] See TSI Application Note ITI - 074 for important wiring information.

Ordering Information

Model	Description
8520	The DustTrak Aerosol Monitor and accessories includes: Auxiliary Analog and Alarm Outputs, Carrying Case, Alkaline Batteries, TrakPro™ Data Analysis Software, Filter, Computer Cable, 25-pin to 9-pin Adapter, Operation Service Manual, Calibration Certificate, 10 mm Nylon Dorr-Oliver Cyclone, Inlet Conditioning Kit 1.0 and 2.5 µm, Sampling Extension Tube, Miscellaneous Service Tools and Two-Year Warranty.

Optional Accessories

Model	Description
8520-1	Environmental Enclosure

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For current information www.tsi.com

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Appendix C – PEMS & FRM Measurements of Blended Audit Gases

Table C-1. Blended Audit Gases for BUG Testing

			Concentration Measured				Concentration Dynamic Blend (1.5% MFC's)			
			NOx ppm	THC ppmC1	CO ppm	CO2 %	NOx ppm	THC ppmC1	CO ppm	CO2 %
PEMs 1a	Zero	n/a	517.03	132.20	128.2	1.726	0	0	0	0
PEMs 1b	Zero	200411041429	543.40	145.00	122.3	1.887	0	0	0	0
PEMs 2	Zero	200411021420	3.00	-1.00	-22.0	0.020	0	0	0	0
PEMs 3	Zero	n/a	-0.05	no meas	-2.9	-0.003	0	0	0	0
PEMs 4	Zero	200502030847	0.374	3.91	65.14	0.001	0	0	0	0
CVSa	Zero	200411021457	-0.04	0.08	n/a	0.001	0	0	0	0
CVSb	Zero	200411041459	-0.01	0.01	n/a	0.001	0	0	0	0
CVSa	Zero	200502030847	0.14	0.37	0.6	0.004	0	0	0	0
CVSb	Zero		-0.16	0.01	0.4	0.004	0	0	0	0
PEMs 1a	Span1	n/a	883.25	186.00	225.3	2.121	863.75	90.22	220.05	2.242
PEMs 1b	Span1	200411041429	941.27	247.20	218.8	2.095	848.27	88.95	218.57	2.243
PEMs 2	Span1	200411021420	880.00	80.00	220.0	2.380	847.47	88.96	218.37	2.242
PEMs 3	Span1	n/a	out of range	no meas	1704.3	1.961	847.28	no meas	218.32	2.242
PEMs 4	Span1	200502030847	918.89	219.42	295.2	5.118	935.3	215.64	241.00	4.942
CVSa	Span1	200411021457	853.73	90.83	220.4	2.277	847.53	90.20	218.38	2.242
CVSb	Span1	200411041459	848.81	91.13	219.1	2.247	847.82	90.13	218.46	2.243
CVSa	Span1	200502030847	931.27	211.81	239.9	4.940	935.3	215.64	241.00	4.942
CVSb	Span1		924.06	215.53	241.3	5.066	935.3	215.64	241.00	4.942
PEMs 1a	Span2	n/a	276.20	30.20	76.7	1.150	280.08	40.97	71.35	1.215
PEMs 1b	Span2	200411041429	299.42	97.70	69.7	1.151	274.58	40.63	70.75	1.215
PEMs 2	Span2	200411021420	289.00	34.00	76.0	1.340	274.74	40.60	70.79	1.216
PEMs 3	Span2	n/a	300.43	no meas	1143.8	1.338	274.70	no meas	70.78	1.215
PEMs 4	Span2		486.00	70.78	142.7	2.457	271.40	90.14	69.93	2.387
CVSa	Span2	200411021457	276.14	41.80	70.6	1.230	274.61	40.85	70.76	1.215
CVSb	Span2	200411041459	274.59	41.84	69.9	1.214	274.60	40.83	70.76	1.215
CVSa	Span2		270.67	89.66	69.4	2.352	271.40	90.14	69.93	2.387
CVSb	Span2		270.51	90.35	69.8	2.403	271.40	90.14	69.93	2.387
PEMs 1a	Span3	n/a	84.45	BDL	44.0	0.654	94.10	25.83	23.97	0.695
PEMs 1b	Span3	200411041429	89.98	15.00	12.0	0.660	92.26	25.62	23.77	0.694
PEMs 2	Span3	200411021420	105.00	20.50	22.0	0.810	92.27	25.63	23.78	0.695
PEMs 3	Span3	n/a	100.90	no meas	642.3	0.773	92.37	no meas	23.80	0.695
PEMs 4	Span3		133.95	50.50	105.6	1.260	91.82	40.84	23.66	1.239
CVSa	Span3	200411021457	92.74	26.15	24.2	0.702	92.34	25.83	23.79	0.695
CVSb	Span3	200411041459	92.24	26.05	24.2	0.690	92.33	25.81	23.79	0.695
CVSa	Span3		91.56	40.57	23.5	1.236	91.82	40.84	23.66	1.239
CVSb	Span3		91.66	41.03	23.6	1.244	91.82	40.84	23.66	1.239
PEMs 1a	Span4	n/a	23.32	BDL	10.0	0.230	28.98	7.91	7.38	0.269
PEMs 1b	Span4	200411041429	23.97	BDL	BDL	0.232	28.42	7.91	7.32	0.269
PEMs 2	Span4	200411021420	36.00	3.60	6.0	0.350	28.42	7.91	7.32	0.269
PEMs 3	Span4	n/a	30.69	no meas	207.3	0.278	28.42	no meas	7.32	0.269
PEMs 4	Span4		23.87	0.64	92.6	0.584	28.34	25.91	7.30	0.576
CVSa	Span4	200411021457	28.56	8.05	n/a	0.269	28.43	7.91	7.32	0.269
CVSb	Span4	200411041459	28.43	8.10	n/a	0.264	28.43	7.91	7.32	0.269
CVSa	Span4		28.37	25.63	7.7	0.568	28.34	25.91	7.30	0.576
CVSb	Span4		28.38	25.96	7.5	0.572	28.34	25.91	7.30	0.576

C-2 Audit Bottle Results for the Chassis Dynamometer Testing

		Concentration Measured				Audit Bottle Standard (1% NIST)			
	Cal Type	NOx ppm	THC ppmC1	CO ppm	CO2 %	NOx ppm	THC ppmC1	CO ppm	CO2 %
PEMS 1	raw	n/a	n/a	n/a	n/a	662	83.85	203.3	5.06
PEMS 2	raw	670.8	77.90	230.00	4.980	662	83.85	203.3	5.06
PEMS 3	dilute	151.5	0.00	22.40	1.436	151.8	23.91	25.14	1.556
PEMS 4	raw	834.7	100.69	184.67	5.943	662	83.85	203.3	5.06
FRM	raw	677.2	83.84	204.51	5.110	662	83.85	203.3	5.06
FRM	dilute	150.5	23.99	24.58	1.558	151.8	23.91	25.14	1.556

Appendix D – BUG Testing Individual Test Results for Each Measurement Device

BUG Test Results for the FRM –Run 1 in grams per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	366	16.2	371	2797	104	250876	51.7	1014	14.9	738.3	0.896	8.25	58.4	291.1	2.535
200411031011	1	450	362	17.0	391	2776	119	251897	51.6	1008	18.4	737.8	0.885	8.50	62.5	296.9	2.580
200411031157	1	450	362	16.3	426	2733	109	250476	53.4	983	22.8	736.5	0.891	8.29	68.0	290.3	2.566
200411031323	1	450	360	16.6	423	2738	105	251646	52.6	990	23.6	735.6	0.876	8.37	67.5	295.8	2.573
200411040805	1	450	364	16.5	348	2794	105	251294	46.8	1016	13.9	738.1	0.901	8.27	55.7	293.4	2.577
200411040944	1	450	363	17.1	352	2791	115	251997	46.1	1014	14.9	738.4	0.893	8.39	56.4	295.9	2.580
200411041120	1	450	363	18.3	365	2777	107	250848	47.6	1018	16.7	737.8	0.906	8.78	58.4	290.1	2.574
		ave	362.9	16.8	382	2772	109	251291	50.0	1006	17.9	737.5	0.893	8.41	61.0	293.4	2.569
		stdev	1.8	0.7	32	26.598	6	580.6	3.0	14	3.9	1.1	0.010	0.19	5.1	2.9	0.016
		COV	0.5%	4.2%	8.4%	1.0%	5.3%	0.2%	6.0%	1.4%	21.9%	0.1%	1.1%	2.2%	8.4%	1.0%	0.6%
200411030833	2	450	240	12.1	244	2181	72	167629	38.4	771.6	14.7	738.1	0.889	7.23	38.3	228.8	1.695
200411031011	2	450	240	12.0	253	2167	69	168757	39.6	763.5	19.3	737.4	0.887	7.15	40.3	231.1	1.730
200411031157	2	450	244	11.3	272	2152	74	168946	41.1	755.7	23.4	736.1	0.891	6.94	43.3	228.5	1.732
200411031323	2	450	241	11.4	272	2156	78	169304	39.6	757.3	23.6	735.3	0.877	6.96	43.2	232.7	1.732
200411040805	2	450	242	10.8	232	2184	60	167429	35.3	769.5	14.2	738.0	0.901	6.72	37.1	229.3	1.718
200411040944	2	450	241	10.5	232	2180	74	168498	34.9	767.5	15.1	738.1	0.895	6.53	37.0	230.5	1.726
200411041120	2	450	241	10.1	245	2168	77	167482	35.5	768.0	16.8	737.4	0.908	6.43	39.0	225.9	1.718
		ave	241.3	11.2	250	2170	72	168292	37.8	764.7	18.2	737.2	0.893	6.85	39.7	229.5	1.722
		stdev	1.3	0.8	17	12.466	6	769	2.5	6.1	4.0	1.1	0.010	0.30	2.6	2.2	0.013
		COV	0.5%	6.8%	6.7%	0.6%	8.2%	0.5%	6.6%	0.8%	22.2%	0.1%	1.2%	4.4%	6.7%	0.9%	0.8%
200411030833	3	450	90.4	8.7	n/a*	869	34	77396	21.4	480.6	15.6	738.3	0.890	7.21	n/a*	120.2	1.045
200411031011	3	450	90.7	9.9	n/a	865	34	77828	25.5	488.4	20.4	738.1	0.889	8.56	n/a	149.6	1.304
200411031157	3	450	90.5	9.6	n/a	860	39	77706	20.1	485.9	24.0	736.9	0.892	8.91	n/a	164.7	1.442
200411031323	3	450	90.7	10.4	n/a	858	40	77972	20.4	486.0	23.8	736.2	0.887	9.38	n/a	165.2	1.446
200411040805	3	450	89.5	9.7	n/a	860	38	77316		489.5	13.9	739.0	0.897	8.88	n/a	163.8	1.435
200411040944	3	450	90.4	9.7	n/a	867	39	78145	19.7	490.6	15.8	739.0	0.897	8.83	n/a	165.2	1.449
200411041120	3	450	90.4	9.9	n/a	860	37	77733	20.1	489.5	18.1	738.2	0.912	8.98	n/a	161.3	1.442
		ave	90.4	9.7	#DIV/0!	863	37	77728	21.2	487.2	18.8	737.9	0.895	8.68	#DIV/0!	155.7	1.366
		stdev	0.4	0.5	#DIV/0!	4	2	296	2.2	3.4	4.1	1.1	0.008	0.69	#DIV/0!	16.6	0.151
		COV	0.5%	5.4%	#DIV/0!	0.5%	6.7%	0.4%	10.3%	0.7%	21.6%	0.1%	0.9%	8.0%	#DIV/0!	10.7%	11.0%
200411030833	4	450	18.40	26.0	115	310	33	37821	32.8	405.7	16.1	738.6	0.890	17.06	29.6	53.6	0.654
200411031011	4	450	18.40	25.7	112	307	31	37785	31.2	404.1	20.9	737.9	0.890	16.81	28.8	52.9	0.652
200411031157	4	450	18.40	24.9	109	303	32	37494	30.7	402.5	23.4	736.7	0.892	17.84	31.3	58.0	0.714
200411031323	4	450	18.40	24.5	109	304	32	37659	29.9	403.0	23.8	736.1	0.893	17.58	31.1	58.1	0.716
200411040805	4	450	18.37	23.0	108	311	32	37822	30.4	404.8	14.3	738.9	0.897	16.65	31.0	59.1	0.719
200411040944	4	450	18.37	22.7	107	309	32	37935	28.8	403.3	15.6	738.9	0.898	16.44	30.7	58.7	0.720
200411041120	4	450	18.40	23.0	107	307	33	37707	29.2	403.3	18.1	738.0	0.912	16.59	30.6	57.4	0.717
		ave	18.4	24.2	110	307	32	37746	30.4	403.8	18.9	737.9	0.896	16.99	30.4	56.8	0.699
		stdev	0.019	1.3	3	3	1	142	1.3	1.1	3.8	1.1	0.008	0.53	0.9	2.5	0.031
		COV	0.1%	5.6%	2.6%	1.0%	2.0%	0.4%	4.4%	0.3%	20.3%	0.2%	0.9%	3.1%	3.0%	4.4%	4.5%

BUG Test Results for the FRM –Run 1 in grams per hp- hour

					Mass Emission g/Hp/hr					Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load Factor	Load kW	THC	CO	kNOx	CO2	PM	scfm	Temp C	Baro mmHg	H	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	100%	365.7	0.033	0.756	5.704	511.6	0.105	1014	14.9	738.3	#	8.25	58.4	291.1	2.535
200411031011	1	450	100%	362.4	0.035	0.806	5.713	518.3	0.106	1008	18.4	737.8	#	8.50	62.5	296.9	2.580
200411031157	1	450	100%	361.7	0.034	0.878	5.635	516.5	0.110	983	22.8	736.5	#	8.29	68.0	290.3	2.566
200411031323	1	450	100%	360.1	0.034	0.877	5.670	521.2	0.109	990	23.6	735.6	#	8.37	67.5	295.8	2.573
200411040805	1	450	100%	364.1	0.034	0.713	5.722	514.7	0.096	1016	13.9	738.1	#	8.27	55.7	293.4	2.577
200411040944	1	450	100%	363.2	0.035	0.723	5.730	517.3	0.095	1014	14.9	738.4	#	8.39	56.4	295.9	2.580
200411041120	1	450	100%	363.2	0.037	0.749	5.702	515.1	0.098	1018	16.7	737.8	#	8.78	58.4	290.1	2.574
			ave	362.9	0.035	0.786	5.696	516.4	0.103	1006	17.9	737.5	#	8.41	61.0	293.4	2.569
			stdev	1.8	0.001	0.069	0.033	3.0	0.006	14	3.9	1.1	#	0.19	5.1	2.9	0.016
			COV	0.5%	4.2%	8.8%	0.6%	0.6%	6.3%	1.4%	21.9%	0.1%	#	2.2%	8.4%	1.0%	0.6%
200411030833	2	450	65%	240.4	0.038	0.758	6.766	520.0	0.119	771.6	14.7	738.1	#	7.23	38.3	228.8	1.695
200411031011	2	450	65%	240.0	0.037	0.786	6.731	524.2	0.123	763.5	19.3	737.4	#	7.15	40.3	231.1	1.730
200411031157	2	450	65%	243.9	0.035	0.832	6.580	516.5	0.126	755.7	23.4	736.1	#	6.94	43.3	228.5	1.732
200411031323	2	450	65%	241.4	0.035	0.839	6.660	523.0	0.122	757.3	23.6	735.3	#	6.96	43.2	232.7	1.732
200411040805	2	450	65%	241.7	0.033	0.717	6.737	516.5	0.109	769.5	14.2	738.0	#	6.72	37.1	229.3	1.718
200411040944	2	450	65%	240.9	0.032	0.718	6.747	521.6	0.108	767.5	15.1	738.1	#	6.53	37.0	230.5	1.726
200411041120	2	450	65%	240.9	0.031	0.757	6.710	518.5	0.110	768.0	16.8	737.4	#	6.43	39.0	225.9	1.718
			ave	241.3	0.035	0.772	6.705	520.0	0.117	764.7	18.2	737.2	#	6.85	39.7	229.5	1.722
			stdev	1.3	0.002	0.050	0.064	3.1	0.008	6.1	4.0	1.1	#	0.30	2.6	2.2	0.013
			COV	0.5%	6.9%	6.4%	1.0%	0.6%	6.5%	0.8%	22.2%	0.1%	#	4.4%	6.7%	0.9%	0.8%
200411030833	3	450	25%	90.4	0.072	n/a*	7.175	638.8	0.176	480.6	15.6	738.3	#	7.21	n/a*	120.2	1.045
200411031011	3	450	25%	90.7	0.081	n/a	7.109	639.7	0.210	488.4	20.4	738.1	#	8.56	n/a	149.6	1.304
200411031157	3	450	25%	90.5	0.079	n/a	7.084	640.0	0.166	485.9	24.0	736.9	#	8.91	n/a	164.7	1.442
200411031323	3	450	25%	90.7	0.086	n/a	7.052	640.9	0.168	486.0	23.8	736.2	#	9.38	n/a	165.2	1.446
200411040805	3	450	25%	89.5	0.081	n/a	7.166	644.1		489.5	13.9	739.0	#	8.88	n/a	163.8	1.435
200411040944	3	450	25%	90.4	0.080	n/a	7.155	645.0	0.163	490.6	15.8	739.0	#	8.83	n/a	165.2	1.449
200411041120	3	450	25%	90.4	0.082	n/a	7.102	641.6	0.166	489.5	18.1	738.2	#	8.98	n/a	161.3	1.442
			ave	90.4	0.080		7.120	641.4	0.175	487.2	18.8	737.9	#	8.68	#DIV/0!	155.7	1.366
			stdev	0.4	0.004		0.046	2.3	0.018	3.4	4.1	1.1	#	0.69	#DIV/0!	16.6	0.151
			COV	0.5%	5.3%		0.6%	0.4%	10.2%	0.7%	21.6%	0.1%	#	8.0%	#DIV/0!	10.7%	11.0%
200411030833	4	450	5%	18.40	1.052	4.655	12.577	1532.4	1.327	405.7	16.1	738.6	#	17.06	29.6	53.6	0.654
200411031011	4	450	5%	18.40	1.039	4.527	12.431	1530.9	1.263	404.1	20.9	737.9	#	16.81	28.8	52.9	0.652
200411031157	4	450	5%	18.40	1.009	4.433	12.292	1519.1	1.243	402.5	23.4	736.7	#	17.84	31.3	58.0	0.714
200411031323	4	450	5%	18.40	0.991	4.405	12.318	1525.8	1.211	403.0	23.8	736.1	#	17.58	31.1	58.1	0.716
200411040805	4	450	5%	18.37	0.933	4.397	12.613	1535.6	1.232	404.8	14.3	738.9	#	16.65	31.0	59.1	0.719
200411040944	4	450	5%	18.37	0.923	4.343	12.555	1540.2	1.168	403.3	15.6	738.9	#	16.44	30.7	58.7	0.720
200411041120	4	450	5%	18.40	0.930	4.329	12.421	1527.8	1.181	403.3	18.1	738.0	#	16.59	30.6	57.4	0.717
			ave	18.4	0.982	4.441	12.458	1530.3	1.232	403.8	18.9	737.9	#	16.99	30.4	56.8	0.699
			stdev	0.0	0.054	0.115	0.127	6.8	0.054	1.1	3.8	1.1	#	0.53	0.9	2.5	0.031
			COV	0.1%	5.5%	2.6%	1.0%	0.4%	4.4%	0.3%	20.3%	0.2%	#	3.1%	3.0%	4.4%	4.5%

BUG Test Results for the FRM –Run 2 in grams per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH	THC ppm	CO ppm	NOx ppm	CO2%
200502020932	1	120	344	21.5	299	2791		240774		1020	17.0	741.6	0.882	9.73	47.1	294.8	2.428
200502021026	1	120	340	21.3	290	2759		237892		1013	17.7	741.6	0.881	9.78	45.4	291.7	2.396
200502021103	1	120	343	20.5	301	2737		238323		1018	18.1	741.3	0.882	9.41	47.5	289.4	2.400
200502021254	1	120	343	19.5	298	2726		240276		1023	19.6	740.4	0.880	8.88	46.9	288.8	2.424
200502021313	1	120	344	20.8	301	2700		239197		1022	19.6	740.2	0.878	9.29	47.3	286.6	2.414
200502021333	1	120	343	20.7	313	2688		239453		1022	19.9	740.0	0.879	9.24	49.2	284.9	2.415
200502021433	1	120	343	20.9	307	2761		240671		1014	20.8	739.8	0.879	9.49	48.5	292.6	2.423
		ave	342.9	20.8	301	2737		239512		1019	19.0	740.7	0.880	9.40	47.4	289.8	2.414
		stdev	1.1	0.6	7	36.230		1130.1		4	1.4	0.8	0.002	0.31	1.2	3.5	0.012
		COV	0.3%	3.0%	2.4%	1.3%		0.5%		0.4%	7.3%	0.1%	0.2%	3.3%	2.5%	1.2%	0.5%
200502020932	2	120	224	21.8	246	2120		161731		763.2	16.9	741.4	0.880	10.04	38.6	224.4	1.634
200502021026	2	120	225	20.5	251	2124		162038		760.3	17.8	741.4	0.881	9.72	39.1	224.6	1.634
200502021103	2	120	226	20.2	248	2102		159323		758.9	18.2	741.1	0.881	9.51	39.0	222.4	1.608
200502021254	2	120	226	18.1	254	2105		160195		762.9	19.6	740.1	0.879	8.64	39.7	223.1	1.621
200502021313	2	120	226	21.7	250	2089		159986		766.4	19.9	739.9	0.879	9.75	39.2	221.4	1.619
200502021333	2	120	226	22.2	252	2087		159189		764.2	20.2	739.7	0.881	9.89	39.4	220.9	1.611
200502021433	2	120	226	21.3	241	2084		160014		757.1	20.6	739.6	0.876	9.85	38.0	221.6	1.612
		ave	225.4	20.8	249	2102		160354		761.9	19.0	740.4	0.880	9.63	39.0	222.6	1.620
		stdev	0.7	1.4	4	16.160		1113		3.2	1.4	0.8	0.002	0.47	0.6	1.5	0.011
		COV	0.3%	6.7%	1.6%	0.8%		0.7%		0.4%	7.3%	0.1%	0.2%	4.8%	1.5%	0.7%	0.7%
200502020932	3	120	85.2	12.0	84.2	818		75837		486.2	17.2	741.8	0.881	8.35	17.549	114.1	1.023
200502021026	3	120	84.3	11.4	79.6	808		75257		483.7	17.7	741.8	0.880	8.22	16.471	112.9	1.013
200502021103	3	120	85.0	10.5	76.9	816		74306		485.0	18.3	741.5	0.881	7.71	16.243	113.8	1.000
200502021254	3	120	85.8	11.4	80.9	805		74072		486.8	19.5	740.6	0.879	7.82	16.895	112.6	1.003
200502021313	3	120	86.0	11.0	78.3	809		73776		484.0	19.9	740.3	0.880	7.68	16.371	113.0	0.999
200502021333	3	120	85.8	11.5	79.6	805		73782		484.5	20.2	740.2	0.879	7.86	16.623	112.7	0.999
200502021433	3	120	84.1	10.7	78.4	797		73950		481.7	20.6	740.1	0.876	7.77	16.537	111.8	0.993
		ave	85.2	11.2	79.7	808		74426		484.6	19.0	740.9	0.879	7.92	16.7	113.0	1.005
		stdev	0.7	0.5	2.4	7		805		1.7	1.3	0.8	0.002	0.26	0.4	0.8	0.010
		COV	0.9%	4.5%	3.0%	0.9%		1.1%		0.3%	6.9%	0.1%	0.2%	3.3%	2.6%	0.7%	1.0%
200502020932	4	500	17.46	27.9	124	315		38190		398.1	17.4	741.8	0.882	15.00	25.5	43.8	0.535
200502021026	4	500	18.29	24.8	123	312		38244		396.4	17.8	741.6	0.880	13.86	25.3	43.5	0.533
200502021103	4	500	18.33	25.9	121	308		37420		396.4	19.2	741.3	0.884	14.14	25.2	42.7	0.522
200502021254	4	120	18.33	21.0	118	310		37219		394.9	19.5	740.5	0.878	11.87	24.4	43.2	0.526
200502021313	4	120	18.33	21.1	117	310		37098		393.7	19.9	740.2	0.879	11.91	24.1	43.2	0.524
200502021333	4	120	18.33	22.1	118	308		37128		393.5	20.3	740.1	0.879	12.34	24.3	43.0	0.524
200502021433	4	500	18.33	25.5	123	303		37395		397.2	20.6	740.0	0.876	13.95	25.6	42.3	0.520
		ave	18.2	24.0	121	309		37528		395.7	19.2	740.8	0.880	13.29	24.9	43.1	0.527
		stdev	0.327	2.7	3	4		487		1.7	1.2	0.8	0.002	1.24	0.6	0.5	0.006
		COV	1.8%	11.2%	2.5%	1.2%		1.3%		0.4%	6.3%	0.1%	0.3%	9.3%	2.5%	1.1%	1.1%

BUG Test Results for PEMS#1 in grams per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	366	51.3	367	3555		253631	23.5	1026				50.36	186.6	1095.5	8.170
200411031011	1	450	362	56.1	397	3638		252350	18.8	1009				55.80	205.0	1140.4	8.271
200411031157	1	450	362	72.5	466	3602		249756	17.6	980				74.96	247.1	1158.2	8.397
200411031323	1	450	360	82.1	426	3708		250352	18.1	984				84.81	221.4	1183.7	8.355
200411040805	1	450	364	51.9	359	3497		249442	19.6	1033				50.46	179.9	1074.8	8.017
200411040944	1	450	363	45.9	367	3587		245581	17.4	1026				44.99	186.1	1106.7	7.922
200411041120	1	450	363	52.6	375	3575		245903	16.7	1022				51.63	193.1	1107.2	7.962
		ave	362.9	58.9	394	3594	#DIV/0!	249574	18.8	1012	#DIV/0!	#DIV/0!	#DIV/0!	59.00	202.7	1123.8	8.156
		stdev	1.8	13.2	39	66.295	#DIV/0!	3006.8	2.3	21.4	#DIV/0!	#DIV/0!	#DIV/0!	14.89	24.1	38.3	0.193
		COV	0.5%	22.4%	10.0%	1.8%	#DIV/0!	1.2%	12.2%	2.1%	#DIV/0!	#DIV/0!	#DIV/0!	25.2%	11.9%	3.4%	2.4%
200411030833	2	450	240	62.4	229	2740		166022	12.5	786.1				80.04	151.1	1093.1	6.924
200411031011	2	450	240	66.9	262	2784		166034	12.4	774.1				86.92	172.8	1125.9	7.020
200411031157	2	450	244	65.2	287	2808		166271	12.5	763.7				85.63	194.8	1149.7	7.116
200411031323	2	450	241	78.5	274	2874		165486	12.3	763.5				103.51	182.6	1173.8	7.065
200411040805	2	450	242	37.3	226	2713		163451	12.9	792.4				47.05	148.5	1076.6	6.780
200411040944	2	450	241	40.2	239	2750		160962	12.1	788.4				50.67	158.7	1095.4	6.705
200411041120	2	450	241	31.7	243	2710		160965	12.1	784.6				40.11	161.5	1087.1	6.751
		ave	241.3	54.6	252	2768	#DIV/0!	164170	12.4	779.0	#DIV/0!	#DIV/0!	#DIV/0!	70.56	167.1	1114.5	6.909
		stdev	1.3	17.9	23	58.628	#DIV/0!	2385	0.3	11.9	#DIV/0!	#DIV/0!	#DIV/0!	24.31	17.1	36.3	0.165
		COV	0.5%	32.8%	9.3%	2.1%	#DIV/0!	1.5%	2.3%	1.5%	#DIV/0!	#DIV/0!	#DIV/0!	34.5%	10.2%	3.3%	2.4%
200411030833	3	450	90.4	34.2	74.9	1065		75984	5.3	500.8				68.43	78.9	662.6	4.943
200411031011	3	450	90.7	40.4	78.4	1088		76002	5.4	494.3				81.83	79.6	681.8	4.981
200411031157	3	450	90.5	45.3	74.4	1100		75529	5.2	487.3				92.46	76.9	696.8	5.002
200411031323	3	450	90.7	41.9	78.4	1107		75913	5.3	488.9				85.12	80.3	700.2	5.021
200411040805	3	450	89.5	32.5	67.2	1052		74351	5.3	503.9				64.56	70.1	653.0	4.828
200411040944	3	450	90.4	20.6	77.0	1062		73935	5.3	503.1				40.61	78.9	658.6	4.795
200411041120	3	450	90.4	27.7	82.8	1047		73580	5.3	499.0				54.69	83.5	653.6	4.803
		ave	90.4	34.7	76.2	1074	#DIV/0!	75042	5.3	496.8	#DIV/0!	#DIV/0!	#DIV/0!	69.67	78.3	672.4	4.910
		stdev	0.4	8.7	4.8	24	#DIV/0!	1052	0.1	6.7	#DIV/0!	#DIV/0!	#DIV/0!	18.27	4.1	20.3	0.099
		COV	0.5%	25.0%	6.3%	2.2%	#DIV/0!	1.4%	1.2%	1.4%	#DIV/0!	#DIV/0!	#DIV/0!	26.2%	5.3%	3.0%	2.0%
200411030833	4	450	18.4	42.6	114	343		37419	5.7	421.1				100.91	135.8	252.9	2.888
200411031011	4	450	18.4	42.5	110	348		37223	5.5	415.9				102.15	131.2	257.8	2.890
200411031157	4	450	18.4	46.0	107	349		36903	5.4	412.1				110.04	131.0	260.5	2.884
200411031323	4	450	18.4	43.5	108	348		37026	5.3	412.1				104.72	129.7	260.0	2.893
200411040805	4	450	18.4	33.6	102	344		36656	5.5	424.5				79.75	126.7	252.5	2.814
200411040944	4	450	18.4	29.7	103	340		36197	5.2	422.7				69.57	126.9	250.3	2.788
200411041120	4	450	18.4	30.8	108	335		36172	5.2	420.2				73.47	129.6	247.7	2.799
		ave	18.4	38.4	107	344	#DIV/0!	36800	5.4	418.4	#DIV/0!	#DIV/0!	#DIV/0!	91.51	130.1	254.5	2.851
		stdev	0.019	6.8	4	5	#DIV/0!	483	0.2	5.0	#DIV/0!	#DIV/0!	#DIV/0!	16.66	3.1	5.0	0.048
		COV	0.1%	17.6%	3.5%	1.5%	#DIV/0!	1.3%	3.6%	1.2%	#DIV/0!	#DIV/0!	#DIV/0!	18.2%	2.4%	2.0%	1.7%

BUG Test Results for PEMS#1 in grams per hp- hour

					Mass Emission g/Hp/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load Factor	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	100%	365.7	0.1046	0.749	7.253		517.4	0.048	1026				50.36	186.6	1095.5	8.170
200411031011	1	450	100%	362.4	0.1155	0.816	7.488		519.5	0.039	1009				55.80	205.0	1140.4	8.271
200411031157	1	450	100%	361.7	0.1495	0.962	7.429		515.2	0.036	980				74.96	247.1	1158.2	8.397
200411031323	1	450	100%	360.1	0.1701	0.882	7.683		518.7	0.038	984				84.81	221.4	1183.7	8.355
200411040805	1	450	100%	364.1	0.1063	0.736	7.165		511.1	0.040	1033				50.46	179.9	1074.8	8.017
200411040944	1	450	100%	363.2	0.0943	0.755	7.366		504.4	0.036	1026				44.99	186.1	1106.7	7.922
200411041120	1	450	100%	363.2	0.1080	0.771	7.343		505.1	0.034	1022				51.63	193.1	1107.2	7.962
			ave	362.9	0.1212	0.810	7.389	#DIV/0!	513.1	0.039	1012	#DIV/0!	#DIV/0!	#	59.00	202.7	1123.8	8.156
			stdev	1.8	0.0277	0.084	0.168	#DIV/0!	6.3	0.005	21.4	#DIV/0!	#DIV/0!	#	14.89	24.1	38.3	0.193
			COV	0.5%	22.9%	10.3%	2.3%	#DIV/0!	1.2%	0.118	2.1%	#DIV/0!	#DIV/0!	#	25.2%	11.9%	3.4%	2.4%
200411030833	2	450	65%	240.4	0.1937	0.710	8.503		515.2	0.039	786.1				80.04	151.1	1093.1	6.924
200411031011	2	450	65%	240.0	0.2080	0.815	8.652		516.0	0.038	774.1				86.92	172.8	1125.9	7.020
200411031157	2	450	65%	243.9	0.1994	0.877	8.589		508.5	0.038	763.7				85.63	194.8	1149.7	7.116
200411031323	2	450	65%	241.4	0.2426	0.848	8.882		511.4	0.038	763.5				103.51	182.6	1173.8	7.065
200411040805	2	450	65%	241.7	0.1151	0.699	8.371		504.4	0.040	792.4				47.05	148.5	1076.6	6.780
200411040944	2	450	65%	240.9	0.1244	0.741	8.515		498.5	0.038	788.4				50.67	158.7	1095.4	6.705
200411041120	2	450	65%	240.9	0.0982	0.752	8.393		498.5	0.037	784.6				40.11	161.5	1087.1	6.751
			ave	241.3	0.1688	0.777	8.558	#DIV/0!	507.5	0.038	779.0	#DIV/0!	#DIV/0!	#	70.56	167.1	1114.5	6.909
			stdev	1.3	0.0553	0.070	0.174	#DIV/0!	7.3	0.001	11.9	#DIV/0!	#DIV/0!	#	24.31	17.1	36.3	0.165
			COV	0.5%	32.8%	8.9%	2.0%	#DIV/0!	1.4%	0.021	1.5%	#DIV/0!	#DIV/0!	#	34.5%	10.2%	3.3%	2.4%
200411030833	3	450	25%	90.4	0.2820	0.618	8.793		627.4	0.044	500.8				68.43	78.9	662.6	4.943
200411031011	3	450	25%	90.7	0.3323	0.645	8.943		624.9	0.044	494.3				81.83	79.6	681.8	4.981
200411031157	3	450	25%	90.5	0.3733	0.613	9.062		622.3	0.043	487.3				92.46	76.9	696.8	5.002
200411031323	3	450	25%	90.7	0.3448	0.645	9.101		624.2	0.043	488.9				85.12	80.3	700.2	5.021
200411040805	3	450	25%	89.5	0.2710	0.560	8.764		619.6	0.044	503.9				64.56	70.1	653.0	4.828
200411040944	3	450	25%	90.4	0.1699	0.636	8.766		610.5	0.044	503.1				40.61	78.9	658.6	4.795
200411041120	3	450	25%	90.4	0.2284	0.683	8.642		607.5	0.044	499.0				54.69	83.5	653.6	4.803
			ave	90.4	0.2860	0.629	8.867	#DIV/0!	619.5	0.044	496.8	#DIV/0!	#DIV/0!	#	69.67	78.3	672.4	4.910
			stdev	0.4	0.0710	0.038	0.171	#DIV/0!	7.6	0.001	6.7	#DIV/0!	#DIV/0!	#	18.27	4.1	20.3	0.099
			COV	0.5%	24.8%	6.0%	1.9%	#DIV/0!	1.2%	0.014	1.4%	#DIV/0!	#DIV/0!	#	26.2%	5.3%	3.0%	2.0%
200411030833	4	450	5%	18.40	1.7260	4.613	13.905		1516.7	0.231	421.1				100.91	135.8	252.9	2.888
200411031011	4	450	5%	18.40	1.7208	4.441	14.087		1508.7	0.224	415.9				102.15	131.2	257.8	2.890
200411031157	4	450	5%	18.40	1.8648	4.355	14.135		1495.8	0.217	412.1				110.04	131.0	260.5	2.884
200411031323	4	450	5%	18.40	1.7624	4.366	14.115		1500.8	0.213	412.1				104.72	129.7	260.0	2.893
200411040805	4	450	5%	18.37	1.3652	4.161	13.958		1488.9	0.224	424.5				79.75	126.7	252.5	2.814
200411040944	4	450	5%	18.37	1.2053	4.197	13.806		1470.2	0.211	422.7				69.57	126.9	250.3	2.788
200411041120	4	450	5%	18.40	1.2490	4.375	13.564		1466.2	0.211	420.2				73.47	129.6	247.7	2.799
			ave	18.4	1.5562	4.358	13.938	#DIV/0!	1492.5	0.219	418.4	#DIV/0!	#DIV/0!	#	91.51	130.1	254.5	2.851
			stdev	0.0	0.2732	0.151	0.205	#DIV/0!	18.9	0.008	5.0	#DIV/0!	#DIV/0!	#	16.66	3.1	5.0	0.048
			COV	0.1%	17.6%	3.5%	1.5%	#DIV/0!	1.3%	0.035	1.2%	#DIV/0!	#DIV/0!	#	18.2%	2.4%	2.0%	1.7%

BUG Test Results for PEMS#2 in gram per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	366	25.7	406	3009	89	246123		984	18.9	731.3	0.885	26.59	208.1	1060.7	8.031
200411031011	1	450	362	37.2	447	3036	87	247276		990	23.0	730.5	0.877	38.28	228.1	1075.0	8.024
200411031157	1	450	362	21.2	482	2963	84	252698		970	25.0	728.9	0.881	22.23	250.8	1065.2	8.365
200411031323	1	450	360	26.7	463	2954	70	254285		977	24.0	727.5	0.869	27.84	239.3	1069.0	8.360
200411040805	1	450	364	34.8	420	2985	77	245614		998	17.0	731.0	0.894	35.56	212.0	1027.2	7.902
200411040944	1	450	363	25.3	416	2992	71	249461		986	20.7	731.3	0.885	26.13	213.3	1053.4	8.128
200411041120	1	450	363	26.6	447	3006	62	248524		982	28.8	730.5	0.904	27.64	230.4	1042.5	8.143
		ave	362.9	28.2	440	2992	77	249140		984	22.5	730.1	0.885	29.18	226.0	1056.1	8.136
		stdev	1.8	5.7	28	28.151	10	3281.9		9.0	4.0	1.4	0.011	5.66	15.8	16.6	0.174
		COV	0.5%	20.1%	6.3%	0.9%	12.8%	1.3%		0.9%	17.6%	0.2%	1.3%	19.4%	7.0%	1.6%	2.1%
200411030833	2	450	240	22.6	273	2278	69	159235		739	19.0	731.3	0.879	31.20	186.8	1077.8	6.922
200411031011	2	450	240	21.9	294	2295	64	160611		746	23.5	730.4	0.878	29.88	199.1	1076.7	6.916
200411031157	2	450	244	17.0	312	2251	60	165338		738	25.0	728.3	0.882	23.41	213.2	1062.9	7.196
200411031323	2	450	241	19.1	300	2273	57	166654		743	23.9	727.5	0.871	26.17	203.8	1078.7	7.201
200411040805	2	450	242	22.8	288	2266	55	160861		738	17.1	731.2	0.894	31.55	197.3	1055.8	7.005
200411040944	2	450	241	16.6	290	2227	51	159547		729	22.8	731.2	0.887	23.28	201.2	1059.3	7.039
200411041120	2	450	241	14.4	297	2229	50	158603		726	23.8	730.4	0.904	20.28	207.7	1049.2	7.054
		ave	241.3	19.2	294	2260	58	161550		737.1	22.2	730.0	0.885	26.54	201.3	1065.8	7.048
		stdev	1.3	3.3	12	25.452	7	3157		7.0	2.9	1.5	0.011	4.43	8.4	11.9	0.116
		COV	0.5%	17.4%	4.0%	1.1%	11.7%	2.0%		1.0%	13.2%	0.2%	1.2%	16.7%	4.2%	1.1%	1.6%
200411030833	3	450	90.4	14.1	105.5	881	35	72277		459	20.5	731.1	0.881	31.26	116.3	669.9	5.058
200411031011	3	450	90.7	14.5	107.5	899	34	73094		468	24.7	729.8	0.879	31.64	116.1	671.3	5.017
200411031157	3	450	90.5	12.0	113.4	886	28	75490		464	25.0	728.3	0.882	26.35	123.4	665.8	5.228
200411031323	3	450	90.7	14.3	102.7	879	28	76052		465	23.0	727.5	0.879	31.45	111.6	661.3	5.256
200411040805	3	450	89.5	14.0	123.4	886	28	75287		468	17.1	731.3	0.890	30.48	133.0	654.0	5.171
200411040944	3	450	90.4	12.6	125.1	885	28	74878		468	25.0	731.1	0.890	27.61	136.0	657.3	5.174
200411041120	3	450	90.4	12.0	127.3	889	26	75305		467	20.7	729.8	0.902	26.28	137.6	649.8	5.190
		ave	90.4	13.4	115.0	887	30	74626		465.5	22.3	729.8	0.886	29.30	124.9	661.4	5.156
		stdev	0.4	1.1	10.2	6	3	1391		3.2	3.0	1.5	0.008	2.45	10.7	8.1	0.087
		COV	0.5%	8.4%	8.9%	0.7%	11.7%	1.9%		0.7%	13.4%	0.2%	1.0%	8.4%	8.5%	1.2%	1.7%
200411030833	4	450	18.4	27.7	123	307	34	34168		366	20.0	730.6	0.881	77.29	170.3	293.3	3.010
200411031011	4	450	18.4	27.6	122	313	34	34443		374	24.7	729.8	0.880	75.31	164.7	292.7	2.964
200411031157	4	450	18.4	25.4	122	303	29	35881		372	24.0	728.3	0.883	69.50	165.0	283.3	3.097
200411031323	4	450	18.4	26.8	120	301	28	36596		376	23.0	727.5	0.884	72.63	160.4	278.2	3.127
200411040805	4	450	18.4	25.0	136	306	27	36737		375	18.0	731.3	0.891	68.05	183.9	282.2	3.151
200411040944	4	450	18.4	23.1	130	307	27	36073		378	25.4	731.1	0.893	62.83	175.1	281.4	3.085
200411041120	4	450	18.4	23.1	136	301	25	35583		371	20.0	729.8	0.903	63.95	186.1	278.1	3.101
		ave	18.4	25.5	127	306	29	35640		373.0	22.2	729.8	0.888	69.94	172.2	284.2	3.076
		stdev	0.019	1.9	7	4	4	997		4.0	2.8	1.4	0.008	5.48	9.9	6.3	0.066
		COV	0.1%	7.6%	5.6%	1.4%	12.2%	2.8%		1.1%	12.7%	0.2%	0.9%	7.8%	5.8%	2.2%	2.2%

BUG Test Results for PEMS#2 in gram per hp- hour

					Mass Emission g/Hp/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load Factor	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmH	kH	THC ppm	CO ppm	NOx ppm	CO2%
200411030833	1	450	100%	365.7	0.052	0.827	6.136	0.181	501.9		984	18.9	731.3	#	26.59	208.1	1060.7	8.031
200411031011	1	450	100%	362.4	0.076	0.920	6.247	0.178	508.8		990	23.0	730.5	#	38.28	228.1	1075.0	8.024
200411031157	1	450	100%	361.7	0.044	0.994	6.109	0.173	521.1		970	25.0	728.9	#	22.23	250.8	1065.2	8.365
200411031323	1	450	100%	360.1	0.055	0.960	6.118	0.144	526.6		977	24.0	727.5	#	27.84	239.3	1069.0	8.360
200411040805	1	450	100%	364.1	0.071	0.860	6.114	0.159	503.1		998	17.0	731.0	#	35.56	212.0	1027.2	7.902
200411040944	1	450	100%	363.2	0.052	0.855	6.143	0.146	512.1		986	20.7	731.3	#	26.13	213.3	1053.4	8.128
200411041120	1	450	100%	363.2	0.055	0.918	6.173	0.128	510.3		982	28.8	730.5	#	27.64	230.4	1042.5	8.143
			ave	362.9	0.0580	0.905	6.149	0.158	512.0		984	22.5	730.1	#	29.18	226.0	1056.1	8.136
			stdev	1.8	0.0116	0.061	0.049	0.020	9.0		9.0	4.0	1.4	#	5.66	15.8	16.6	0.174
			COV	0.5%	20.1%	6.7%	0.8%	12.6%	1.8%		0.9%	17.6%	0.2%	#	19.4%	7.0%	1.6%	2.1%
200411030833	2	450	65%	240.4	0.070	0.848	7.067	0.214	493.9		739	19.0	731.3	#	31.20	186.8	1077.8	6.922
200411031011	2	450	65%	240.0	0.068	0.914	7.128	0.200	498.9		746	23.5	730.4	#	29.88	199.1	1076.7	6.916
200411031157	2	450	65%	243.9	0.052	0.953	6.883	0.182	505.5		738	25.0	728.3	#	23.41	213.2	1062.9	7.196
200411031323	2	450	65%	241.4	0.059	0.927	7.021	0.177	514.8		743	23.9	727.5	#	26.17	203.8	1078.7	7.201
200411040805	2	450	65%	241.7	0.070	0.889	6.991	0.170	496.2		738	17.1	731.2	#	31.55	197.3	1055.8	7.005
200411040944	2	450	65%	240.9	0.051	0.899	6.892	0.159	493.9		729	22.8	731.2	#	23.28	201.2	1059.3	7.039
200411041120	2	450	65%	240.9	0.044	0.919	6.900	0.155	491.0		726	23.8	730.4	#	20.28	207.7	1049.2	7.054
			ave	241.3	0.0593	0.907	6.983	0.180	499.2		737.1	22.2	730.0	#	26.54	201.3	1065.8	7.048
			stdev	1.3	0.0104	0.033	0.096	0.021	8.3		7.0	2.9	1.5	#	4.43	8.4	11.9	0.116
			COV	0.5%	17.6%	3.7%	1.4%	11.8%	1.7%		1.0%	13.2%	0.2%	#	16.7%	4.2%	1.1%	1.6%
200411030833	3	450	25%	90.4	0.116	0.870	7.273	0.291	596.5		459	20.5	731.1	#	31.26	116.3	669.9	5.058
200411031011	3	450	25%	90.7	0.119	0.883	7.388	0.282	600.8		468	24.7	729.8	#	31.64	116.1	671.3	5.017
200411031157	3	450	25%	90.5	0.099	0.934	7.301	0.230	621.8		464	25.0	728.3	#	26.35	123.4	665.8	5.228
200411031323	3	450	25%	90.7	0.118	0.844	7.227	0.234	625.1		465	23.0	727.5	#	31.45	111.6	661.3	5.256
200411040805	3	450	25%	89.5	0.117	1.028	7.381	0.236	627.2		468	17.1	731.3	#	30.48	133.0	654.0	5.171
200411040944	3	450	25%	90.4	0.104	1.032	7.304	0.227	618.0		468	25.0	731.1	#	27.61	136.0	657.3	5.174
200411041120	3	450	25%	90.4	0.099	1.051	7.336	0.218	621.5		467	20.7	729.8	#	26.28	137.6	649.8	5.190
			ave	90.4	0.1103	0.949	7.316	0.245	615.8		465.5	22.3	729.8	#	29.30	124.9	661.4	5.156
			stdev	0.4	0.0092	0.087	0.058	0.029	12.2		3.2	3.0	1.5	#	2.45	10.7	8.1	0.087
			COV	0.5%	8.4%	9.2%	0.8%	11.6%	2.0%		0.7%	13.4%	0.2%	#	8.4%	8.5%	1.2%	1.7%
200411030833	4	450	5%	18.40	1.122	4.986	12.448	1.386	1384.4		366	20.0	730.6	#	77.29	170.3	293.3	3.010
200411031011	4	450	5%	18.40	1.117	4.935	12.687	1.379	1395.5		374	24.7	729.8	#	75.31	164.7	292.7	2.964
200411031157	4	450	5%	18.40	1.028	4.928	12.273	1.163	1453.8		372	24.0	728.3	#	69.50	165.0	283.3	3.097
200411031323	4	450	5%	18.40	1.085	4.842	12.190	1.122	1482.8		376	23.0	727.5	#	72.63	160.4	278.2	3.127
200411040805	4	450	5%	18.37	1.015	5.534	12.438	1.094	1491.6		375	18.0	731.3	#	68.05	183.9	282.2	3.151
200411040944	4	450	5%	18.37	0.939	5.291	12.474	1.103	1464.6		378	25.4	731.1	#	62.83	175.1	281.4	3.085
200411041120	4	450	5%	18.40	0.936	5.505	12.210	1.024	1441.7		371	20.0	729.8	#	63.95	186.1	278.1	3.101
			ave	18.4	1.0348	5.146	12.389	1.182	1444.9		373.0	22.2	729.8	#	69.94	172.2	284.2	3.076
			stdev	0.0	0.0780	0.292	0.177	0.143	41.2		4.0	2.8	1.4	#	5.48	9.9	6.3	0.066
			COV	0.1%	7.5%	5.7%	1.4%	12.1%	2.9%		1.1%	12.7%	0.2%	#	7.8%	5.8%	2.2%	2.2%

BUG Test Results for PEMS#3 in grams per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions		
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH
200411030833	1	450	366		320	3117		256987	45.6		16.3	740.1	0.896
200411031011	1	450	362		340	2951		254444	42.5		21.6	739.4	0.888
200411031157	1	450	362		357	2834		246819	42.5		24.6	738.0	0.893
200411031323	1	450	360		336	2727		245247	40.4		25.0	736.6	0.870
200411040805	1	450	364		274	2826		237760	35.2		14.6	740.1	0.901
200411040944	1	450	363		281	2954		251947	37.4		16.8	740.4	0.895
200411041120	1	450	363		321	2917		253363	39.8		18.7	739.4	0.908
		ave	362.9	#DIV/0!	318	2904	#DIV/0!	249509	40.5	#DIV/0!	19.7	739.1	0.893
		stdev	1.8	#DIV/0!	31	124.196	#DIV/0!	6639.6	3.5	#DIV/0!	4.1	1.4	0.012
		COV	0.5%	#DIV/0!	9.7%	4.3%	#DIV/0!	2.7%	8.5%	#DIV/0!	21.1%	0.2%	1.3%
200411030833	2	450	240		178	2233		157695	31.9		16.8	740.1	0.890
200411031011	2	450	240		200	2259		164115	31.7		23.0	739.4	0.891
200411031157	2	450	244		215	2183		160201	31.6		24.8	737.7	0.894
200411031323	2	450	241		187	2091		157592	29.6		25.0	736.8	0.875
200411040805	2	450	242		159	2144		152529	28.7		15.2	740.0	0.898
200411040944	2	450	241		165	2242		162679	29.7		17.7	740.0	0.897
200411041120	2	450	241		192	2210		162483	27.7		18.7	739.2	0.911
		ave	241.3	#DIV/0!	185	2194	#DIV/0!	159613	30.1	#DIV/0!	20.2	739.1	0.894
		stdev	1.3	#DIV/0!	20	59.814	#DIV/0!	4004	1.6	#DIV/0!	4.0	1.3	0.011
		COV	0.5%	#DIV/0!	10.5%	2.7%	#DIV/0!	2.5%	5.4%	#DIV/0!	19.9%	0.2%	1.2%
200411030833	3	450	90.4		34.1	841		68888	15.3		17.9	740.1	0.888
200411031011	3	450	90.7		33.4	821		68683	14.1		23.4	739.2	0.888
200411031157	3	450	90.5		24.3	788		66210	14.4		25.0	737.6	0.892
200411031323	3	450	90.7		24.2	761		64045	13.1		25.1	736.8	0.891
200411040805	3	450	89.5		35.3	817		66108	12.9		15.5	740.4	0.898
200411040944	3	450	90.4		23.1	823		68604	14.5		17.9	740.0	0.897
200411041120	3	450	90.4		38.5	800		67038	15.3		18.7	739.1	0.911
		ave	90.4	#DIV/0!	30.4	807	#DIV/0!	67082	14.2	#DIV/0!	20.5	739.1	0.895
		stdev	0.4	#DIV/0!	6.4	26	#DIV/0!	1783	0.9	#DIV/0!	3.9	1.3	0.008
		COV	0.5%	#DIV/0!	20.9%	3.3%	#DIV/0!	2.7%	6.5%	#DIV/0!	19.1%	0.2%	0.9%
200411030833	4	450	18.4										
200411031011	4	450	18.4										
200411031157	4	450	18.4										
200411031323	4	450	18.4		8	159		18108	11.4		24.9	736.7	0.890
200411040805	4	450	18.4		20	129		14434	9.2		15.8	740.5	0.896
200411040944	4	450	18.4		22	138		15017	7.7		18.8	740.0	0.901
200411041120	4	450	18.4		25	165		18585	11.6		19.3	739.1	0.913
		ave	18.4	#DIV/0!	19	148	#DIV/0!	16536	10.0	#DIV/0!	19.7	739.1	0.900
		stdev	0.019	#DIV/0!	7	17	#DIV/0!	2113	1.9	#DIV/0!	3.8	1.7	0.009
		COV	0.1%	#DIV/0!	38.8%	11.6%	#DIV/0!	12.8%	18.6%	#DIV/0!	19.3%	0.2%	1.0%

BUG Test Results for PEMS#3 in grams per hp- hour

					Mass Emission g/Hp/hr						Exh Flow	Ambient Conditions		
Test Name	Mode	Time sec	Load Factor	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH
200411030833	1	450	100%	365.7		0.652	6.356		524.0	0.093		16.3	740.1	0.896
200411031011	1	450	100%	362.4		0.700	6.072		523.5	0.087		21.6	739.4	0.888
200411031157	1	450	100%	361.7		0.736	5.843		508.9	0.088		24.6	738.0	0.893
200411031323	1	450	100%	360.1		0.696	5.648		507.8	0.084		25.0	736.6	0.870
200411040805	1	450	100%	364.1		0.561	5.788		486.9	0.072		14.6	740.1	0.901
200411040944	1	450	100%	363.2		0.576	6.064		517.2	0.077		16.8	740.4	0.895
200411041120	1	450	100%	363.2		0.659	5.990		520.2	0.082		18.7	739.4	0.908
			ave	362.9	#DIV/0!	0.654	5.966	#DIV/0!	512.6	0.083	#DIV/0!	19.7	739.1	0.893
			stdev	1.8	#DIV/0!	0.065	0.232	#DIV/0!	13.1	0.007	#DIV/0!	4.1	1.4	0.012
			COV	0.5%	#DIV/0!	10.0%	3.9%	#DIV/0!	2.5%	0.085	#DIV/0!	21.1%	0.2%	1.3%
200411030833	2	450	65%	240.4		0.552	6.924		489.1	0.099		16.8	740.1	0.890
200411031011	2	450	65%	240.0		0.621	7.017		509.7	0.098		23.0	739.4	0.891
200411031157	2	450	65%	243.9		0.657	6.671		489.7	0.097		24.8	737.7	0.894
200411031323	2	450	65%	241.4		0.576	6.460		486.8	0.092		25.0	736.8	0.875
200411040805	2	450	65%	241.7		0.491	6.612		470.4	0.088		15.2	740.0	0.898
200411040944	2	450	65%	240.9		0.511	6.939		503.5	0.092		17.7	740.0	0.897
200411041120	2	450	65%	240.9		0.593	6.842		502.9	0.086		18.7	739.2	0.911
			ave	241.3	#DIV/0!	0.572	6.781	#DIV/0!	493.2	0.093	#DIV/0!	20.2	739.1	0.894
			stdev	1.3	#DIV/0!	0.059	0.203	#DIV/0!	13.3	0.005	#DIV/0!	4.0	1.3	0.011
			COV	0.5%	#DIV/0!	10.3%	3.0%	#DIV/0!	2.7%	0.054	#DIV/0!	19.9%	0.2%	1.2%
200411030833	3	450	25%	90.4		0.281	6.938		568.5	0.126		17.9	740.1	0.888
200411031011	3	450	25%	90.7		0.275	6.744		564.5	0.116		23.4	739.2	0.888
200411031157	3	450	25%	90.5		0.200	6.490		545.3	0.119		25.0	737.6	0.892
200411031323	3	450	25%	90.7		0.199	6.258		526.3	0.108		25.1	736.8	0.891
200411040805	3	450	25%	89.5		0.294	6.806		550.6	0.108		15.5	740.4	0.898
200411040944	3	450	25%	90.4		0.190	6.795		566.1	0.119		17.9	740.0	0.897
200411041120	3	450	25%	90.4		0.318	6.599		553.2	0.126		18.7	739.1	0.911
			ave	90.4	#DIV/0!	0.251	6.661	#DIV/0!	553.5	0.117	#DIV/0!	20.5	739.1	0.895
			stdev	0.4	#DIV/0!	0.053	0.230	#DIV/0!	14.8	0.008	#DIV/0!	3.9	1.3	0.008
			COV	0.5%	#DIV/0!	21.1%	3.5%	#DIV/0!	2.7%	0.064	#DIV/0!	19.1%	0.2%	0.9%
200411030833	4	450	5%	18.40										
200411031011	4	450	5%	18.40										
200411031157	4	450	5%	18.40										
200411031323	4	450	5%	18.40		0.337	6.442		733.6	0.462		24.9	736.7	0.890
200411040805	4	450	5%	18.37		0.796	5.230		586.0	0.374		15.8	740.5	0.896
200411040944	4	450	5%	18.37		0.896	5.594		609.6	0.314		18.8	740.0	0.901
200411041120	4	450	5%	18.40		1.009	6.680		752.9	0.471		19.3	739.1	0.913
			ave	18.4	#DIV/0!	0.760	5.987	#DIV/0!	670.5	0.405	#DIV/0!	19.7	739.1	0.900
			stdev	0.0	#DIV/0!	0.295	0.687	#DIV/0!	84.9	0.075	#DIV/0!	3.8	1.7	0.009
			COV	0.1%	#DIV/0!	38.8%	11.5%	#DIV/0!	12.7%	0.185	#DIV/0!	19.3%	0.2%	1.0%

BUG Test Results for PEMS #4 in grams per hour

				Mass Emission g/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	RH not kH	THC ppmC	CO ppm	NOx ppm	CO2%
200502020932	1	120	344	89.0	101	2639		214800		977	17.7	743.5	8.200	60.8	58.0	1104	7.86
200502021026	1	120	340	83.2	105	2727		216196		966	17.9	743.4	8.170	55.6	61.5	1108	7.87
200502021103	1	120	343	81.4	113	2680		214322		971	18.3	743.0	7.96	56.5	67.9	1103	7.89
200502021254	1	120	343	59.9	85	2657		216024		971	19.6	742.0	7.270	43.3	49.7	1094	7.95
200502021313	1	120	344	48.8	86	2618		213232		965	20.1	741.8	7.080	34.5	51.9	1084	7.92
200502021333	1	120	343	50.4	84	2594		214418		965	20.3	741.6	6.940	35.3	50.7	1072	7.94
200502021433	1	120	343	59.0	263	2624		216326		966	20.8	741.4	6.640	48.9	182.5	1084	8.01
		ave	342.9	67.4	120	2649		215045		969	19.2	742.4	7.466	47.8	74.6	1093	7.92
		stdev	1.1	16.7	64	44.498		1168.1		4	1.3	0.9	0.636	10.5	48.0	13	0.05
		COV	0.3%	24.8%	53.6%	1.7%		0.5%		0.5%	6.5%	0.1%	8.5%	21.9%	64.4%	1.2%	0.7%
200502020932	2	120	224	74.2	88	1997		140750		725.7	17.5	743.3	8.340	71.8	68.4	1098.2	6.93
200502021026	2	120	225	102.6	101	1998		140333		720.2	18.0	743.5	8.110	96.5	78.3	1109	6.97
200502021103	2	120	226	75.6	98	1993		140788		723.1	18.4	743.0	7.960	72.6	75.3	1103	6.99
200502021254	2	120	226	67.9	65	2004		141805		723.8	19.6	742.0	7.300	62.2	50.0	1107	7.00
200502021313	2	120	226	67.0	91	1977		141249		722.2	20.4	741.7	6.890	62.7	71.1	1094	7.01
200502021333	2	120	226	44.6	75	1936		137717		719.6	20.6	741.4	6.750	43.6	58.9	1091	7.00
200502021433	2	120	226	45.3	263	1965		141587		716.4	20.9	741.3	6.580	44.1	205.8	1096	7.06
		ave	225.4	68.2	112	1982		140604		721.6	19.3	742.3	7.419	64.8	86.8	1100	6.99
		stdev	0.7	19.8	68	23.963		1372		3.1	1.4	0.9	0.715	18.3	53.4	7	0.04
		COV	0.3%	29.1%	61.0%	1.2%		1.0%		0.4%	7.1%	0.1%	9.6%	28.2%	61.5%	0.6%	0.6%
200502020932	3	120	85.2	77.6	1.2	733		67545		481.9	17.6	744.8	8.270	110.4	1.177	608	5.01
200502021026	3	120	84.3	58.1	2.4	725		66993		480.2	17.7	743.2	8.280	79.9	2.642	603	4.99
200502021103	3	120	85.0	59.3	7.2	737		67123		480.1	18.4	742.9	7.970	82.4	8.269	613	5.00
200502021254	3	120	85.8	50.5	0.0	732		67723		480.3	19.6	742.0	7.320	70.3	0.000	608	5.04
200502021313	3	120	86.0	38.9	0.0	732		67192		479.3	20.5	741.7	6.840	55.8	0.112	610	5.01
200502021333	3	120	85.8	24.9	0.0	727		67161		477.3	21.0	741.5	6.550	35.4	0.000	608	5.03
200502021433	3	120	84.1	35.9	120.0	715		66821		473.4	20.6	741.4	6.750	50.7	142.546	604	5.05
		ave	85.2	49.3	18.7	729		67223		478.9	19.3	742.5	7.426	69.3	22.1	608	5.02
		stdev	0.7	17.6	44.7	7		312		2.8	1.4	1.2	0.743	24.7	53.2	4	0.02
		COV	0.9%	35.7%	239.5%	1.0%		0.5%		0.6%	7.4%	0.2%	10.0%	35.6%	240.6%	0.6%	0.4%
200502020932	4	500	17.46	67.8	83	271		37713		410.4	17.1	743.6	8.560	104.5	104.3	250.8	3.04
200502021026	4	500	18.29	72.7	67	275		38201		414.1	17.7	743.2	8.280	110.6	83.7	252	3.04
200502021103	4	500	18.33	101.4	67	276		38437		416.4	19.1	742.9	7.610	151.9	83.1	251	3.04
200502021254	4	120	18.33	59.6	32	272		36207		423.9	19.6	741.9	7.320	95.1	42.0	256	3.06
200502021313	4	120	18.33	50.3	48	274		36321		424.2	20.4	741.7	6.910	80.4	63.2	258	3.06
200502021333	4	120	18.33	34.2	25	273		36299		423.0	21.3	741.5	6.420	54.3	33.0	257	3.06
200502021433	4	500	18.33	42.2	185	276		38906		417.4	20.5	741.3	6.790	63.6	228.7	250	3.07
		ave	18.2	61.2	72	274		37441		418.5	19.3	742.3	7.413	94.3	91.1	254	3.05
		stdev	0.327	22.4	54	2		1145		5.3	1.5	0.9	0.790	32.7	65.6	3	0.01
		COV	1.8%	36.6%	74.2%	0.7%		3.1%		1.3%	7.9%	0.1%	10.7%	34.7%	71.9%	1.3%	0.4%

BUG Test Results for PEMS #4 in grams per hp- hour

					Mass Emission g/hp/hr						Exh Flow	Ambient Conditions			Concentration Measured (wet)			
Test Name	Mode	Time sec	Load Factor	Load kW	THC	CO	kNOx	NO2	CO2	PM	scfm	Temp C	Baro mmHg	kH not kH	THC ppmC	CO ppm	NOx ppm	CO2%
200502020932	1	120	100%	344	0.193	0.220	5.726		466.0		977	17.7	743.5	8.200	121.6	58.0	1730	7.86
200502021026	1	120	100%	340	0.182	0.230	5.975		473.7		966	17.9	743.4	8.170	111.1	61.5	1735	7.87
200502021103	1	120	100%	343	0.177	0.245	5.828		466.0		971	18.3	743.0	7.96	113.1	67.9	1727	7.89
200502021254	1	120	100%	343	0.130	0.185	5.777		469.7		971	19.6	742.0	7.270	86.6	49.7	1713	7.95
200502021313	1	120	100%	344	0.106	0.187	5.680		462.6		965	20.1	741.8	7.080	69.0	51.9	1697	7.92
200502021333	1	120	100%	343	0.110	0.183	5.641		466.3		965	20.3	741.6	6.940	70.7	50.7	1679	7.94
200502021433	1	120	100%	343	0.128	0.571	5.706		470.3		966	20.8	741.4	6.640	97.9	182.5	1697	8.01
			ave	342.9	0.1	0	6		468		969	19.2	742.4	7.466	95.7	74.6	1711	7.92
			stdev	1.1	0.0	0	0.112		3.6		4	1.3	0.9	0.636	21.0	48.0	21	0.05
			COV	0.3%	24.9%	53.5%	1.9%		0.8%		0.5%	6.5%	0.1%	8.5%	21.9%	64.4%	1.2%	0.7%
200502020932	2	120	65%	224	0.247	0.293	6.643		468.1		725.7	17.5	743.3	8.340	143.7	68.4	1720	6.93
200502021026	2	120	65%	225	0.341	0.335	6.633		466.0		720.2	18.0	743.5	8.110	193.1	78.3	1736	6.97
200502021103	2	120	65%	226	0.250	0.324	6.593		465.7		723.1	18.4	743.0	7.960	145.2	75.3	1728	6.99
200502021254	2	120	65%	226	0.225	0.214	6.629		469.1		723.8	19.6	742.0	7.300	124.4	50.0	1733	7.00
200502021313	2	120	65%	226	0.221	0.301	6.516		465.5		722.2	20.4	741.7	6.890	125.5	71.1	1714	7.01
200502021333	2	120	65%	226	0.148	0.248	6.406		455.6		719.6	20.6	741.4	6.750	87.2	58.9	1708	7.00
200502021433	2	120	65%	226	0.150	0.870	6.489		467.4		716.4	20.9	741.3	6.580	88.3	205.8	1716	7.06
			ave	225.4	0.2	0	7		465		721.6	19.3	742.3	7.419	129.6	86.8	1722	6.99
			stdev	0.7	0.1	0	0.090		5		3.1	1.4	0.9	0.715	36.6	53.4	10	0.04
			COV	0.3%	29.3%	60.8%	1.4%		1.0%		0.4%	7.1%	0.1%	9.6%	28.2%	61.5%	0.6%	0.6%
200502020932	3	120	25%	85.2	0.680	0.011	6.424		591.7		481.9	17.6	744.8	8.270	220.8	1.177	952	5.01
200502021026	3	120	25%	84.3	0.514	0.021	6.417		592.7		480.2	17.7	743.2	8.280	159.8	2.642	944	4.99
200502021103	3	120	25%	85.0	0.521	0.063	6.469		589.3		480.1	18.4	742.9	7.970	164.9	8.269	960	5.00
200502021254	3	120	25%	85.8	0.439	0.000	6.368		588.7		480.3	19.6	742.0	7.320	140.5	0.000	953	5.04
200502021313	3	120	25%	86.0	0.337	0.000	6.352		582.9		479.3	20.5	741.7	6.840	111.7	0.112	955	5.01
200502021333	3	120	25%	85.8	0.216	0.000	6.318		583.9		477.3	21.0	741.5	6.550	70.9	0.000	952	5.03
200502021433	3	120	25%	84.1	0.318	1.064	6.341		592.4		473.4	20.6	741.4	6.750	101.4	142.546	945	5.05
			ave	85.2	0.4	0.2	6		589		478.9	19.3	742.5	7.426	138.6	22.1	952	5.02
			stdev	0.7	0.2	0.4	0		4		2.8	1.4	1.2	0.743	49.3	53.2	5	0.02
			COV	0.9%	35.9%	239.7%	0.8%		0.7%		0.6%	7.4%	0.2%	10.0%	35.6%	240.6%	0.6%	0.4%
200502020932	4	500	5%	17.46	2.897	3.534	11.592		1611.4		410.4	17.1	743.6	8.560	208.9	104.3	393	3.04
200502021026	4	500	5%	18.29	2.965	2.741	11.227		1558.1		414.1	17.7	743.2	8.280	221.1	83.7	394	3.04
200502021103	4	500	5%	18.33	4.127	2.735	11.240		1564.4		416.4	19.1	742.9	7.610	303.7	83.1	393	3.04
200502021254	4	120	5%	18.33	2.426	1.294	11.051		1473.7		423.9	19.6	741.9	7.320	190.1	42.0	401	3.06
200502021313	4	120	5%	18.33	2.047	1.954	11.154		1478.3		424.2	20.4	741.7	6.910	160.9	63.2	404	3.06
200502021333	4	120	5%	18.33	1.392	1.001	11.098		1477.4		423.0	21.3	741.5	6.420	108.6	33.0	403	3.06
200502021433	4	500	5%	18.33	1.718	7.509	11.233		1583.5		417.4	20.5	741.3	6.790	127.2	228.7	392	3.07
			ave	18.2	2.5	3	11		1535		418.5	19.3	742.3	7.413	188.6	91.1	397	3.05
			stdev	0.327	0.9	2	0		58		5.3	1.5	0.9	0.790	65.4	65.6	5	0.01
			COV	1.8%	36.6%	73.8%	1.6%		3.7%		1.3%	7.9%	0.1%	10.7%	34.7%	71.9%	1.3%	0.4%

Appendix E – Statistical Comparisons between FRM and PEMS for BUG Testing (in g/hr)

	THC (g/hr)			CO (g/hr)				NO_x (g/hr)				CO_2 (g/hr)				PM (g/hr)	
	PEMS1	PEMS2	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS3
100% load																	
Paired T-Test	0.000	0.002	0.000	0.073	0.000	0.000	0.000	0.000	0.000	0.018	0.002	0.196	0.141	0.505	0.000	0.000	0.000
Unpaired T-test	0.000	0.000	0.000	0.555	0.004	0.003	0.000	0.000	0.000	0.018	0.001	0.164	0.114	0.493	0.000	0.000	0.000
F-Test	0.000	0.000	0.000	0.638	0.725	0.925	0.000	0.043	0.894	0.002	0.630	0.001	0.001	0.000	0.938	0.000	0.750
65% load																	
Paired T-Test	0.001	0.000	0.001	0.709	0.000	0.000	0.002	0.000	0.000	0.290	0.000	0.002	0.000	0.001	0.000	0.000	0.000
Unpaired T-test	0.000	0.000	0.000	0.892	0.000	0.000	0.000	0.000	0.000	0.304	0.000	0.001	0.000	0.000	0.000	0.000	0.000
F-Test	0.000	0.002	0.000	0.439	0.417	0.715	0.000	0.002	0.106	0.001	0.360	0.014	0.003	0.001	0.624	0.000	0.325
25% load																	
Paired T-Test	0.000	0.000	0.001	NA	NA	NA	0.012	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.001
Unpaired T-test	0.000	0.000	0.000	NA	NA	NA	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F-Test	0.000	0.085	0.000	NA	NA	NA	0.000	0.001	0.342	0.000	0.934	0.007	0.002	0.000	0.036	0.000	0.061
5% load																	
Paired T-Test	0.001	0.010	0.004	0.045	0.002	NA	0.048	0.000	0.283	NA	0.000	0.003	0.002	NA	0.823	0.000	NA
Unpaired T-test	0.000	0.173	0.001	0.269	0.000	0.000	0.035	0.000	0.398	0.000	0.000	0.000	0.000	0.000	0.856	0.000	0.000
F-Test	0.001	0.399	0.000	0.511	0.044	0.054	0.000	0.199	0.374	0.001	0.173	0.009	0.000	0.000	0.056	0.000	0.450

Appendix F – Chassis Dynamometer Integrated Individual Test Results for Each Measurement Device

Integrated Test Results for the FRM in grams per cycle

				Mass Emission g/cycle					Exh Flow	Concentration Measured (wet)				
Test Name	Trace	Cycle Dur	Load hp	THC	CO	kNOx	CO2	PM	scfm	THC ppm	CO ppm	NOx ppm	CO2%	kH
200504211014	UDDS	1060		1.30	28.2	57.8	13628	3.55	347	5.12	26.5	31.8	0.807	0.946
200504211054	UDDS	1060		0.48	24.0	58.8	13728	3.61	348	4.34	22.7	32.5	0.812	0.942
200504211152	UDDS	1060		1.18	23.3	59.2	14228	3.77	353	4.86	21.2	33.1	0.832	0.929
200504211413	UDDS	1060		0.57	24.9	59.4	14276	3.81	353	3.49	22.7	32.1	0.836	0.965
200504211446	UDDS	1060		0.73	23.7	62.0	14531	4.00	356	4.47	21.1	33.7	0.854	0.957
200504220900	UDDS	1060		1.36	31.5	55.9	14409	4.07	362	5.36	28.2	29.8	0.845	0.978
200504220935	UDDS	1060		0.93	28.1	55.6	13943	3.87	349	4.83	25.0	29.6	0.823	0.976
		ave	#DIV/0!	0.9	26.2	58.4	14106	3.8	352.6	4.64	23.9	31.8	0.830	0.956
		stdev	#DIV/0!	0.4	3.1	2.207	345.0	0.2	5.2	0.62	2.7	1.6	0.017	0.018
		COV	#DIV/0!	37.7%	11.7%	3.8%	2.4%	4.9%	1.5%	13.3%	11.3%	4.9%	2.0%	1.9%
200504201057	50CRUISE	757		1.32	24.0	94.0	24581	4.30	664.3	5.85	30.2	72.0	1.970	0.954
200504201233	50CRUISE	757		0.85	23.7	95.2	24766	4.20	663.8	5.36	29.6	72.7	1.982	0.956
200504201315	50CRUISE	757		1.28	22.1	95.4	24507	3.98	658.6	5.55	27.6	72.9	1.966	0.956
200504201405	50CRUISE	757		1.09	22.4	97.1	24948	4.16	665.0	4.78	27.8	74.4	2.000	0.954
200504201443	50CRUISE	757		0.99	22.3	98.2	24709	4.29	665.1	4.66	27.8	74.8	1.986	0.959
200504201514	50CRUISE	757		1.02	21.0	99.4	24796	4.95	666.9	4.76	26.2	75.9	1.992	0.959
200504210814	50CRUISE	757		1.48	28.9	87.7	23989	3.42	672.2	6.52	37.6	66.9	1.930	0.957
		ave	#DIV/0!	1.1	23.5	95.3	24614	4.2	665.1	5.35	29.5	72.8	1.975	0.957
		stdev	#DIV/0!	0.2	2.6	3.834	310.9	0.5	4.1	0.69	3.8	2.9	0.023	0.002
		COV	#DIV/0!	19.0%	11.1%	4.0%	1.3%	10.8%	0.6%	12.8%	12.8%	4.0%	1.2%	0.2%
200504191000	NTE_1290	1110		2.62	20.8	172.2	32112	4.12	515.7	8.79	18.7	89.2	1.754	0.963
200504210849	NTE_1290	1110		1.93	24.9	147.4	30227	3.44	507.8	6.19	22.9	77.0	1.662	0.955
200504191046	NTE_1500	1110		1.97	29.0	174.6	37353	4.49	629.2	6.01	25.3	91.0	2.038	0.958
200504220740	NTE_1500	1110		1.43	28.4	182.8	38092	n/a	640.4	5.38	25.4	95.1	2.079	0.959
200504191234	NTE_1770	1110		2.22	32.6	202.8	46741	7.81	800.0	6.03	28.6	105.3	2.551	0.962
200504220814	NTE_1770	1110		2.25	34.6	202.5	47532	n/a	805.1	6.51	29.6	103.5	2.599	0.975
200504191326	NTE_Stepped	1530		2.45	32.0	206.7	49267	6.76	590.8	5.71	20.6	77.6	1.954	0.963
200504191505	NTE_Stepped	1530		2.36	30.1	203.0	50262	5.58	599.5	5.65	19.4	77.2	1.991	0.951
200504191627	NTE_Stepped	1530		2.22	30.1	205.2	49824	5.38	602.8	5.07	19.3	78.2	1.972	0.948
200504210927	NTE_Stepped	1530		1.61	32.1	199.0	49236	5.75	600.9	4.57	21.4	76.0	1.961	0.946
200504211237	NTE_Stepped	1530		1.72	25.8	210.6	51038	6.59	595.5	4.82	16.8	80.3	2.023	0.949
200504211320	NTE_Stepped	1530		1.77	27.5	215.3	51355	7.52	616.7	4.40	10.5	48.8	1.243	0.966

Integrated Test Results for PEMS#1 in gram per cycle

Test Name	Trace	Cycle Dur	Load hp	Mass Emission g/cycle THC	CO	kNOx	NO2	CO2	PM	Exh Flow scfm
200504211014	UDDS	1060								
200504211054	UDDS	1060								
200504211152	UDDS	1060								
200504211413	UDDS	1060								
200504211446	UDDS	1060								
200504220900	UDDS	1060		-0.036	16.185	42.784		8220.939		298.69
200504220935	UDDS	1060		-0.035	18.069	53.845		10116.395		346.57
		ave	#DIV/0!	0.0	17.127	48.315	#DIV/0!	9168.7	#DIV/0!	323
		stdev	#DIV/0!	0.0	1.332	7.821	#DIV/0!	1340.3	#DIV/0!	33.9
		COV	#DIV/0!	-3.2%	7.8%	16.2%	#DIV/0!	14.6%	#DIV/0!	10.5%
200504201057	50CRUISE	757		0.26	18.03	77.48		18759.33		678.11
200504201233	50CRUISE	757								
200504201315	50CRUISE	757								
200504201405	50CRUISE	757								
200504201443	50CRUISE	757								
200504201514	50CRUISE	757								
200504210814	50CRUISE	757		0.36	26.64	87.96		20342.47		487.75
		ave	#DIV/0!	0.3	22.333	82.722	#DIV/0!	19550.9	#DIV/0!	582.9
		stdev	#DIV/0!	0.1	6.091	7.408	#DIV/0!	1119.4	#DIV/0!	134.6
		COV	#DIV/0!	21.5%	27.3%	9.0%	#DIV/0!	5.7%	#DIV/0!	23.1%
200504191000	NTE_1290	1110								
200504210849	NTE_1290	1110		0.225	22.337	155.483		25438.646		521.67
200504191046	NTE_1500	1110								
200504220740	NTE_1500	1110		0.773	23.860	205.638		32922.549		707.71
200504191234	NTE_1770	1110								
200504220814	NTE_1770	1110		0.391	31.908	253.427		45479.916		914.84
200504191326	NTE_Stepped	1530								
200504191505	NTE_Stepped	1530								
200504191627	NTE_Stepped	1530		2.125	22.627	189.423		42741.103		688.42
200504210927	NTE_Stepped	1530								
200504211237	NTE_Stepped	1530								
200504211320	NTE_Stepped	1530								

Integrated Test Results for PEMS#2 in gram per cycle

Date				Mass Emission g/cycle						Exh Flow	Concentration Measured (wet)				
yyyymmddhhmm	Trace	Cycle Dur	Load Hp	THC	CO	kNOx	NO2	CO2	PM	scfm	THC ppm	CO ppm	NOx ppm	CO2%	kH
200504211014	UDDS	1062	76.2	1.267	35.3	64.1	0.92	13999.5		361.1	10.3	120	166.2	2.97	0.918
200504211054	UDDS	1063	77.8	1.486	28.3	65.3	1.29	14152.7		359.7	12.7	94	170.4	2.99	0.913
200504211152	UDDS	1063	79.3	0.966	26.9	66.3	1.51	14430.6		364.2	7.6	86	171.3	2.99	0.906
200504211413	UDDS	1022	81.2	1.391	28.9	64.0	0.06	14330.2		368.8	11.7	98	163.0	3.07	0.929
200504211446	UDDS	1063	80.6	1.097	29.8	68.3	0.30	14793.6		367.5	8.7	98	169.2	3.06	0.924
200504220900	UDDS	1063	78.1	1.182	37.2	65.3	1.78	14457.3		375.4	9.0	116	154.0	2.93	0.963
200504220935	UDDS	1063	77.3	1.207	34.7	64.3	0.02	14286.9		364.5	9.7	111	155.3	2.97	0.959
		ave	78.6	1.23	31.6	65.4	0.8	14350	#DIV/0!	366	9.97	103.3		2.998	0.930
		stdev	1.8	0.17	4.0	1.5	0.7	252.0	#DIV/0!	5.3	1.76	12.4		0.051	0.022
		COV	2.3%	14.2%	0.1	2.3%	85.9%	1.8%	#DIV/0!	1.4%	17.7%	12.0%		1.7%	2.4%
200504201057	50CRUISE	760	203.0	1.086	27.7	99.7	1.58	24985.4		678.7	7.5	87	209.7	4.84	0.929
200504201233	50CRUISE	760	203.1	0.870	29.3	102.0	2.10	24914.6		678.2	6.3	92	214.6	4.83	0.929
200504201315	50CRUISE	760	200.9	0.827	29.0	102.0	2.55	24629.6		672.1	5.5	93	216.0	4.81	0.930
200504201405	50CRUISE	694	222.3	0.674	27.9	102.7	2.54	24796.4		727.9	4.7	93	223.9	5.11	0.925
200504201443	50CRUISE	760	203.1	1.296	25.2	102.5	1.23	25431.1		683.1	9.0	80	212.7	4.89	0.930
200504201514	50CRUISE	760	206.0	1.218	25.8	103.6	1.57	25536.8		682.2	8.4	81	216.2	4.92	0.927
200504210814	50CRUISE	760	200.9	1.266	35.4	97.8	2.17	24997.6		684.3	8.8	111	203.1	4.82	0.931
		ave	205.6	1.03	28.6	101.5	2.0	25042	#DIV/0!	686.7	7.16	91.0		4.890	0.929
		stdev	7.6	0.24	3.3	2.0	0.5	329	#DIV/0!	18.6	1.68	10.4		0.106	0.002
		COV	3.7%	23.6%	11.7%	2.0%	26.1%	1.3%	#DIV/0!	2.7%	23.5%	11.4%		2.2%	0.2%
		missed test start on 20054201405 and 200504191505													
200504191000	NTE_1290	1112	209.1	1.181	31.3	183.1	5.32	33293.5		537.8	7.8	92	369.1	6.07	0.936
200504210849	NTE_1290	1113	202.9	1.588	37.5	165.9	5.29	32331.3		523.7	11.0	118	336.5	6.05	0.927
200504191046	NTE_1500	1112	233.0	0.930	39.5	193.1	6.37	37841.0		647.9	5.0	97	325.2	5.75	0.936
200504220740	NTE_1500	1113	243.0	1.233	38.3	203.2	8.26	39287.1		653.4	6.6	93	344.3	5.92	0.920
200504191234	NTE_1770	1113	268.6	2.314	46.5	212.5	4.26	47913.3		822.1	9.6	91	275.8	5.77	0.934
200504220814	NTE_1770	1113	277.0	2.234	46.3	214.5	5.41	48301.1		814.1	9.3	91	284.1	5.89	0.924
200504191326	NTE_Steppe	1533	220.6	1.952	50.1	222.8	5.18	50357.8		608.3	7.8	89	256.0	5.44	0.933
200504191505	NTE_Steppe	1419	224.5	1.683	44.9	203.7	6.74	47711.3		621.4	7.0	84	249.6	5.42	0.918
200504191627	NTE_Steppe	1533	223.7	2.173	40.0	215.2	7.17	50900.1		611.8	8.5	69	248.6	5.49	0.914
200504210927	NTE_Steppe	1532	224.9	1.019	51.4	219.5	4.82	51343.0		614.9	4.0	93	259.0	5.60	0.920
200504211237	NTE_Steppe	1533	231.9	1.153	34.8	233.4	8.61	51980.3		608.3	4.3	60	270.7	5.62	0.921
200504211320	NTE_Steppe	1533	233.7	1.850	36.5	231.2	6.42	53003.7		617.3	7.0	63	265.9	5.74	0.930

Integrated Test Results for PEMS#3 in grams per cycle

Date yyyymmddhhmm	Trace	Cycle Dur	Load hp	THC	Mass Emission g/cycle CO	kNOx	NO2	CO2	PM	Exh Flow scfm	kH
200504211014	UDDS	1061			22.4	73.6		15134	3.14		0.940
200504211054	UDDS	1062			19.3	68.2		15371	3.03		0.943
200504211152	UDDS	1061			13.4	71.6		15414	3.24		0.930
200504211413	UDDS	1062			17.0	69.7		15635	3.24		0.959
200504211446	UDDS	1062			13.5	73.9		15827	3.43		0.951
200504220900	UDDS	1063			24.1	70.0		15441	3.02		0.977
200504220935	UDDS	1061			21.0	67.4		14931	2.87		0.957
		ave	#DIV/0!	#DIV/0!	18.7	70.6		15393	3.1	#DIV/0!	0.951
		stdev	#DIV/0!	#DIV/0!	4.2	2.513		297.6	0.2	#DIV/0!	0.015
		COV	#DIV/0!	#DIV/0!	22.5%	3.6%		1.9%	5.9%	#DIV/0!	1.6%
200504201057	50CRUISE	759			19.9	107.4		28502	4.14		0.948
200504201233	50CRUISE	759			17.9	110.6		28336	3.82		0.948
200504201315	50CRUISE	759			20.1	113.3		29020	3.95		0.950
200504201405	50CRUISE	759			13.9	107.2		27054	3.76		0.941
200504201443	50CRUISE	758			15.4	108.0		27266	3.87		0.944
200504201514	50CRUISE	759			11.9	115.7		27940	3.66		0.950
200504210814	50CRUISE	759			25.5	107.9		27578	3.80		0.944
		ave	#DIV/0!	#DIV/0!	17.8	110.0		27957	3.9	#DIV/0!	0.946
		stdev	#DIV/0!	#DIV/0!	4.6	3.322		707.9	0.2	#DIV/0!	0.003
		COV	#DIV/0!	#DIV/0!	25.7%	3.0%		2.5%	4.0%	#DIV/0!	0.4%
200504191000	NTE_1290	1112			12.0	193.2		35825	4.18		0.958
200504210849	NTE_1290	1112			16.6	177.9		34741	3.25		0.943
200504191046	NTE_1500	1113			21.1	200.2		42804	6.26		0.942
200504220740	NTE_1500	1112			19.7	209.0		42278	4.44		0.937
200504191234	NTE_1770	1111			25.0	227.2		52372	11.67		0.955
200504220814	NTE_1770	1112			25.3	234.1		53304	8.28		0.947
200504191326	NTE_Stepped	1507			21.0	229.1		54092	4.76		0.944
200504191505	NTE_Stepped										
200504191627	NTE_Stepped										
200504210927	NTE_Stepped	1532			20.4	242.2		56582	4.84		0.941
200504211237	NTE_Stepped	1532			10.0	254.9		57666	5.15		0.956
200504211320	NTE_Stepped	1532			13.3	258.0		57846	6.44		0.955

Integrated Test Results for PEMS #4 in grams per cycle

Date				Mass Emission g/cycle						Exh Flow	Concentration Measured (wet)				
yyyymmddhhmm	Trace	Cycle Dur	Load Hp	THC	CO	kNOx	NO2	CO2	PM	scfm	THC ppm	CO ppm	NOx ppm	CO2%	kH
200504211014	UDDS	1060	21.58			71.7		16058		347.05	149.27		167.9	3.334	
200504211054	UDDS	1060	22.32	1.28		74.0		15851		346.54	11.40		173.4	3.281	
200504211152	UDDS	1060	22.52	1.28		74.9		16108		353.00	10.41		171.9	3.253	
200504211413	UDDS	1060	22.76	1.43		73.6		16023		351.56	12.06		168.9	3.279	
200504211446	UDDS	1060	23.31	1.26		76.0		16238		354.45	10.44		173.3	3.288	
200504220900	UDDS	1060	22.22	1.56		70.3		15834		364.87	12.35		159.8	3.120	
200504220935	UDDS	1060	22.20	1.38		72.1		15800		350.52	11.29		169.8	3.199	
		ave	22.4	1.364	#DIV/0!	73.2	#DIV/0!	15987	#DIV/0!	353	31.03	#DIV/0!	169.3	3.251	#DIV/0!
		stdev	0.5	0.1	#DIV/0!	2.0	#DIV/0!	163.7	#DIV/0!	6.2	52.14	#DIV/0!	4.7	0.071	#DIV/0!
		COV	2.4%	8.5%	#DIV/0!	0.0	#DIV/0!	1.0%	#DIV/0!	1.7%	168.0%	#DIV/0!	2.8%	2.2%	#DIV/0!
200504201057	50CRUISE														
200504201233	50CRUISE														
200504201315	50CRUISE														
200504201405	50CRUISE														
200504201443	50CRUISE														
200504201514	50CRUISE														
200504210814	50CRUISE	757	42.00	1.4		121.0		29166		688.01	9.73		231.2	5.567	
		ave	42.0	1.4	#DIV/0!	121.0	#DIV/0!	29166	#DIV/0!	688	9.73	#DIV/0!	231.2	5.567	#DIV/0!
		stdev	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
		COV	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
200504191000	NTE_1290														
200504210849	NTE_1290	1110	63.08	1.8		206.7		36694		512.82	13.15		395.3	6.993	
200504191046	NTE_1500														
200504220740	NTE_1500	1110	75.27	1.0		250.3		48093		655.94	5.74		407.8	7.586	
200504191234	NTE_1770														
200504220814	NTE_1770	1110	85.66	0.9		263.7		52976		817.76	3.85		320.7	6.389	
200504191326	NTE_Stepped														
200504191505	NTE_Stepped														
200504191627	NTE_Stepped														
200504210927	NTE_Stepped	1530	95.77	1.8		206.7		58030		624.65	7.33		322.4	6.617	
200504211237	NTE_Stepped	1530	98.85	1.7		272.6		60995		607.20	6.68		293.1	6.624	
200504211320	NTE_Stepped	1530	99.69	1.7		266.3		60803		617.92	6.86		292.6	6.693	

Appendix G – Statistical Comparisons between FRM and PEMS for Integrated Chassis Dynamometer Cycles (p-values)

	THC			CO				NO_x				CO_2				PM
	PEMS1	PEMS2	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS1	PEMS2	PEMS3	PEMS4	PEMS3
UDDS																
Paired T-Test	0.114	0.157	0.011	0.132	0.000	0.000	NA	0.415	0.000	0.000	0.000	0.147	0.005	0.000	0.000	0.000
Unpaired T-test	0.008	0.074	0.016	0.006	0.016	0.002	NA	0.010	0.000	0.000	0.000	0.000	0.157	0.000	0.000	0.000
F-Test	0.005	0.110	0.027	0.640	0.527	0.466	NA	0.024	0.378	0.761	0.805	0.016	0.464	0.729	0.092	0.974
50 mph cruise																
Paired T-Test	0.017	0.605	NA	0.266	0.001	0.001	NA	0.510	0.001	0.000	NA	0.144	0.016	0.000	NA	0.138
Unpaired T-test	0.001	0.653	NA	0.676	0.012	0.014	NA	0.010	0.006	0.000	NA	0.000	0.025	0.000	NA	0.094
F-Test	0.457	0.901	NA	0.115	0.434	0.196	NA	0.203	0.212	0.737	NA	0.023	0.821	0.065	NA	0.018
NTE 1290																
Paired T-Test	NA	0.351	NA	NA	0.055	0.015	NA	NA	0.162	0.117	NA	NA	0.174	0.062	NA	0.699
Unpaired T-test	NA	0.156	NA	NA	0.090	0.111	NA	NA	0.434	0.219	NA	NA	0.261	0.063	NA	0.923
F-Test	NA	0.901	NA	NA	0.758	0.941	NA	NA	0.772	0.702	NA	NA	0.601	0.665	NA	0.807
NTE 1550																
Paired T-Test	NA	0.380	NA	NA	0.016	0.029	NA	NA	0.030	0.008	NA	NA	0.253	0.083	NA	NA
Unpaired T-test	NA	0.183	NA	NA	0.005	0.009	NA	NA	0.095	0.050	NA	NA	0.409	0.009	NA	NA
F-Test	NA	0.653	NA	NA	0.659	0.567	NA	NA	0.872	0.950	NA	NA	0.601	0.788	NA	NA
NTE 1770																
Paired T-Test	NA	0.574	NA	NA	0.055	0.065	NA	NA	0.067	0.082	NA	NA	0.130	0.008	NA	NA
Unpaired T-test	NA	0.426	NA	NA	0.006	0.014	NA	NA	0.009	0.015	NA	NA	0.158	0.011	NA	NA
F-Test	NA	0.383	NA	NA	0.139	0.178	NA	NA	0.187	0.054	NA	NA	0.580	0.896	NA	NA
NTE Stepped																
Paired T-Test	NA	0.083	0.784	NA	0.005	0.001	NA	NA	0.001	0.005	0.136	NA	0.003	0.001	0.001	0.011
Unpaired T-test	NA	0.171	0.209	NA	0.004	0.001	NA	NA	0.002	0.000	0.021	NA	0.043	0.000	0.000	0.103
F-Test	NA	0.472	0.032	NA	0.030	0.133	NA	NA	0.532	0.104	0.002	NA	0.757	0.188	0.228	0.979

Appendix H – bs and fs Emissions Results for NTE Steady State Cycles

	bsNOx			bsTHC			bsCO		BsCO2		
	FRM	PEMS2	PEMS4	FRM	PEMS2	PEMS4	FRM	PEMS2	FRM	PEMS2	PEMS4
1290 70% load #1	1.92	2.11	#N/A	#DIV/0!	0.01	#N/A	0.29	0.44	462.0	490.4	#N/A
1290 70% load #2	1.80	2.08	2.53	0.02	0.02	0.02	0.32	0.52	450.8	493.4	556.3
1290 100% load #1	2.29	2.43	#N/A	#DIV/0!	0.00	#N/A	0.26	0.37	453.6	478.2	#N/A
1290 100% load #2	2.20	2.46	3.13	0.02	0.01	0.01	0.24	0.38	442.5	481.1	552.4
1500 40% load #1	2.50	2.80	#N/A	0.04	0.03	#N/A	0.80	1.05	584.7	602.9	#N/A
1500 40% load #2	2.33	2.67	3.24	0.04	0.04	0.04	0.72	0.91	567.0	598.7	727.9
1500 70% load #1	1.82	2.00	#N/A	0.02	0.01	#N/A	0.35	0.48	471.0	488.7	#N/A
1500 70% load #2	1.76	1.99	2.46	0.01	0.01	0.01	0.32	0.46	462.9	491.4	597.9
1500 100% load #1	2.03	2.19	#N/A	0.02	0.00	#N/A	0.27	0.38	466.6	484.3	#N/A
1500 100% load #2	2.09	2.31	2.96	0.01	0.00	0.00	0.27	0.37	460.4	483.2	599.7
1770 40% load #1	1.82	2.07	#N/A	0.04	0.05	#N/A	0.75	0.97	598.7	630.3	#N/A
1770 40% load #2	1.79	1.98	2.30	0.04	0.05	0.03	0.75	0.93	575.9	608.3	630.0
1770 70% load #1	1.82	1.95	#N/A	0.02	0.02	#N/A	0.35	0.52	520.0	543.4	#N/A
1770 70% load #2	1.79	1.96	2.32	0.02	0.02	0.01	0.34	0.50	509.3	535.2	574.1
1770 100% load #1	2.34	2.40	#N/A	0.02	0.01	#N/A	0.24	0.37	508.5	524.2	#N/A
1770 100% load #2	2.30	2.40	3.02	0.02	0.01	0.00	0.25	0.36	498.9	520.2	575.4

	fsNOx			fsTHC			fsCO	
	FRM	PEMS2	PEMS4	FRM	PEMS2	PEMS4	FRM	PEMS2
1290 70% load #1	0.013	0.014	#N/A	#DIV/0!	0.00009	#N/A	0.00007	0.00008
1290 70% load #2	0.013	0.014	0.014	0.00017	0.00011	0.00013	0.00017	0.00016
1290 100% load #1	0.016	0.017	#N/A	#DIV/0!	0.00003	#N/A	0.00017	0.00018
1290 100% load #2	0.016	0.017	0.018	0.00013	0.00005	0.00005	0.00019	0.00020
1500 40% load #1	0.014	0.015	#N/A	0.00023	0.00017	#N/A	0.00006	0.00011
1500 40% load #2	0.013	0.014	0.014	0.00022	0.00020	0.00016	0.00004	0.00011
1500 70% load #1	0.012	0.013	#N/A	0.00014	0.00007	#N/A	0.00017	0.00016
1500 70% load #2	0.012	0.013	0.013	0.00010	0.00010	0.00007	0.00017	0.00015
1500 100% load #1	0.014	0.015	#N/A	0.00011	0.00002	#N/A	0.00035	0.00023
1500 100% load #2	0.014	0.016	0.016	0.00004	0.00003	0.00002	0.00019	0.00019
1770 40% load #1	0.010	0.011	#N/A	0.00019	0.00025	#N/A	0.00004	0.00016
1770 40% load #2	0.010	0.010	0.012	0.00019	0.00025	0.00014	0.00004	0.00013
1770 70% load #1	0.011	0.012	#N/A	0.00014	0.00014	#N/A	0.00015	0.00021
1770 70% load #2	0.011	0.012	0.013	0.00014	0.00014	0.00005	0.00016	0.00021
1770 100% load #1	0.015	0.015	#N/A	0.00010	0.00009	#N/A	0.00013	0.00013
1770 100% load #2	0.015	0.015	0.017	0.00010	0.00008	0.00000	0.00015	0.00015

Appendix I – Statistical Comparisons for NTE Steady State Cycles (g/bhp-hr)

		NOx		CO2		CO	THC	
		PEMS2	PEMS4	PEMS2	PEMS4	PEMS2	PEMS2	PEMS4
1290 70% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000	NA	NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	NA	NA
	F-Test	0.270	NA	0.477	NA	0.492	0.000	NA
1290 70% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.000	0.053
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.000	0.077
	F-Test	0.937	0.939	0.139	0.691	0.888	0.007	0.004
1290 100% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000	NA	NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	NA	NA
	F-Test	0.651	NA	0.642	NA	0.735	NA	NA
1290 100% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-Test	0.849	1.000	0.534	0.814	0.796	0.000	0.000
1500 40% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000	0.000	NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	0.000	NA
	F-Test	0.311	NA	0.656	NA	0.211	0.051	NA
1500 40% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.460	0.219
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.462	0.182
	F-Test	0.008	0.118	0.334	0.000	0.022	0.000	0.006
1500 70% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000	0.000	NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	0.000	NA
	F-Test	0.001	NA	0.558	NA	0.942	0.078	NA
1500 70% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.040	0.001
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.490	0.170
	F-Test	0.280	0.370	0.413	0.796	0.896	0.451	0.596
1500 100% load #1	Paired T-Test	0.073	NA	0.000	NA	0.000	0.000	NA
	Unpaired T-test	0.007	NA	0.000	NA	0.001	0.000	NA
	F-Test	0.947	NA	0.115	NA	0.608	0.370	NA
1500 100% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Unpaired T-test	0.000	0.000	0.000	0.000	0.001	0.000	0.278
	F-Test	0.882	0.630	0.247	0.283	0.946	0.052	0.835
1770 40% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000		NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	0.000	NA
	F-Test	0.525	NA	0.992	NA	0.006	0.307	NA
1770 40% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-Test	0.885	0.469	0.415	0.673	0.012	0.287	0.445
1770 70% load #1	Paired T-Test	0.000	NA	0.000	NA	0.000	0.065	NA
	Unpaired T-test	0.000	NA	0.000	NA	0.000	0.278	NA
	F-Test	0.436	NA	0.989	NA	0.405	0.077	NA
1770 70% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.275	0.000
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.446	0.000
	F-Test	0.041	0.134	0.566	0.406	0.547	0.015	0.020
1770 100% load #1	Paired T-Test	0.001	NA	0.000	NA	0.000	0.000	NA
	Unpaired T-test	0.003	NA	0.000	NA	0.000	0.000	NA
	F-Test	0.477	NA	0.021	NA	0.992	0.913	NA
1770 100% load #2	Paired T-Test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Unpaired T-test	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	F-Test	0.085	0.065	0.304	0.072	0.955	0.957	0.804

Appendix J Statistical Comparisons for NTE Stepped Cycles (g/bhp-hr)

		NOx		CO2		CO	THC	
		PEMS2	PEMS4	PEMS2	PEMS4	PEMS2	PEMS2	PEMS4
NTE_Stepped_1	Paired T-Test	0.000	0.018	0.001	0.000	0.005	0.007	0.000
	Unpaired T-test	0.003	0.001	0.020	0.000	0.022	0.020	0.000
	F-Test	0.634	0.046	0.818	0.749	0.182	0.247	0.322
NTE_Stepped_2	Paired T-Test	0.000	0.180	0.000	0.000	0.002	0.773	0.103
	Unpaired T-test	0.002	0.086	0.001	0.000	0.002	0.847	0.027
	F-Test	0.593	0.046	0.976	0.749	0.024	0.150	0.322
NTE_Stepped_3	Paired T-Test	0.004	0.081	0.000	0.002	0.003	0.033	0.240
	Unpaired T-test	0.000	0.013	0.000	0.000	0.001	0.093	0.198
	F-Test	0.302	0.166	0.959	0.887	0.069	0.161	0.287
NTE_Stepped_4	Paired T-Test	0.001	0.255	0.000	0.000	0.002	0.014	0.286
	Unpaired T-test	0.000	0.246	0.000	0.000	0.001	0.079	0.299
	F-Test	0.793	0.044	0.580	0.741	0.015	0.285	0.196
NTE_Stepped_5	Paired T-Test	0.000	0.093	0.000	0.000	0.001	0.004	0.092
	Unpaired T-test	0.000	0.046	0.001	0.000	0.005	0.067	0.083
	F-Test	0.034	0.014	0.892	0.821	0.118	0.667	0.910
NTE_Stepped_6	Paired T-Test	0.002	0.039	0.000	0.000	0.002	0.002	0.445
	Unpaired T-test	0.000	0.008	0.000	0.000	0.011	0.107	0.413
	F-Test	0.323	0.094	0.721	0.622	0.144	0.796	0.939
NTE_Stepped_7	Paired T-Test	0.001	0.029	0.001	0.000	0.002	0.249	0.269
	Unpaired T-test	0.000	0.002	0.001	0.000	0.003	0.518	0.118
	F-Test	0.640	0.300	0.319	0.931	0.042	0.524	0.443
NTE_Stepped_8	Paired T-Test	0.000	0.019	0.000	0.000	0.001	0.032	0.412
	Unpaired T-test	0.003	0.001	0.001	0.000	0.000	0.086	0.221
	F-Test	0.599	0.568	0.542	0.718	0.025	0.333	0.928
NTE_Stepped_9	Paired T-Test	0.000	#N/A	0.000	#N/A	0.002	0.012	#N/A
	Unpaired T-test	0.000	#N/A	0.000	#N/A	0.001	0.019	#N/A
	F-Test	0.836	#N/A	0.765	#N/A	0.017	0.188	#N/A
NTE_Stepped_10	Paired T-Test	0.001	#N/A	0.000	#N/A	0.001	0.031	#N/A
	Unpaired T-test	0.000	#N/A	0.000	#N/A	0.001	0.077	#N/A
	F-Test	0.767	#N/A	0.699	#N/A	0.032	0.203	#N/A
NTE_Stepped_11	Paired T-Test	0.000	#N/A	0.000	#N/A	0.001	0.017	#N/A
	Unpaired T-test	0.000	#N/A	0.000	#N/A	0.002	0.056	#N/A
	F-Test	0.744	#N/A	0.915	#N/A	0.100	0.405	#N/A
NTE_Stepped_12	Paired T-Test	0.011	#N/A	0.010	#N/A	0.006	0.028	#N/A
	Unpaired T-test	0.001	#N/A	0.002	#N/A	0.035	0.134	#N/A
	F-Test	0.807	#N/A	0.109	#N/A	0.208	0.770	#N/A

Appendix K – PM data for PEMS 3, 5, 7, 8 and FRM including EC/OC

Setup Information			Other Values		PM Values (g/cycle)							Exh Flow	Ambient Conditions		
Test Name	Trace	Cycle Dur	Vmix_m3	SecDF	FRM	PEMS 3	PEMS 5	PEMS 7	PEMS 8	FRM EC	FRM OC	scfm	Temp C	Baro mmHg	kH
200504211014	UDDS	1060	1000.7	2.516	3.55	3.14	5.65	3.09	5.16	2.45	0.59	347	19.5	752.7	0.946
200504211054	UDDS	1060	1000.7	2.516	3.61	3.03	6.39	3.08	5.26	2.55	0.63	348	20.2	752.6	0.942
200504211152	UDDS	1060	1000.8	2.516	3.77	3.24	6.77	3.26	5.54	n/a	n/a	353	22.1	752.4	0.929
200504211413	UDDS	1060	1000.8	2.516	3.81	3.24	5.86	3.34	5.41	n/a	n/a	353	24.9	751.7	0.965
200504211446	UDDS	1060	1000.7	2.516	4.00	3.43	6.10	3.48	5.73	n/a	n/a	356	25.1	751.2	0.957
200504220900	UDDS	1060	1000.7	2.516	4.07	3.02	5.60	n/a	5.16	n/a	n/a	362	19.6	751.0	0.978
200504220935	UDDS	1060	1000.6	2.516	3.87	2.87	5.34	n/a	4.99	n/a	n/a	349	18.4	751.1	0.976
		ave	1001	2.516	3.81	3.14	5.96	3.25	5.32	2.50	0.61	353	21.4	751.8	0.956
		stdev	0.054	0.000	0.19	0.19	0.50	0.17	0.25	0.07	0.03	5	2.7	0.8	0.018
		COV	0%	0%	5%	6%	8%	5%	5%	3%	4%	1.5%	12.7%	0.1%	1.9%
200504201057	50CRUISE	757	714.5	2.516	4.30	4.14	6.74	3.53	5.64	3.08	0.85	664	18.1	753.5	0.954
200504201233	50CRUISE	757	714.6	2.516	4.20	3.82	6.45	3.46	5.55	3.03	0.81	664	20.5	752.8	0.956
200504201315	50CRUISE	757	714.3	2.516	3.98	3.95	6.31	3.33	5.32	2.86	0.74	659	20.7	752.8	0.956
200504201405	50CRUISE	757	714.3	2.516	4.16	3.76	6.29	3.38	5.51	2.84	0.77	665	21.1	752.8	0.954
200504201443	50CRUISE	757	714.4	2.516	4.29	3.87	6.30	3.44	5.60	2.97	0.61	665	21.0	752.8	0.959
200504201514	50CRUISE	757	714.3	2.516	4.95	3.66	6.10	partial	5.40	2.74	0.83	667	20.8	752.5	0.959
200504210814	50CRUISE	757	714.5	2.516	3.42	3.80	6.74	3.51	5.60	2.42	0.59	672	17.0	753.4	0.957
		ave	714	2.516	4.19	3.86	6.42	3.44	5.52	2.85	0.74	665	19.9	752.9	0.957
		stdev	0.098	0.000	0.45	0.15	0.24	0.08	0.12	0.22	0.11	4.1	1.6	0.4	0.002
		COV	0%	0%	11%	4%	4%	2%	2%	8%	14%	0.6%	8.3%	0.0%	0.2%
200504191000	NTE_1290	1110	1047.3	1.573	4.12	4.18	6.02	n/a	n/a	n/a	n/a	516	16.5	750.4	0.963
200504210849	NTE_1290	1110	1047.2	2.516	3.44	3.25	5.52	2.90	4.88	2.42	0.59	508	17.2	753.2	0.955
200504191046	NTE_1500	1110	1047.2	1.573	4.49	6.26	6.43	n/a	n/a	n/a	n/a	629	17.5	750.4	0.958
200504220740	NTE_1500	1110	1047.2	2.516	n/a	4.44			6.52	n/a	n/a	640	18.9	749.5	0.959
200504191234	NTE_1770	1110	1047.1	2.061	7.81	11.67	8.25	invalid	9.69	n/a	n/a	800	19.8	750.2	0.962
200504220814	NTE_1770	1110	1047.1	2.516	n/a	8.28	10.15	n/a	10.53	n/a	n/a	805	19.7	750.0	0.975
200504191326	NTE_Stepped	1530	1443.9	1.139	invalid	4.76	n/a	partial	6.62	n/a	n/a	591	20.0	750.0	0.963
200504191505	NTE_Stepped	1530	1443.9	2.516	5.58	n/a	6.23	4.20	7.70	n/a	n/a	599	19.6	750.3	0.951
200504191627	NTE_Stepped	1530	1443.9	2.516	5.38	n/a	6.00	4.18	7.41	n/a	n/a	603	19.2	750.4	0.948
200504210927	NTE_Stepped	1530	1444.1	2.516	5.75	4.84	7.42	4.40	8.33	3.61	1.27	601	18.3	753.1	0.946
200504211237	NTE_Stepped	1530	1443.9	2.516	6.59	5.15	8.65	5.28	10.42	n/a	n/a	596	24.8	752.3	0.949
200504211320	NTE_Stepped	1530	2383.0	2.516	7.52	6.44	7.11	6.01	10.35	n/a	n/a	617	25.0	750.9	0.966

Appendix L – Statistical results for PEMS 3, 5, 7, 8, and EC compared to FRM gravimetric

Paired t-test	PEMS 5	PEMS 7	PEMS 8	PEMS 3	EC
UDDS	0.000	0.000	0.000	0.000	0.015
50 MPH Cruise	0.000	0.008	0.000	0.138	0.000
NTE 1290	0.029	n/a	n/a	n/a	n/a
NTE 1500	n/a	n/a	n/a	n/a	n/a
NTE 1770	n/a	n/a	n/a	n/a	n/a
NTE stepped	0.102	0.000	0.001	0.018	n/a

unpaired t-test	PEMS 5	PEMS 7	PEMS 8	PEMS 3	EC
UDDS	0.000	0.000	0.000	0.000	0.000
50 MPH Cruise	0.000	0.002	0.000	0.094	0.000
NTE 1290	0.042	n/a	n/a	n/a	n/a
NTE 1500	n/a	n/a	n/a	n/a	n/a
NTE 1770	n/a	n/a	n/a	n/a	n/a
NTE stepped	0.174	0.036	0.018	0.170	n/a

F-test	PEMS 5	PEMS 7	PEMS 8	PEMS 3	EC
UDDS	0.033	0.892	0.483	0.974	0.587
50 MPH Cruise	0.154	0.001	0.004	0.018	0.107
NTE 1290	0.807	n/a	n/a	0.807	n/a
NTE 1500	n/a	n/a	n/a	n/a	n/a
NTE 1770	n/a	n/a	n/a	n/a	n/a
NTE stepped	0.742	0.858	0.285	0.866	n/a

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[3] US Environmental Protection Agency, *Test Plan to Determine PEMS Measurement Allowances for the Gaseous Emissions Under the Manufacturer-Run Heavy-duty Diesel Engine In-Use Testing Program*, EPA Docket #OAR-2004-0072-0069, May 2005, p. 9.

[4] Kean, A. J., Sawyer, R. J., Harley, R. A., *A Fuel-Based Assessment of Off-Road Diesel Engine Emissions,* J. Air & Waste Manage. Assoc. **50**:1929-1939 (2000)

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