Title

PM PEM’s Pre-Measurement Allowance – On-Road Evaluation and Investigation

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Publication Date

2009

Final Report

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January 2009

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Disclaimer

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Acknowledgments

The authors thank the following organizations and individuals for their valuable contributions to this project.

The authors acknowledge the support of the MASC that includes EPA, CARB, and the EMA for assistance in developing and carrying out this program.

The authors acknowledge Sensors Inc., Horiba, and AVL for providing the PM PEMS as an in-kind contribution to the program and in providing assistance and training during the set up of the on-road testing.

We acknowledge the funding from the California Air Resources Board (CARB).

We acknowledge Mr. Donald Pacocha, University of California at Riverside, for his contribution in setting up and executing this field project, the data collection and quality control.

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Abstract

Regulatory agencies are in the process of implementing an in-use testing program for heavy-duty diesel vehicles that will include testing with portable emissions measurement systems (PEMS) under in-use driving conditions. An important aspect of this regulation is the Measurement Allowance program where EPA, CARB, and the Engine Manufacturers Association (EMA) are working together to systematically evaluate various sources of error for gaseous and PM measurements with PEMS in comparison with laboratory measurements. This error is then accounted for in the regulatory standards as a "Measurement Allowance". A comprehensive program has already been conducted for the gas-phase measurement allowance, with the PM measurement allowance program about to begin. The main objective of this work was to provide preliminary measurements from PM PEMS to assess the accuracy of PM measurements under in-use conditions and provide a basis for the development of the more comprehensive Measurement Allowance program. The MASC utilized the University of California, Riverside (UCR) Bourns College of Engineering – Center for Environmental Research and Technology's (CE-CERT) Mobile Emissions Laboratory (MEL) to perform the initial in-use PM PEMS evaluation.

For this program, PM PEMS were directly compared with the MEL over a series of different on-road driving conditions. Prior to the on-road testing, MEL underwent a 40CFR Part 1065 self-audit focused on PM sampling. In-use measurements were made from a class 8 truck whose in-use PM emissions levels averaged 0.043 g/hp-h, which is near the 0.03 g/hp-h in-use threshold level. The goal was to test a vehicle at or slightly above the Not-To-Exceed (NTE) threshold to investigate sources of error for the PM instruments at levels where their performance is most critical. The on-road driving courses included segments near sea level, in coastal regions, in desert regions, and on longer uphill inclines. PM measurements in real-time were made with a variety of different PM instruments from manufacturers preparing for the PM Measurement Allowance program, as well as other commercially available instruments such as a Dekati DMM and TSI Dustrak. These measurements were directly compared with gravimetric PM mass measurements that were collected with the MEL under 1065 compliant sampling conditions. Measurements were made under conditions where NTE events would be expected (e.g., uphill driving segments) and for varying durations to provide a range of mass loadings. Comparisons of the performance of the instruments and PM mass measurements from 0.02 to 0.1 g/hp-h are be presented. The results of this study are expected to be an important component of PM Measurement Allowance program development.

Acronyms and Abbreviations

ARB	Air Resources Board
bs	brake specific
CARB	California Air Resources Board
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFO	critical flow orifice
CFR	Code of Federal Regulations
CO	carbon monoxide
COV	coefficient of variation
CO2	carbon dioxide
CVS	constant volume sampling
DMM	Dekati Mass Monitor
Dp	particle diameter
DPF	diesel particulate filter
DR	dilution ratio
EAD	electrical aerosol detector
EC	elemental carbon
ECM	engine control module
EMA	Engine Manufacturers Association
EPA	United States Environmental Protection Agency
FID	flame ionization detector
FTP	Federal Test Procedure
g/mi	grams per mile
g/hp-h	grams per brake horsepower hour
lpm	liters per minute
MA	Measurement Allowance
MASC	Measurement Allowance Steering Committee
MDL	minimum detection limit
MEL	CE-CERT’s Mobile Emissions Laboratory
MFC	mass flow controller
nm	nanometers
NMHC	non-methane hydrocarbons
NTE	Not-to-exceed
NO_x	nitrogen oxides
OC	organic carbon
PEMS	portable emissions measurement systems
PM	particulate matter
QCM	quartz crystal microbalance
RPM	revolutions per minute
scfm	standard cubic feet per minute
SEE	standard error estimate
SMPS	scanning mobility particle sampler
SOF	soluble organic fraction
SwRI	Southwest Research Institute

THC	total hydrocarbons
UCR	University of California at Riverside
ULSD	ultralow sulfur diesel

Executive Summary

In recent years, the US Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have promulgated regulations to further control diesel emissions. The most recent regulation has targeted in-use emissions and the protocols required to make those measurements. An important aspect of the in-use regulation is the measurement error between a portable emissions measurement system (PEMS) and a Code of Federal Regulations (CFR) reference laboratory. The measurement error is accounted for in the regulatory standards as a "Measurement Allowance". A Measurement Allowance Steering Committee (MASC) was formed between the EPA, CARB and Engine Manufactures Association (EMA) to work together in developing a PEMS measurement allowance. A comprehensive program has already been conducted for the gas-phase measurement allowance, with the PM measurement allowance program about to begin.

The main objective of this work was to provide preliminary measurements from PM PEMS to assess the accuracy of PM measurements under in-use conditions and provide a basis for the development of the more comprehensive Measurement Allowance (MA) program. The MASC relied on the University of California, Riverside (UCR) Bourns College of Engineering – Center for Environmental Research and Technology's (CE-CERT) Mobile Emissions Laboratory (MEL) to perform the in-use, pilot PM PEMS evaluation. For this program, PM PEMS were directly compared with the MEL over a series of different on-road driving conditions. Prior to the on-road testing, MEL underwent a 40CFR Part 1065 audit focused on PM sampling.

PM 1065 Audit

Part of the program design required that UCR's MEL undergo a 40CFR Part 1065 self-audit for PM criteria selected by the MASC, as shown in Table ES-1 below. All checks were found to pass and the system to comply with 40CFR Part 1065.

CFR Reference	Analyzer Verified	1065 Section Title
1065.307	THC FID	Linearity
1065.307	PM balance	Linearity
1065.307	PM filter temperature	Linearity
1065.341	CVS propane check	CVS and batch sampler verification
1065.341	PM filter sample flow propane check	CVS and batch sampler verification
1065.345	PM sample flow meter	Vacuum leak verification
1065.390	PM balance independent certification	PM balance and weighing
1065.390	PM balance	Zero, span, and reference sample verifications
1065.545	PM filter flow meter controller	Validation of proportional flow control for batch sampling

Table ES-1. PM 1065 MEL PM self audit list performed

On-Road Testing Description

PM PEMS

Five PM PEMS were tested in this program, representing different levels of technology and technological advancement with respect to meeting the in-use testing requirements, as shown in

Table ES-2. PEMS1 and PEMS2 both were being considered for full participation in the PM measurement allowance. These are both complete systems with the self contained ability to measure PM mass, exhaust flow rate, regulated gaseous emissions, and the engine parameters needed to calculate the applicable criteria for NTE events. PEMS3 is being considered as an alternative method. When used in conjunction with either PEMS 1 or PEMS2, PEMS3 can provide the comprehensive data collection required for in-use testing. PEMS4 and 5 are both instruments that UCR has currently installed in the MEL, and hence these instruments are utilized in typical operation. Neither of these instruments is capable of measuring gas-phase emissions or engine parameters, so these instruments are included only for informational purposes.

PEMS #	Manufacturer	Unit/Model	Gases	PM
1	Horiba	OBS-TRPM system	X	X
2	Sensors	PPMD (Sensors Inc. QCM)	X	X
3	AVL	Photoacoustic Microsoot Sensor		X
4	Dekati	Dekati Mass Monitor		X
5	TSI	DustTrak		X

Table ES-2. PEMS Included in the On-Road Testing Program

Test Routes

The PM PEMS were tested over 4 different routes representing different driving conditions, elevations, and environmental conditions. The routes included local Riverside freeway driving and trips from Riverside to San Diego, CA, to Baker, CA and the Nevada state line, and to Palm Springs/Indio, CA. These routes generally had many elevation changes, which provided a sufficient amount of time in the NTE zone. Force NTE events were triggered over the course of the road tests to provide sampling conditions for the MEL and PEMS. The routes spanned elevations from sea level to 5,000 feet and temperatures from moderate coastal to hot desert climates.

Test Vehicle

The test vehicle was UCR’s in-house class 8 truck, with a 2000 Caterpillar C-15, 14.6 liter engine, housed in a Freightliner chassis. The engine is certified to the EPA 2000 emissions regulations and had an FTP certification of 0.08 g/hp-h PM and 3.7 g/hp-h NO_x. This engine was not equipped with an aftertreatment system since emissions levels from an aftertreatment system would be to low to adequately represent levels near the failure threshold point for the in-use NTE standard of 0.03 g/hp-h. The average in-use PM emission rate for the 170 measured events was 0.043 g/hp-h. The MEL trailer itself provided the load for the on-road testing, with a weight of approximately 65,000 lbs.

On-Road Testing Results

The filter masses for this program were targeted to be between 50 and 200 µg during the triggered events. This was a filter loading level deemed to be reliable for gravimetric weighing. The filter masses for each NTE event are presented in Figure ES-1, along with the corresponding test durations and PM emission rates in g/hp-h. The results show that the filter masses ranged from approximately 50 µg to over 400 µg, with most of the test filter mass values within the targeted 50-200 µg range.

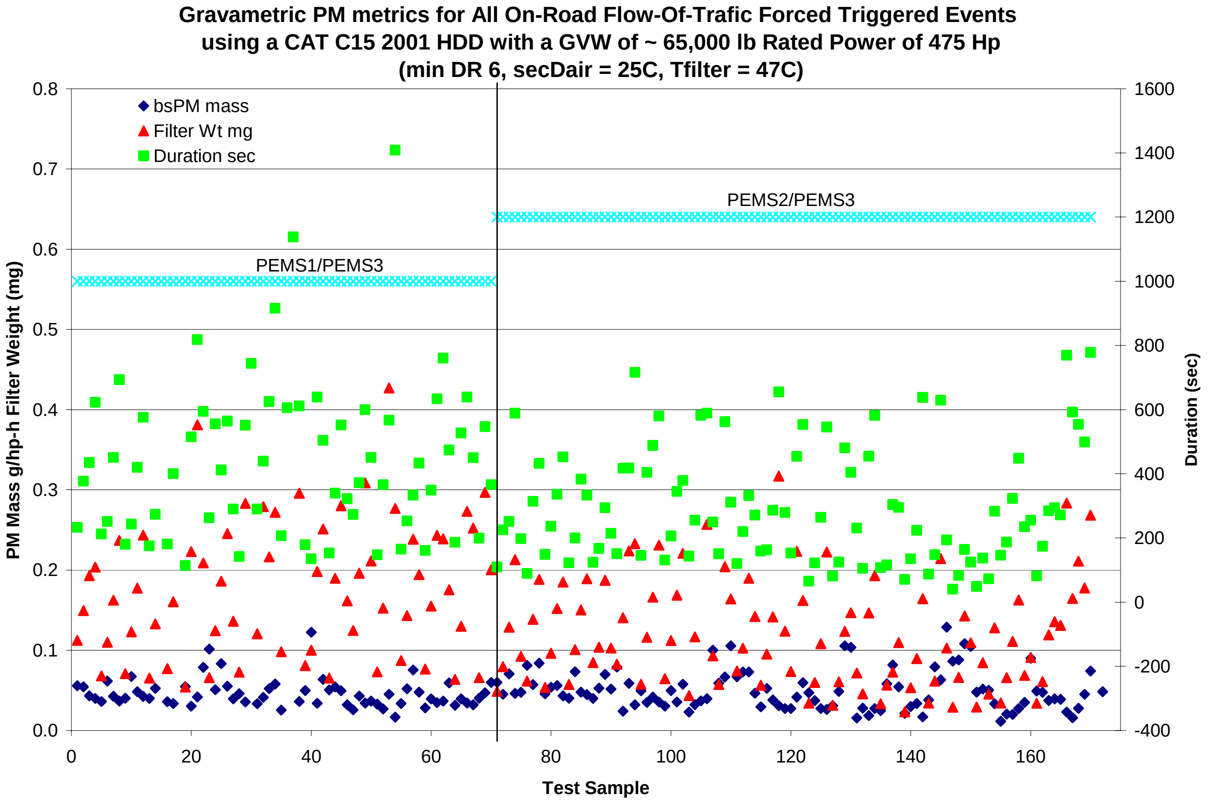


Figure ES-1. Filter Mass, Test Duration, and PM Emission Level for the Individual Triggered NTE Events for the MEL.

The correlation between the PM PEMS and MEL PM gravimetric measurements is shown in Figure ES-2 for PEMS 1-3. These three instruments are being considered for further application in the actual PM measurement allowance program. The correlation for primary PEMS1 was poor when averaged over all the data (R^2=0.013).

The correlation for primary PEMS2 was R^2=0.57 over the range of test conditions utilized, with a slope of 1.51, indicating a bias toward higher masses. It should be noted that the data in the Figures relating to PEMS2 are all based on the original data set provided to CE-CERT. Subsequently, as of the November 2008 MASC meeting, the PEMS2 manufacturer reported a change in the QCM sensitivity that would have the effect of increasing the PM mass by 1.5 times, as discussed in Section 3.4. The data in this report were not updated to reflect this increase in PM mass due to program timing and an allocation of resources to the main PM MA program. As such, the PM masses reported for PEMS2 should be 1.5 times higher than those provided in the Figures.

The correlation between the PEMS3 and the MEL PM measurements is relatively good with an $R^2 = 0.96$, but shows a low bias relative to the MEL (slope = 0.91). Since PEMS3 measurement principle is designed for the measurement of PM soot, as opposed to direct PM total mass, the low bias for this instrument is not surprising.

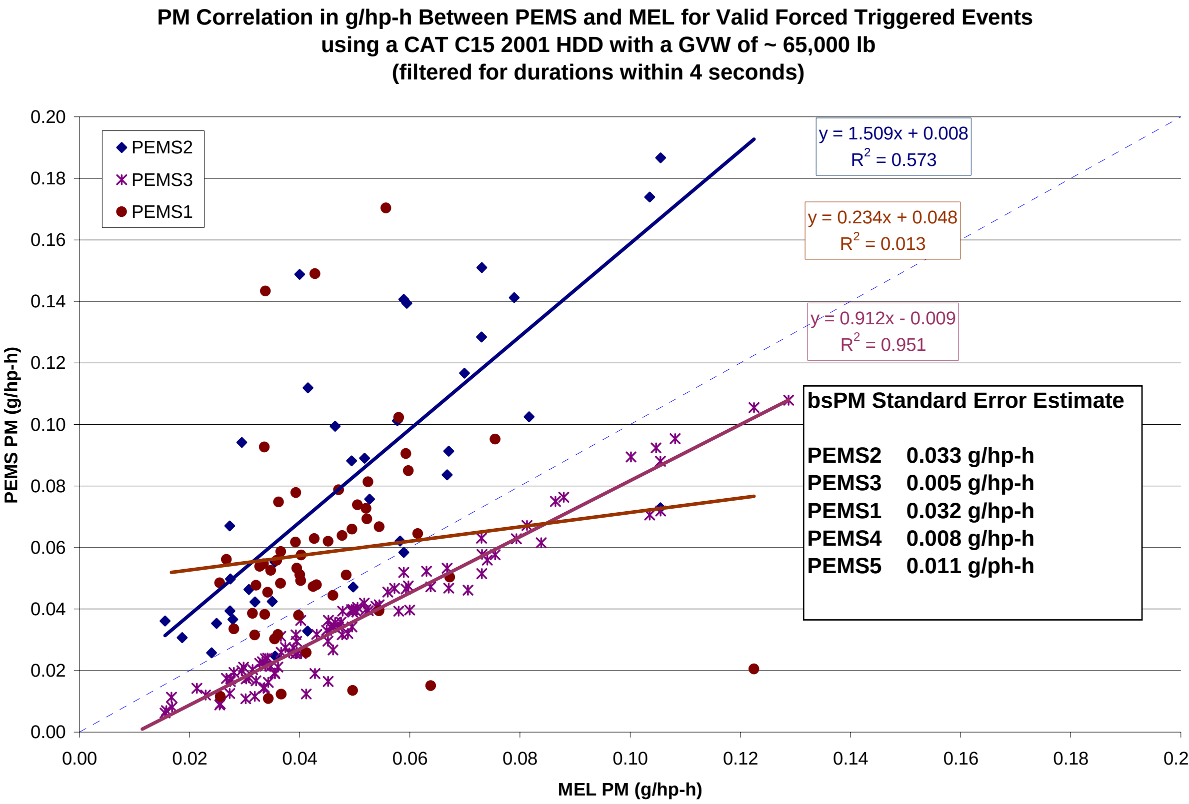


Figure ES-2. Correlation between the MEL Gravimetric and PEMS1-3 PM Measurements on a g/hp-h basis

The corresponding deltas in the PM measurements between the PEMS and the MEL are shown in Figure ES-3. The data provide some indication of the absolute deviations found during the testing. It should be noted that these values represent preliminary data and are not meant to be indicative of any values that would be related to the actual PM measurement allowance.

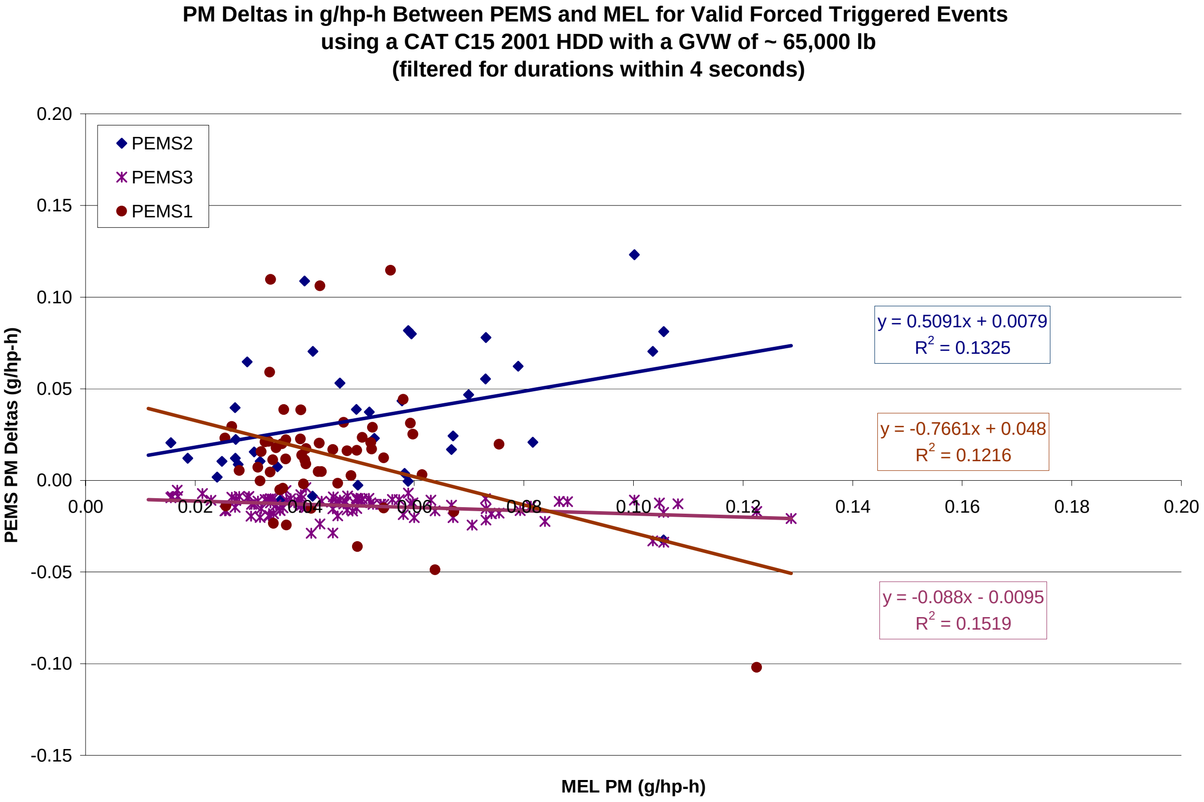


Figure ES-3. PM Deltas as a function of MEL PM Values

For PEMS1, several improvements were made to optimize the instrument performance over the course of testing. Figure ES-4 shows the results from the final day of testing, when the instrument was operating at its optimal level. The results show a much improved correlation at $R^2 = 0.56$, with a systematic positive bias in the measurement as indicated by the slope of 1.23.

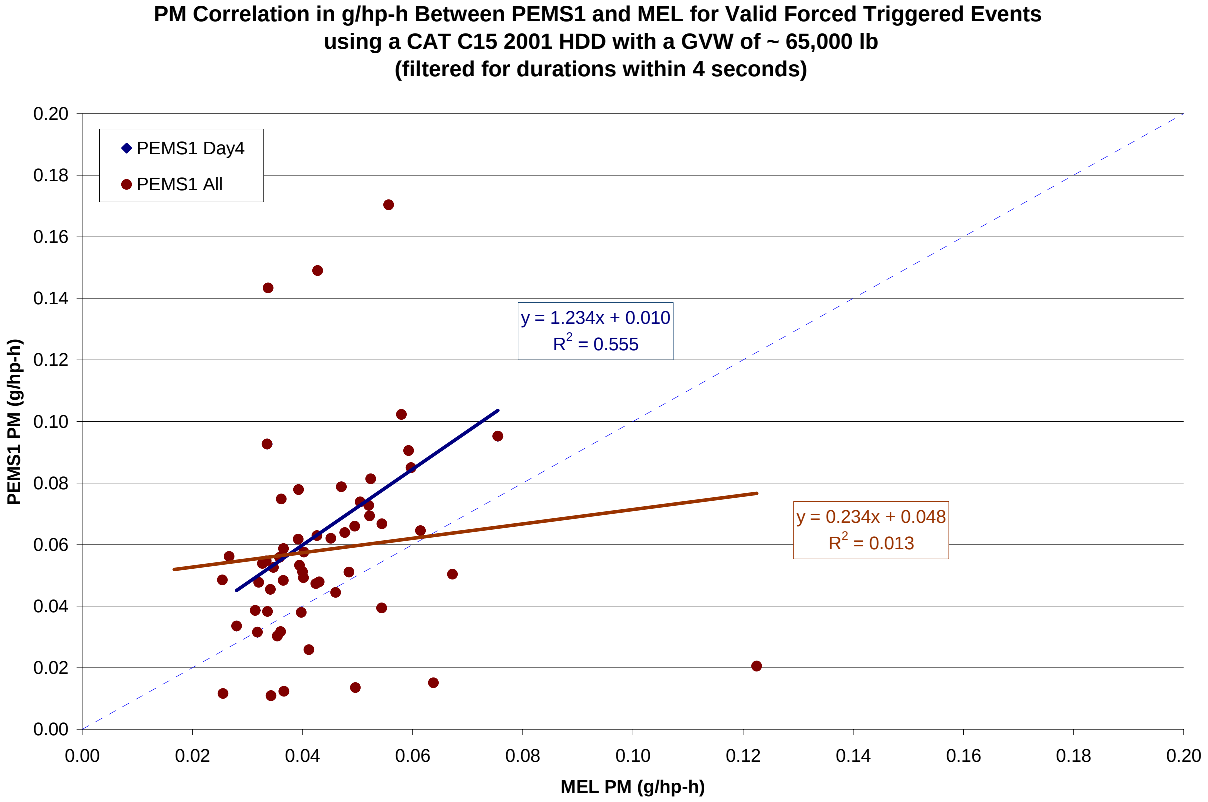


Figure ES-4. Correlation between the MEL Gravimetric and PEMS1 PM Measurements on a g/hp-h basis for all data and data from the fourth day of testing

The instrument manufacturer for PEMS 3 provided some additional analysis as part of this program, in an effort to better incorporate the soluble organic fraction (SOF) fraction to allow measurement of total PM with their instrument. A summary of the instrument manufacturer's data is included here for completeness. Their analysis essentially utilizes a correction factor based on the soot, THC concentration and sampling conditions to estimate SOF, based in part on work by Clerc and Johnson (1982). The analysis also accounts for thermophoretic losses and sulfate contribution. The results utilizing the correction factor method are presented in Figure ES-5. The data correction was only calculated for the tests conducted with the Sensors system. These results show a good correlation with the MEL gravimetric PM values (R^2 = 0.94) and essentially eliminate the bias seen in Figure ES-2.

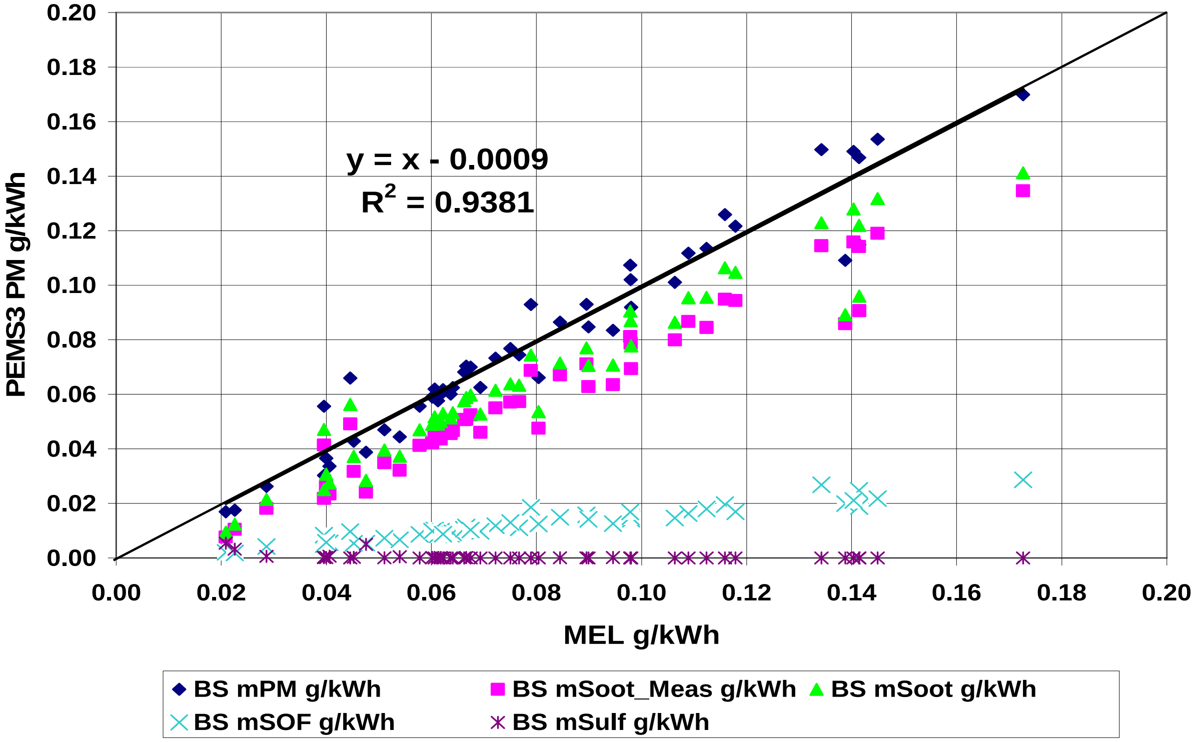


Figure ES-5. Correlation between the MEL Gravimetric and PEMS3 PM Measurements on a g/hp-h basis after Application of the data correction method

The PM correlations for PEMS4 and PEMS5 are shown in Figure ES-6. The results for PEMS4 show that the instrument shows a reasonable correlation with the MEL gravimetric PM measurement (R^2 = 0.70), but the values are biased low relative to the MEL PM measurements. PEMS5 is an internal UCR instrument that is regularly operated in the MEL. This instrument is calibrated against the PM filter masses, so it does not represent an independent measure of PM. PEMS3 does show a reasonable correlation (R^2 = 0.86) with the MEL PM gravimetric values and a good slope value. In typical service using the manufacturer's calibration, it is expected that this instrument would have a greater bias relative to standard gravimetric PM values.

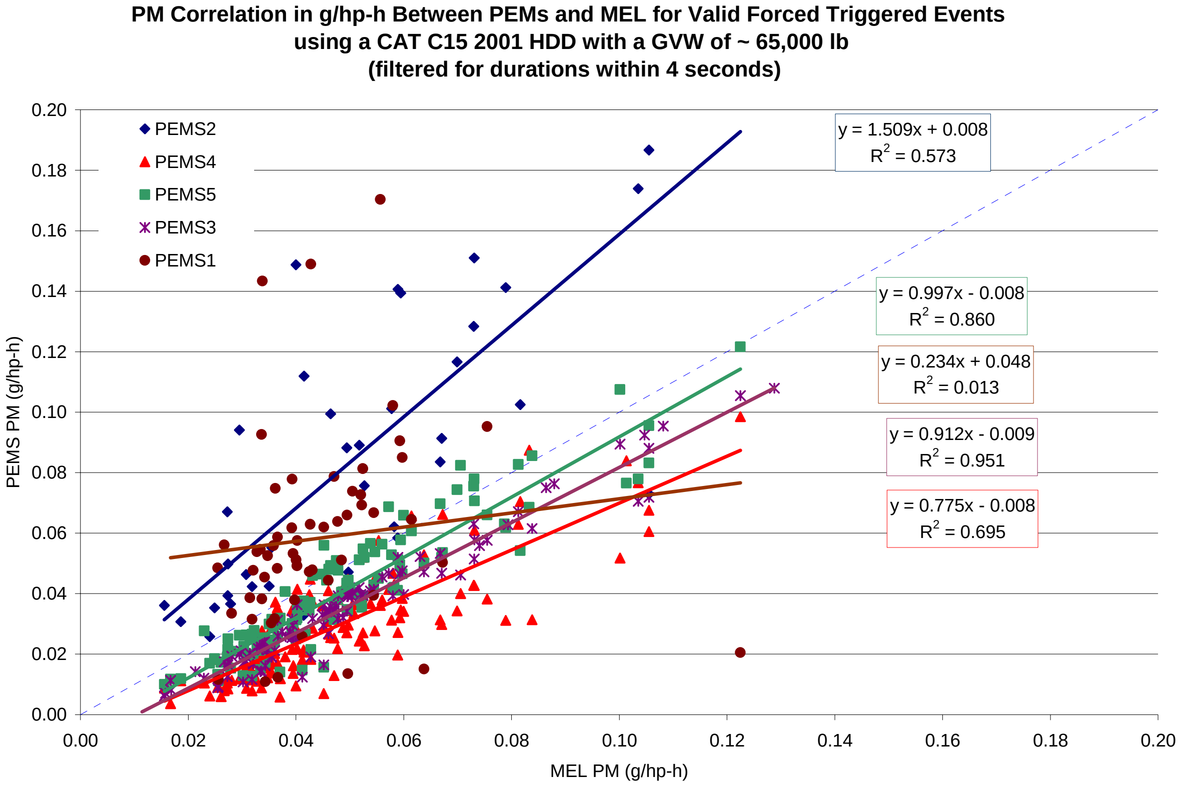


Figure ES-6. Correlation between the MEL Gravimetric and PEMS4 and PEMS5 PM Measurements on a g/hp-h basis

Lessons Learned from In-Use Operational Experience and Elements for Possible Investigation and Inclusion in the PM Measurement Allowance Test Plan

The PEMS1 system had several problems associated with the main system components such as the dilution air system, gravimetric filter box system, and the electrical aerosol detector (EAD) system. The dilution air system problems included a failed air compressor, faulty piezo valve connector, dilution system control adjustment, faulty regulator, and overheating. The EAD system had technical issues such as overheating under the hot roadway level temperatures and signal communication problems. The signal problems appeared to be a result of the level of commercial availability, and these problems should be worked out with future versions of PEMS1.

PEMS2 had several sampling issues that were a result of lack of in-use operational experience and problems with not performing routine checks on startup for both the PM and gaseous PEMS combined. Some additional data was likely lost due to on-going changes in the correlation testing related to issues such as the PEMS2 dilution, crystal operation, and NTE triggering. The PEMS2 software required some type of low level configuration by the PEMS2 manufacturer and was not at a stage where it could be operated from generic, stand-alone software. PEMS2 also had many software-related problems in providing the data quickly to UCR, with several of the problems being attributed to using the session manager according to the PEMS manufacture. Another issue relating to correlations with a full CVS tunnel is the impact of negative pressure imposed on the PEMS2 inlet by the CVS.

Due to the nature of this study, with the forced NTE events and operation by the PEMS manufacturer, some issues could not be investigated. Since UCR did not operate or process the raw data, UCR was unable to evaluate the full range of operation experience that might be found in the field under typical operation. During a similar in-use PM PEMS study where UCR staff operated the PEMS2 equipment, several additional sources of operational errors and possible biases were discovered [Durbin et al. 2009]. These include potential issues with post processor validation, crystal drift, signal spikes, sampling delay, and zero offsets in the pressure transducers. No additional independent testing of the PEMS1 system has been performed to our knowledge.

Since forced NTE events were used, the switching behavior of either PEMS1 or 2 when they encounter a rapid succession of shorter NTE events could not be evaluated. The ability to handle such rapid switching will depend on a number of factors including the volume of the sampler and valve switching control and algorithms. PEMS2 employs a special logic scheme that requires the crystal to not be resampled for a period of at least 300 seconds from the time of the previous sample. This can cause NTE events to be missed during a typical sampling day.

PEMS3 problems were primarily electronics overheating issues that were due in part to its close proximity to the engine compartment.

In addition to the operational issues identified for PEMS1 and 2, some additional consideration was given to fundamental operational differences for the instruments and their correlation with filter mass. For PEMS1 with the EAD, this could include the impact of particle size on the charging efficiency, the difference between gravimetric methods that are proportional to particle volume and diffusion charging that is proportional to surface area, particle losses, or nucleation impacts. For PEMS2 with a quartz crystal microbalance, this could include the charging efficiency and deposition efficiency on the crystal surface and the quartz crystal calibration. Other factors to consider in comparing both PEMS with the constant volume sampler (CVS) gravimetric PM measurements include artifacts, differences in residence time or dilution methods, and the proximity of sampling points from the exhaust and any associated losses.

1.0 Background

Government agencies are in the process of implementing a series of regulations that will control emissions of both oxides of nitrogen (NO_x) and particulate matter (PM) from diesel engines in use and ensure the low emission levels can be maintained throughout the course of the engine's lifetime. One of the most important regulations with respect to controlling in-use emissions is the Not-To Exceed (NTE) regulation, which requires in-use emissions testing to evaluate emissions in a defined portion of the engine map known as the NTE control area, and the protocols required to make those measurements. In-use testing under the NTE program will be conducted with portable emissions measurement systems (PEMS) under in-use driving conditions. An important aspect of this regulation is Measurement Allowance (MA) program, where the United States Environmental Protection Agency (EPA), California Air Resources Board (CARB), and the Engine Manufacturers Association (EMA) are working together to systematically evaluate various sources of error for gaseous and PM measurements with PEMS in comparison with laboratory measurements. This error is then accounted for in the regulatory standards as a "Measurement Allowance". A comprehensive program has already been conducted for the gas-phase measurement allowance [Miller et al., 2007, 2008; Buckingham et al. 2007; Fiest et al. 2007], with the PM measurement allowance program about to begin.

This program was conducted as a preliminary or pilot study to the main PM measurement allowance program. PM PEMS were directly compared with the University of California, Riverside (UCR) Bourns College of Engineering – Center for Environmental Research and Technology's (CE-CERT) Mobile Emissions Laboratory (MEL) over a series of different on-road driving conditions. The MEL is unique in that it contains a full 1065 compliant constant volume sampling (CVS) system with gravimetric PM measurements, while being fully operational under on-the-road driving conditions. Measurements were made from a class 8 truck whose PM emissions levels were approximately at the level that would be found for a vehicle failing the in-use PM emissions standard, to test the PM instruments at levels where their performance is most critical. The on-road driving courses included segments near sea level, in coastal regions, in desert regions, and on longer uphill inclines. PM measurements in real-time were made with a variety of different PM instruments from manufacturers preparing for the PM Measurement Allowance program, as well as other commercially available instruments, such as a Dekati Mass Monitor (DMM) and DustTrak. These measurements were directly compared with PM mass measurements that were collected with the MEL under 1065 compliant sampling conditions. A 1065 self-audit for PM measurements was also conducted on the MEL as part of this program.

The main goal of this work was to provide preliminary measurements from PM PEMS to assess the accuracy of PM measurements under in-use conditions and provide a basis for the development of the more comprehensive Measurement Allowance program. The results from this program will also aid the PM PEMS MA Program in other areas of interest:

- Lessons learned from first hand experience using PM PEMS in real world in-vehicle applications.
- Identifying areas that need special attention during the PM Measurement Allowance test plan development.

- Help identifying areas that need to be different or eliminated altogether, compared to the gaseous MA program.
- Partial validation of the Monte Carlo Model to be used to quantify the Measurement Allowance for PM PEMS.

2.0 PM 1065 Audit

2.1 1065 Audit Overview

As part of the validation of the UCR MEL for the on-road testing, a PM specific 1065 self-audit was performed on the UCR MEL. A description of the MEL is provided in Appendix A and Cocker et al. (2004a, 2004b). Prior to conducting the audit, the 1065 regulations were reviewed and the MEL trailer subsystems were modified as needed.

The 1065 self-audit of the trailer included linearity, vacuum, and batch sampler verifications for all analyzers used to measure PM emissions. Table 2-1 summarizes the tests performed in the audits. The template used for the audit was designed by EPA in conjunction with the Measurement Allowance Steering Committee (MASC).

CFR Reference	Analyzer Verified	1065 Section Title
1065.307	THC FID	Linearity
1065.307	PM balance	Linearity
1065.307	PM filter temperature	Linearity
1065.341	CVS propane check	CVS and batch sampler verification
1065.341	PM filter sample flow propane check	CVS and batch sampler verification
1065.345	PM sample flow meter	Vacuum leak verification
1065.390	PM balance independent certification	PM balance and weighing
1065.390	PM balance	Zero, span, and reference sample verifications
1065.545	PM filter flow meter controller	Validation of proportional flow control for batch sampling

Table 2-1. PM 1065 MEL PM self audit list performed

2.2 1065 Audit Results

1065.307 Linearity

Linearity verification was performed for the total hydrocarbon (THC) instrument, the PM balance, and filter face temperature. In addition UCR performed linearity checks on all its mass flow controllers (MFC) and system filter temperatures. A comprehensive list of the linearity checks is provided in Table 2-2. All instruments meet the Slope, Intercept, standard error estimates (SEE), and R^2 requirements specified in the CFR40 1065.307.

1065.341 Propane Verification

Two propane verifications are required to verify PM measurements under 1065. These are for the primary tunnel and the secondary tunnel. The 1065 regulation includes provisions for a propane mass balance through the secondary dilution tunnel similar to the procedures for the primary tunnel. This was accomplished using the same critical flow orifice (CFO) kit used on the primary tunnel. The primary dilution tunnel propane recovery was 99.1% and the secondary dilution tunnel recovery was 98.5%. These results meet the 1065 requirements for both the primary (±2%) and secondary (±5%) tunnels.

Linearity Checks

Table 2-2 Linearity checks were performed on selected analyzers, temperature sensors, and mass flow controllers (MFCs).

Sensor Name	Units	Date	**Slope**			**Intercept**			**SEE**			**r^2**			**Overall** Pass/Fail
			Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	
CO	ppm		tbd												
CO2	%		tbd												
NOx	ppm		tbd												
THC	ppm	09/17/07	0.99975	0.99 / 1.01	Pass	0.031	0.940	Pass	0.059	0.940	Pass	0.9999980	0.998	Pass	Pass
CH4	ppm		tbd												
TC_room	C	08/06/07	tbd												
TC_mini_in	C	08/06/07	0.99940	0.99 / 1.01	Pass	0.074	0.996	Pass	0.158	0.996	Pass	0.9999895	0.998	Pass	Pass
TC_mini_out	C	08/06/07	1.00003	0.99 / 1.01	Pass	0.015	0.996	Pass	0.134	0.996	Pass	0.9999925	0.998	Pass	Pass
TC_Hxout	C	08/06/07	0.99817	0.99 / 1.01	Pass	0.157	0.996	Pass	0.181	0.996	Pass	0.9999862	0.998	Pass	Pass
TC_Hxin	C	08/06/07	1.00405	0.99 / 1.01	Pass	-0.258	0.996	Pass	0.138	0.996	Pass	0.9999921	0.998	Pass	Pass
TC_cont	C	08/06/07													
TC_oven	C	08/06/07	1.00054	0.99 / 1.01	Pass	-0.036	0.996	Pass	0.213	0.996	Pass	0.9999810	0.998	Pass	Pass
TC_split	C	08/06/07	1.00449	0.99 / 1.01	Pass	-0.146	0.996	Pass	0.229	0.996	Pass	0.9999783	0.998	Pass	Pass
TC_filter	C	08/06/07	0.99150	0.99 / 1.01	Pass	0.347	0.996	Pass	0.155	0.996	Pass	0.9999898	0.998	Pass	Pass
T_CVSd	C	08/06/07	0.99924	0.99 / 1.01	Pass	0.171	2.938	Pass	0.127	2.938	Pass	0.9999990	0.998	Pass	Pass
T_CVSt	C	08/06/07	1.00106	0.99 / 1.01	Pass	-0.226	2.938	Pass	0.147	2.938	Pass	0.9999987	0.998	Pass	Pass
T_CFO	C	08/06/07	tbd												
TC_exh_post	C	08/06/07	0.99692	0.99 / 1.01	Pass	1.555	5.970	Pass	1.039	5.970	Pass	0.9999875	0.998	Pass	Pass
TC_exh_pre	C	08/06/07	0.99941	0.99 / 1.01	Pass	0.346	5.970	Pass	0.399	5.970	Pass	0.9999982	0.998	Pass	Pass
TC_CVS_in	C	08/06/07	1.00454	0.99 / 1.01	Pass	-1.430	5.970	Pass	2.045	5.970	Pass	0.9999524	0.998	Pass	Pass
PM_balance	mg	08/09/07	1.00133	0.99 / 1.01	Pass	0.005	1.000	Pass	0.174	1.000	Pass	0.9999868	0.998	Pass	Pass
MFC41	sccm	06/21/07	tbd												
MFC42	slpm	06/21/07	1.00178	0.99 / 1.01	Pass	-0.001	0.010	Pass	0.002	0.010	Pass	0.9999799	0.998	Pass	Pass
MFC43	slpm	06/21/07	1.00049	0.99 / 1.01	Pass	0.001	0.096	Pass	0.011	0.096	Pass	0.9999927	0.998	Pass	Pass
MFC44	slpm	06/21/07	0.99704	0.99 / 1.01	Pass	0.001	0.016	Pass	0.004	0.016	Pass	0.9999701	0.998	Pass	Pass
MFC45	slpm	06/21/07	1.00073	0.99 / 1.01	Pass	-0.003	0.274	Pass	0.011	0.274	Pass	0.9999991	0.998	Pass	Pass
MFC46	slpm	06/21/07	tbd												
MFC47	slpm	06/21/07	tbd												
MFC61	slpm	06/21/07	0.99731	0.99 / 1.01	Pass	-0.134	1.171	Pass	0.618	1.171	Pass	0.9998648	0.998	Pass	Pass
MFC62	slpm	06/21/07	1.00038	0.99 / 1.01	Pass	-0.083	1.059	Pass	0.195	1.059	Pass	0.9999837	0.998	Pass	Pass
MFC63	slpm	06/21/07	1.00087	0.99 / 1.01	Pass	0.022	0.272	Pass	0.081	0.272	Pass	0.9999483	0.998	Pass	Pass
MFC64	slpm	06/21/07	1.00129	0.99 / 1.01	Pass	-0.007	0.264	Pass	0.052	0.264	Pass	0.9999772	0.998	Pass	Pass
MFC65	slpm	06/21/07	1.00007	0.99 / 1.01	Pass	-0.016	0.274	Pass	0.029	0.274	Pass	0.9999928	0.998	Pass	Pass
MFC66	slpm	06/21/07	0.99645	0.99 / 1.01	Pass	0.011	0.066	Pass	0.022	0.066	Pass	0.9999306	0.998	Pass	Pass
MFC67	slpm	06/21/07	tbd												
MFC68	slpm	06/21/07	0.99418	0.99 / 1.01	Pass	0.187	0.551	Pass	0.256	0.551	Pass	0.9998521	0.998	Pass	Pass
MFC69	slpm	06/21/07	1.00087	0.99 / 1.01	Pass	-0.049	0.521	Pass	0.095	0.521	Pass	0.9999769	0.998	Pass	Pass
MFC70	slpm	06/21/07	tbd												

Standard conditions at 20C, 1 atm

1065.345 Vacuum Leak

The secondary filter system was checked for leaks under vacuum and positive pressure. The system was sealed off at the probe tip and the flow through the sample system was monitored. The indicated flow was less than 50 standard cubic centimeters per minute (sccm) of the minimum nominal flow is 10,000 sccm, which amounts to less than a 0.5% leak, as specified in 1065.345

1065.390 PM Balance Verification

The Code of Federal Regulations (CFR) requires two procedures for the weighing scale or balance verification. One is from an independent outside source and the other is from filter weighing procedures (zero, span, and reference filters) spanning the test program period. The Mettler Toledo manufacturer certified the balance on 7/9/2007. A copy of this certification is provided in Appendix B. The balance met the tolerances in 1065.390 for linearity and independent accuracy evaluation. Prior to weighing the tare and final filter weights, the balance was exercised through its routine with reference filters, zero and span calibration. The net gain of reference filter mass during this project was -0.0003 mg, which is less than the 0.010 mg specified in the CFR. UCR also verified other contamination sources, such as carrying filters to the job site (trip blanks), loading and unloading filters that are carried to the job site (static blanks) and loading and leaving the filters in the holders during a typical test (dynamic blanks) in addition to the CFR defined reference filter that stays in the filter conditioning room. The trip, static, and dynamic filter weights for this project were -0.0027, -0.0006, and -0.0015 mg. The most recent tunnel blank was 0.0027 mg, which was sampled with over 1 m^3 of dilution air at the 1065 conditions of 47°C ±5°C. UCR also verified the micro balance linearity with internal standard calibration weights ranging from 0 mg to 200 mg. The balance passed the 1065.307 linearity specifications and the data is provided in Table 2-2.

1065.545 PM filter flow proportionality

This audit tests the ability of a sample system to measure flow across a filter in proportion to varying exhaust flow rates. Since the MEL laboratory uses a CVS, where the CVS total flow is the sum of the exhaust and dilution flow, the filter flow proportionality is really the ability of the CVS total flow to remain constant. The MEL proportionality during random selection of various in-use test runs was less than the 3.5% of mean sample filter flow rate with a max of 2.4% and a minimum of -3% and a single standard deviation about the mean of 0.7%. The proportionality metric covered all in-use operation from idling, decelerations, gear shifting and NTE operation.

3.0 On-Road Testing– Experimental Procedures

Comparisons were made between the UCR MEL and the PEMS under in-use conditions designed to generate NTE events and provide a variety of environmental conditions, including variations in temperature, elevation, etc. The experimental procedures and test routes are described in this section.

3.1 Test Vehicle

The test vehicle was UCR's in-house class 8 truck, with a 2000 Caterpillar C-15, 14.6 liter engine, housed in a Freightliner chassis. The MEL trailer itself provided the load for the on-road testing. The gross vehicle weight of the tractor and trailer is 65,000 lbs. The UCR truck had a mileage of approximately 18,000 miles at the time of testing. The engine was certified to the 2000 model year level which is 0.1 g/hp-h PM and a 4 g/hp-h NO_x. The actual certification level data show the engine had Federal Test Procedure (FTP) emissions levels of 0.08 g/hp-h PM and 3.7 g/hp-h NO_x. This engine was not equipped with an aftertreatment system since emissions levels from an aftertreatment system would be to low to adequately represent levels near the failure threshold point for the in-use NTE standard of 0.03 g/hp-h. The lug curve and associated data are provided in Figure 3-1 and Table 2-1, respectively.

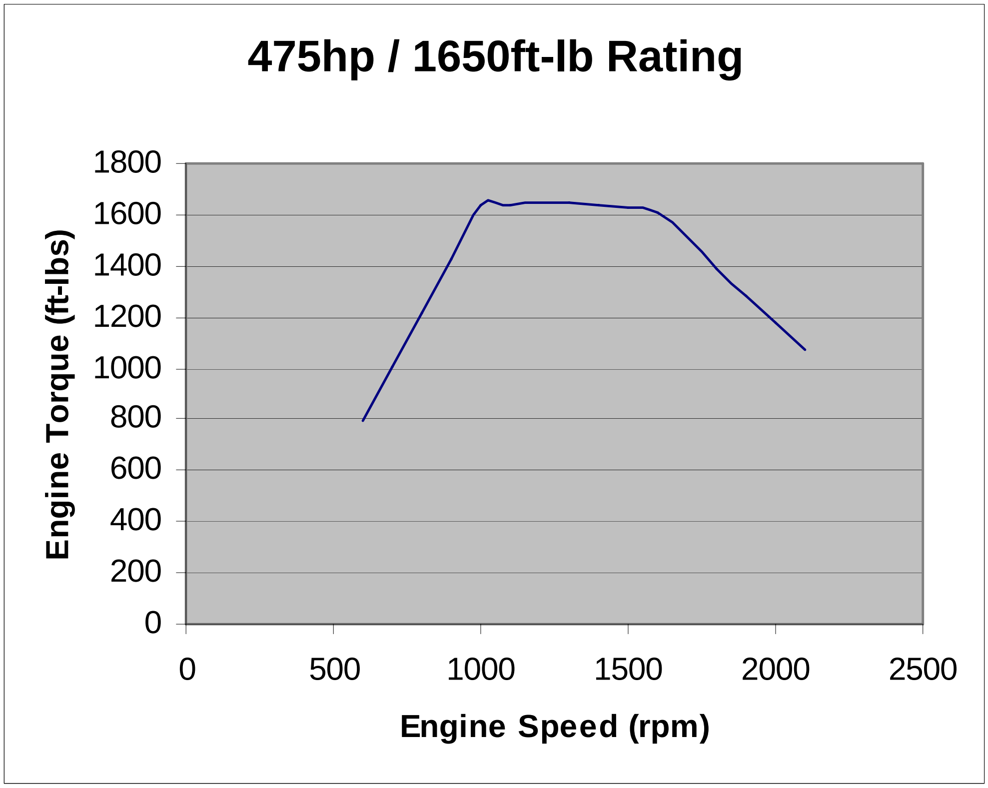


Figure 3-1 Caterpillar C-15 lug curve

Table 3-1 Caterpillar C-15 lug curve data

Engine Speed (rpm)	Engine Torque (lb-ft)	Engine Power (hp)
600	797	91.1
700	1006	134.1
800	1215	185.1
900	1423	243.9
1000	1633	310.8
1100	1642	344.0
1200	1650	377
1300	1648	408
1400	1640	437
1500	1629	465
1600	1609	490
1700	1515	490
1800	1387	475
1900	1281	463
2000	1177	448
2100	1075	430

3.2 PEMS Tested

A total of five PEMS systems were tested as part of this program. These 5 PEMS represent different levels of technology and technological advancement with respect to meeting the in-use testing requirements. The PEMS are listed in Table 3-2 along with the system name, manufacturer and emissions capability. PEMS1 and PEMS2 both were being considered for full participation in the PM measurement allowance. These are both complete systems with the self-contained ability to measure PM mass, exhaust flow rate, regulated gaseous emissions, and the engine parameters needed to calculate the applicable criteria for NTE events. PEMS3 provides a measurement of soot particulate only. PEMS3 was tested in conjunction with both PEMS1 and 2, to provide the necessary gaseous emissions, flow rates, and engine parameters needed to provide the required emission rates in grams per brake horsepower (g/hp-h). PEMS4 and 5 are both instruments that UCR has currently installed in the MEL, and hence these instruments are utilized in typical operation. Neither of these instruments is capable of measuring gas-phase emissions or engine parameters, so these instruments are included only for informational purposes. It should also be noted that PEMS5 is typically calibrated using Arizona road dust, as per the manufacturer. UCR calibrated this PEMS with gravimetric filters when it was first purchased in 2005 and has since run on this same span calibration. As such, it does not represent a fully independent measure of PM.

Table 3-2. PEMS Included in the On-Road Testing Program

PEMS #	Manufacturer	Unit/Model	Gases	PM
1	Horiba	OBS-TRPM system	X	X
2	Sensors	PPMD (Sensors Inc. QCM)	X	X
3	AVL	Photoacoustic Microsoot Sensor		X
4	Dekati	Dekati Mass Monitor		X
5	TSI	DustTrak		X

PEMS1-3 were operated by the manufacturer, due to their level of development and the research nature of the testing. It was decided by the PM MASC that data representing the best operational practices, as measured by the manufacturers, was desired. This would eliminate any invalid data due to operational issues. UCR operated PEMS4 and PEMS5 since these PEMS are owned by UCR and have been integrated into the MEL for several years. By the end of the testing program, UCR operated PEMS 3 since its level of commercial available was further along compared to PEMS1 and PEMS2. At the time of testing, neither PEMS1 nor PEMS2 had a manual to refer to for operation and installation. Manuals for both PEMS1 and 2 were provided to UCR subsequently, in January 2008, in conjunction with training for the main PM MA program. PEMS3 is not a complete system and requires the exhaust flow and ECM measurements of PEMS1 or PEMS2 in order to meet the PM MA requirements.

Each PEMS manufacturer was asked to operate their PEMS in such a way that the data could be investigated for compliance to 1065 for proportionality, drift corrections and other test-to-test verifications. For example, PEMS2 has a session manager that tracks audit performance and zero drift through out the day. This audit data is required to perform the drift verification procedures in the CFR. Unfortunately, due to the level of PEMS2 system completeness, the audit tracking did not work well with the gas/PM combined system and thus prevented the PM audit data from being processed. Thus, no audit data was available with any of the PM systems except for what the manufacturer did off line. Also, gas-phase emissions were not provided by either PEMS1 or PEMS2 for the program. All audit data for each PEMS, if provided at all, was provided by each manufacturer’s individual off line analysis and was not part of any automated or UCR post processing efforts.

The current PM PEMS are fairly bulky and require a lot of physical area, thus it was decided to operate PEMS1 and PEMS2 at separate times as opposed to simultaneously. PEMS1 was chosen to go first using a coin toss during a MASC meeting. PEMS3, 4, and 5 were operated simultaneously during both PEMS1 and PEMS2 testing. PEMS1 operated during the first 70 forced events and PEMS 2 for the remaining 100 forced events.

3.3 Horiba/AVL Operation PEMS1/PEMS3

PEMS1 and PEMS3 were operated simultaneously. PEMS1 is a complete system including gas emissions, exhaust flow, engine control module (ECM) J1939 interface, and the PM proportional diluter/sampler and mass measurement system. PEMS3 is only a PM concentration sensor and thus requires PEMS exhaust flow and engine control module (ECM) J1939 signals from another source in order to calculate PM mass rate emissions with units of g/hp-h.

The principal of operation for PEMS1 is based on a combination of direct mass measurements (gravimetric filter) and electrical PM size concentration measurements (TSI electrical aerosol detector [EAD] instrument). The PM mass collection on a filter is a batch operation, thus PEMS1 uses a proportional diluter to maintain exhaust flow proportionality for the gravimetric PM measurements. The real-time PM concentration is also measured on the same diluted sample path as the gravimetric filter, and thus the EAD signal is proportionally exhaust flow weighted. The real-time PM sampling location has the benefit of minimizing particle formation differences between the gravimetric filter and EAD signal.

The EAD measurement is a real-time signal that can be processed and time-aligned post test. The EAD measurement is based on a parameter called aerosol length and is reported as mm/cm^3. The EAD measures the current generated when unipolarily charged particles pass an electrometer. The EAD result is a number concentration times the average diameter, as explained in detail in the TSI EAD operating manual. The reported signal is thus a measure of particle length, with a relationship to diameter to the power of 1.133 ($D^{1.133}$). The EAD signal is then converted from length to mass units by assuming a particle density and converting the signal from length ($D^{1.133}$) to mass (D^3).

The basic idea behind the PEMS1 NTE bsPM reporting is as follows. The filter mass is sampled over the course of a full day, but only during operation in the NTE zone. Typical operation will be one gravimetric filter over 8 hours of vehicle operation where the expectation is that only a fraction of the 8 hours will be in the NTE zone and thus only a fraction of the 8 hours will be on the gravimetric filter. The PM mass on the gravimetric filter is then used to calibrate the EAD signal. The real-time concentration detector is, in essence, calibrated with a daily in-use gravimetric filter over common filter sampled intervals. The integrated EAD signal concentration is calibrated to the PM mass collected on the filter over the entire day. The calibrated EAD signal is then converted from length to mass for real-time NTE events “post test” to produce a bsPM NTE emission rate. Although the gravimetric filter is not directly used to produce NTE bsPM emissions, there is a connection between the real-time particle concentration and gravimetric mass that gives PEMS1 a level of confidence that any sampling artifact, whether it is size, composition, or dilution, will be captured by the PM gravimetric filter, and thus translated through to the EAD signal for a representative bsPM in-use measurement.

The PEMS1 gravimetric filter measurement is a direct comparison to the MEL reference method where similar dilution ratios, face velocities, and filter temperatures are maintained, as per 1065. During this study, the MEL and PEMS1 face velocities were matched at 50 cc/s. The MEL will be upgraded to face velocities of 100 cc/s for future testing by increasing the sample flow rate capacity. This flow rate will match the flow rates planned at the Southwest Research Institute (SwRI) for the main PM MA program. Thus, the PEMS1 face velocities may be a source of error at SwRI if PEMS1 does not change their filter sample flow rate. Besides face velocity there should be no biases to other full flow CVS reference systems except for possible proportionality control issues.

For this study, actual real-time NTE operation was not exercised and only forced events were exercised. As such, errors associated with short NTE events (i.e., rapid filter sampling on and off conditions) were not evaluated. There were four forced events each hour where PEMS1 sampled one filter and the MEL sampled four filters. PEMS1 sampled these events as if they were NTE events and the total mass was used to proportion the EAD real-time signal to the individual masses for a specific event. The correlation plots presented in this study are a comparison to the proportioned EAD signal for the four forced events. The magnitude of filter loading for PEMS1 ranged from 600 µg to 1300 µg, with an average of 1000 µg. The filter weight of 1000 µg is on the high side of what would be expected during a typical 8 hours of in-use sampling of DPF level emissions thus this correlation was designed to show the PEMS1 in a more optimum condition rather than intended operation. PEMS1 sampled 70 filter events over the course of four days. Of those events the PEMS1 manufacturer provided results for 62 events, but was only partially confident in 14 data points on the last day of operation. There were several technical and operation problems that prevented higher data collection efficiency. These problems are described in section 5 in more detail.

PEMS3 is a more straight forward measurement system due to its relative simplicity and commercial availability, however, it only measures soot concentration. PM is composed of many parts, soot or elemental carbon (EC), organic carbon (OC), ash, and sulfate particles (and associated water mass with each unit of sulfate mass). PEMS3 measures modulated laser light absorbed by particles. EC particles absorb the modulated laser light strongly, while OC and sulfate particles absorb a negligible amount of this light. The absorbed light heats and cools the particles causing periodic pressure waves. The pressure waves are measured by a microphone, which is correlated to PM mass concentration (i.e., soot concentration). The PEMS3 manufacturer realizes the measurement principal does not detect total PM mass, and is investigating using empirical relationships between other exhaust measurements and engine behavior to predict OC and sulfate masses to estimate a total PM mass. Some preliminary results based on previous prediction models are presented in this study based on information provided by the PEMS3 manufacturer. PEMS3 sampled with a fixed dilution of four to one for the engine-out levels in this study. It is expected that the PEMS3 dilution will drop to three to one for levels targeted in the MA program. Using exhaust flow and flow-aligned PM concentration, PEMS3 converts their concentration signal to a mass emission rate. Then using the J1939 broadcast torque and revolutions per minute (RPM) for the engine, the data are converted to bsPM.

Installation PEMS1/PEMS3

Several logistical issues arose during the PEMS1 installation due to its level of development. The PEMS3 installation was straight forward and followed the manual, except for some overheating issues due to high ambient temperatures (40-45°C) and its location outside near the asphalt and closest to the engine. PEMS1 is a full PM and gaseous system and thus required space for all its components. Figure 3-2 shows the PEMS1 equipment mounted inside the air-conditioned, vibration isolated mobile laboratory trailer and Figure 3-3 through Figure 3-5 show the PEMS1 and PEMS3 equipment mounting outside the trailer on the frame of the vehicle. The equipment located inside the trailer was the PEMS1 gaseous instrument, the control laptop and the signal break out box, and the PEMS3 control laptop. The equipment located on the frame was the PEMS1 dilution air box, compressor box, EAD box, filter box, power conditioning box, proportional sample probe, and heated transfer line, and PEMS3 dilution cell, heated transfer line, soot detector and sample conditioner.

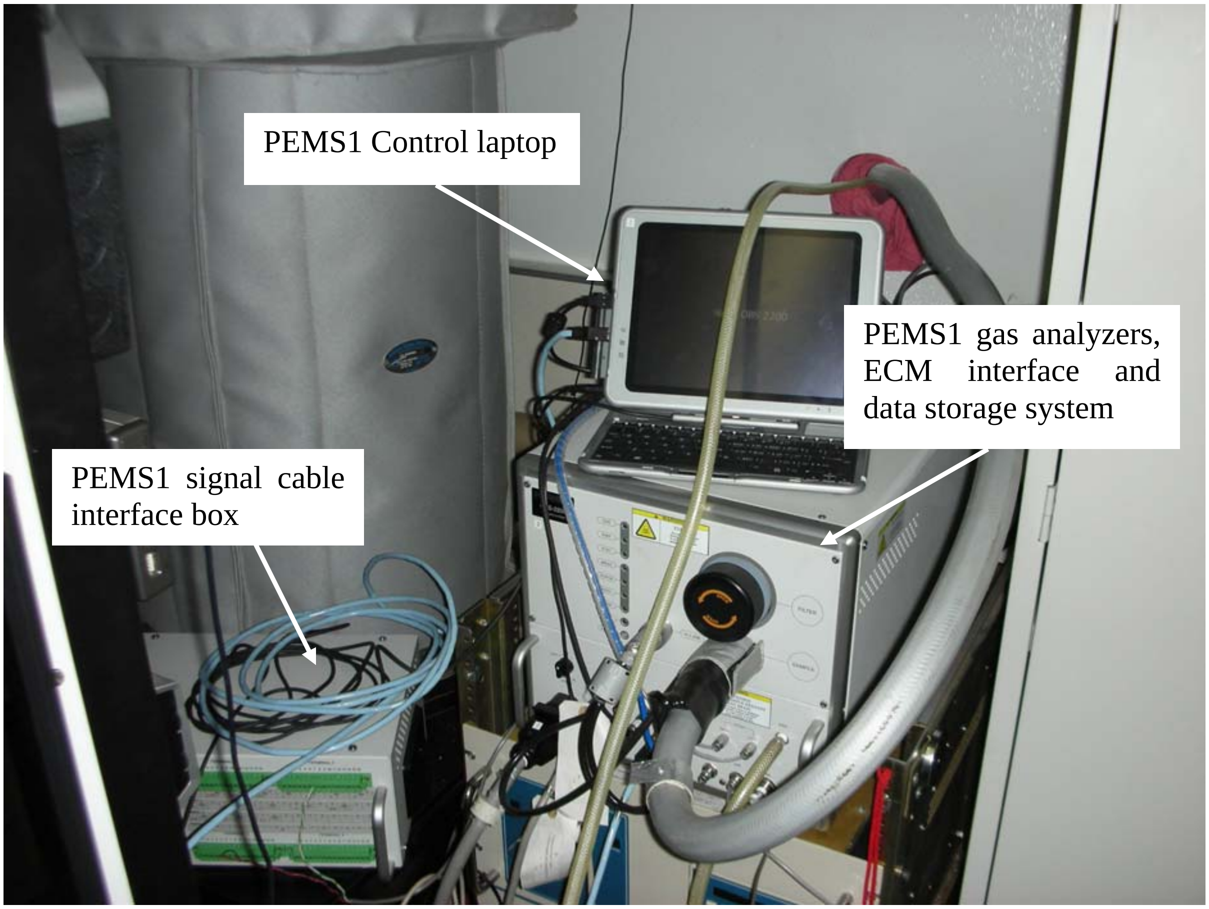


Figure 3-2 PEMS1 installation inside the MEL trailer

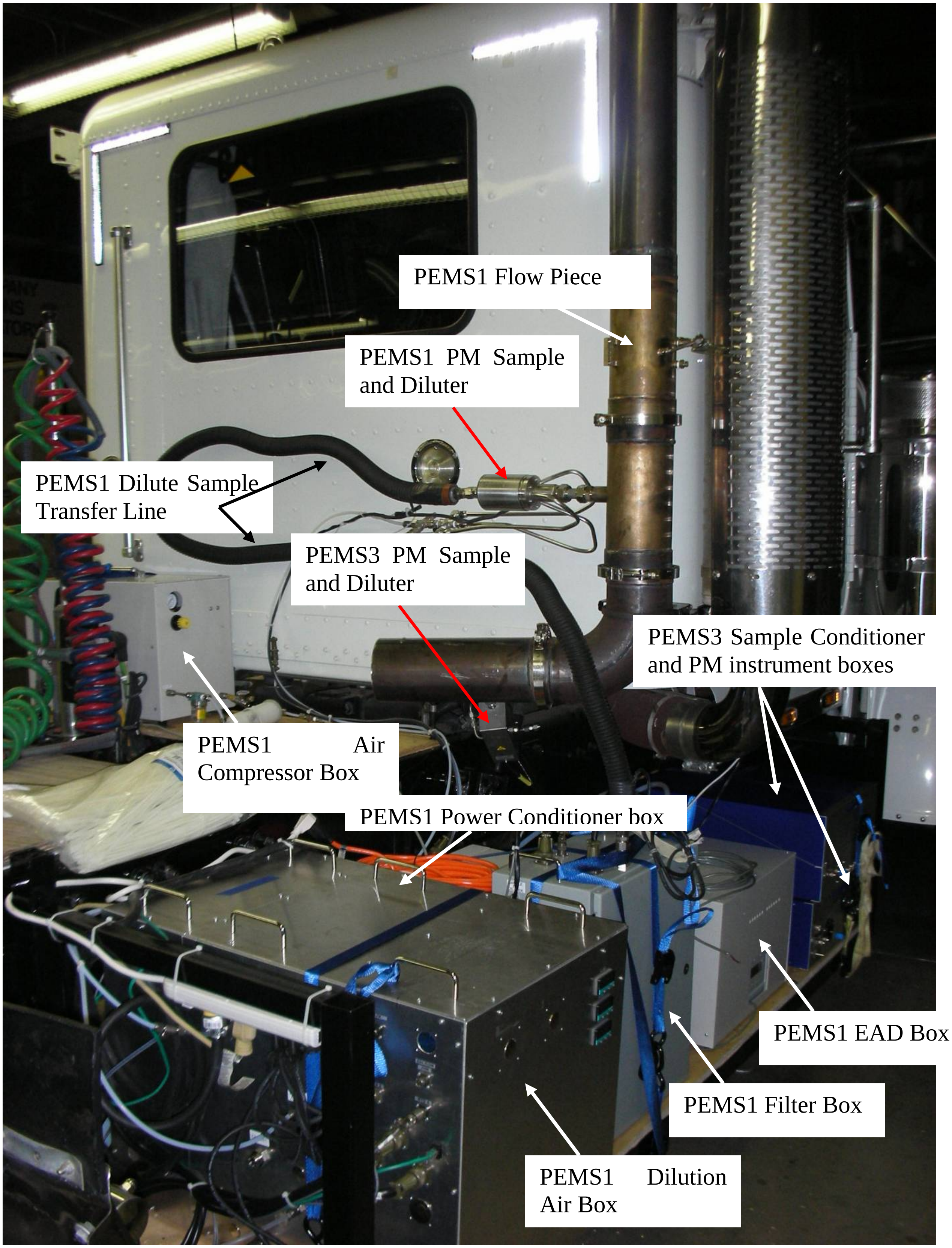


Figure 3-3 Vehicle installation for PEMS1 and PEMS3

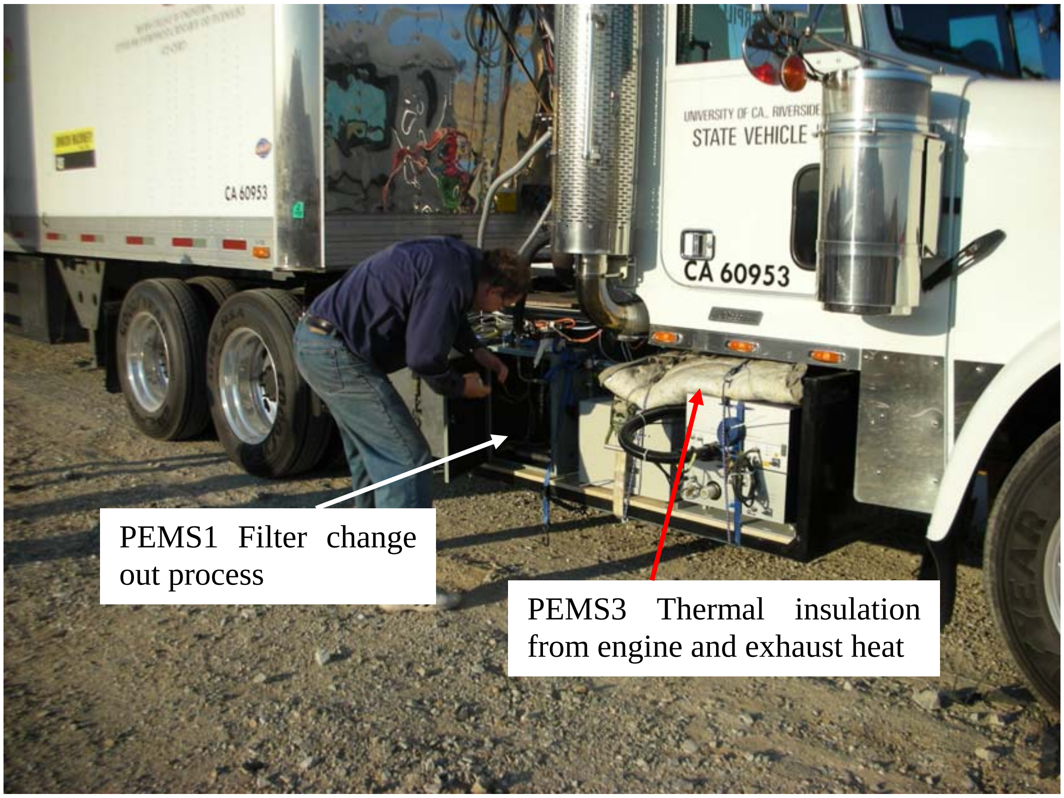


Figure 3-4 PEMS1 changing filters between test runs and PEMS3 thermal blanket

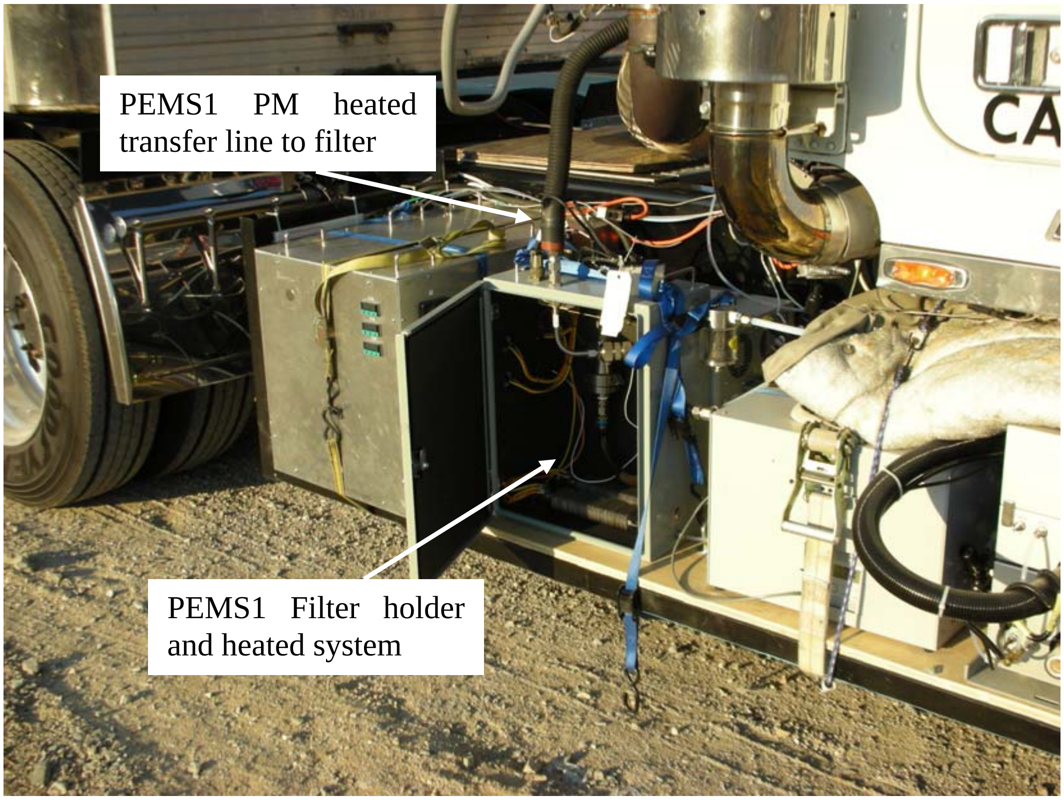


Figure 3-5. PEMS1 filter holder system after changing filters

Since PEMS1 and PEMS2 were not sampled simultaneously there was an effort to make the two separate installations as identical as possible. Both PEMS exhaust flow meters were installed in roughly the same location in the transfer line. Since PEMS3 sampled with both PEMS1 and PEMS2, PEMS3 sample section was kept constant throughout the PEMS correlation. The PEMS3 manufacturer would have preferred a location farther from the engine, but preference for this test was given to PEMS1 and 2, as they provided complete systems. The PEMS1 gas-phase heated sampling line and exhaust flow meter lines extended from the inside of the laboratory to the exhaust system, which was about 5 meters. The PEMS1 heated PM sampling line extended from the dilution box to the sample probe, which was about 5 meters. PEMS3 heated sample line was about 3 meters, and extended from the dilution cell to the sample conditioner.

PEMS1 required several resources from the MEL in order to operate as a portable instrument, such as compressed air (supplied air compressor failed); flame ionization detector (FID) air, FID fuel, Zero air, two circuits of 120V 20 amps each, and UCR filter weighing operation. The FID fuel and air was mostly a convenience as the gas-phase measurement part was not being evaluated, but the compressed air and filter weighing resources are directly needed to measure PM. The dilution air is needed to operation the proportional diluter. The filter weighing operation includes tarred filters, filter conditioning, filter logging, filter weighing, filter recording, filter processing and filter handling.

PEMS3 utilized two resources from the MEL, a compressed air source and a single 120VAC, 20 amp circuit. The PEMS3 manufacturer provided a DC to AC converter, but to facilitate operations, UCR chose to provide the PEMS a single 120 VAC, 20 amp circuit (of which only a few amps were used). The compressed air was used to cool the PEMS internal circuit boards and to provide dilution air for the PEMS3 constant diluter. The PEMS3 system provided compressed air for the dilution system, but they preferred to use a more stable source of compressed air for this test. It is uncertain how dilution air stability could affect PEMS3 measurement accuracy. The compressed air used to cool their instrument was an in-field attempt to fix an overheating problem. The manufacturer plans on offering future units with an active cooling system to prevent overheating. This added cooling will add to the power requirements, but should improve data collection efficiency.

3.4 Sensors/AVL Operation PEMS2/PEMS3

PEMS2 and PEMS3 were operated simultaneously for the last part of this PM PEMS study. PEMS2 is a complete system including gas emissions, exhaust flow, ECM J1939 interface, PM proportional diluter/sampler and mass measurement system. PEMS3 again required the PEMS2 exhaust flow and ECM J1939 signals in order to calculate bsPM. PEMS2 and PEMS3 were used and combined over the final 100 forced events.

PEMS2 principal of operation is based on direct PM mass measurements and proportional dilution using a partial flow sampler. The PEMS2 PM system is based on quartz crystal microbalance (QCM) technology. The PEMS2 manual reports the QCM sensitivity at 150 Hz/µg. The PEMS2 manufacturer, however, at the November 2008 MASC meeting updated this sensitivity to 100 Hz/µg. They also suggested multiplying all the QCM masses by a ratio of

150/100 to correct for this parameter change. This will have the effect of increasing the PM mass by 1.5 times. The data in this report were not updated to reflect this increase in PM mass due to program timing and an allocation of resources to the main PM MA program. As such, the PM masses reported for PEMS2 should be 1.5 times higher than those provided in the Figures. QCM technology employs piezoelectric crystals where aerosol particles are deposited on the crystal surface after being charged in a high concentration of unipolar ions. The charged particles then enter an electric field and are attracted to the crystal surface where they are deposited. Thus, the PEMS2 definition of PM is based on the ability of a particle to be charged and deposited on the crystal surface. The oscillation frequency of the crystal decreases with increasing mass load. Thus, by detecting the frequency change of the crystal, the mass deposited can be determined. Knowing the mass deposited, sample flow rate, proportionality, exhaust flow, and J1939 broadcast engine speed and torque, PEMS2 calculates bsPM.

Installation PEMS2/PEMS3

The gaseous and PM systems of PEMS2 were mounted on a frame where the passenger side fuel tank is typically located (see Figure 3-6). Typically, when the PEMS2 is mounted outside the cab there is an environmental enclosure for rain and vibration. UCR utilized the vibration table shipped with PEMS2 system and performed all testing absent of moisture or rain to prevent the need for the environmental enclosure. The vibration table was mounted to the frame system and the gas-phase PEMS2 was strapped to the vibration table. There were no additional straps around the gas-phase PEMS2 and the frame, since this would have prevented proper isolation. The PM part of PEMS2 was strapped directly to the frame since this part of the instrumentation does not require a vibration table. Also, the PEMS2 manufacturer requested to be mounted furthest from the exhaust and engine heat and thus was mounted down stream of the QCM. The QCM is typically installed on the catwalk behind the cab, as shown in Figure 3-7. The frame mounting in this study is very similar to the standard QCM mounting, with the only difference being a slightly lower to ground distance and off to the passenger side of the truck.

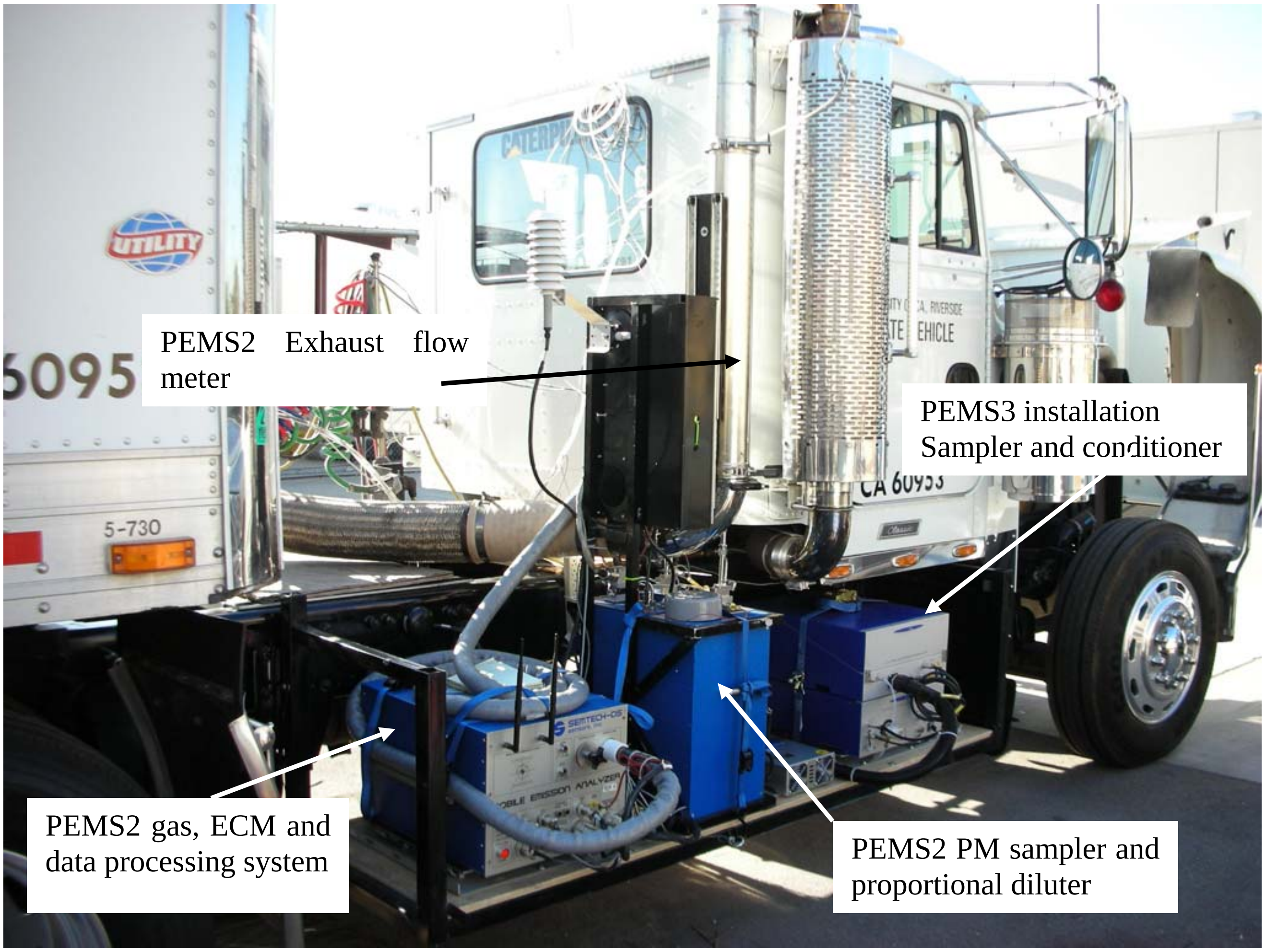


Figure 3-6. PEMS2 and PEMS3 installation outside of cab on test vehicle frame rails

The sample location for PM and gaseous emissions was identical to the setup for the PEMS1 system. The only difference is how the PEMS2 system draws its PM sample out of the bottom of the 90 degree elbow. Inherent to the PEMS2 design is an all metal short transfer line to minimize PM losses. The flow meter sample location was kept similar between the PEMS1 and PEMS2, as explained earlier.

Resources that were provided to PEMS2 by UCR included FID fuel from the MEL laboratory and one 120 VAC circuit of 20 amps power from MEL. PEMS2 provided all the resources for stand alone operation. It was decided by the Committee and UCR staff to provide resources to facility ease of operation. It should also be pointed out that the PEMS2 did not have a vehicle battery system in parallel to the Semtech DS and PPMD. Any power spikes would not be buffered and would subject the systems to an unstable supply of 12 VDC. A battery system could be used as a power buffer to help prevent operational problems.

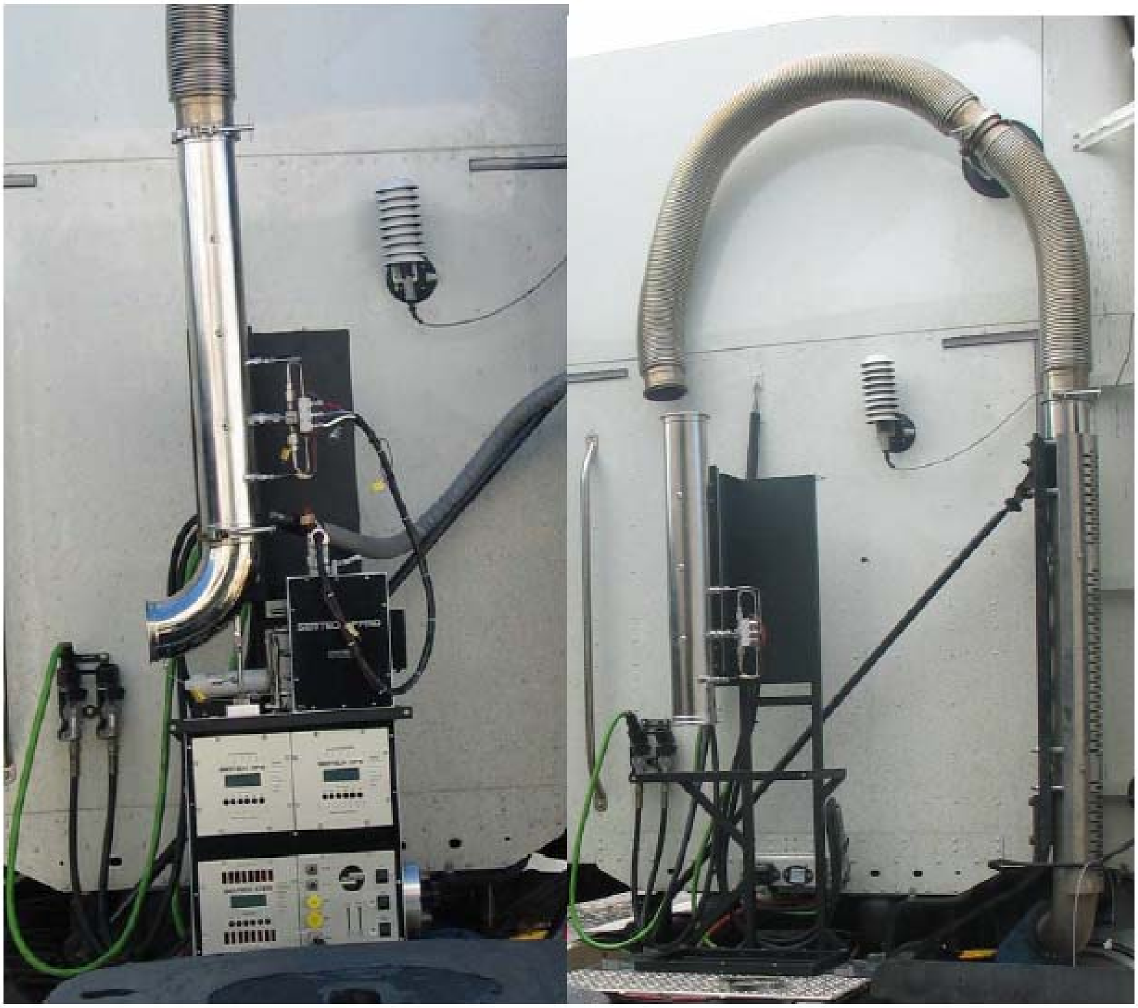


Figure 3-7 PEMS2 Manufacturer recommended installation details (ref manual)

Figure 3-8. On-road testing route 3 during MEL filter change out and PEMS inspection

3.5 Dekati DMM PEMS4

PEMS4 was operated by UCR following the recommended operating procedures provided by the manufacturer (DMM manual). Leak checks and zero calibrations were performed daily during startup. The instrument was allowed to warm up for approximately thirty minutes and then a zero procedure was performed. During filter change outs and MEL calibration, the PEMS4 zero was verified. The PEMS4 zero was not adjusted through-out the course of testing, however. Also, the PEMS4 flow rate was verified to make proper corrections for actual flow versus nominal flow. Each day the PEMS4 was cleaned following the manufacturers procedures and the charger voltage was documented to establish start up charger voltage.

The PEMS4 was installed in the MEL laboratory and typically sampled from a separate high dilution, secondary dilution tunnel. This secondary tunnel is separate from the one used for the PM mass measurements. The nominal PEMS4 dilution for this study was set at 80 to 1 in order to prevent instrument over ranging. It was noticed near the end of the study that the 80 to 1 dilution was causing average NTE concentrations to be less than 50 µg/m^3, which is near the low end of the PEMS4 analog output resolution scale. It was decided to try and increase the nominal concentration for PEMS4 to higher levels by moving it to the primary CVS dilution tunnel (2.7

to 1). Then it was noticed that the analog signal was being truncated during hard accelerations. Finally, PEMS4 sample was moved to the gravimetric filter dilution system which was set to the dilution ratio specifications of 1065 (6 to 1). No statistically significant correlation differences were noticed between the different sampling locations and dilution ratios.

The PEMS4 analog signal is integrated and time aligned with the MEL emissions system and has been for some time. Recently, UCR has noticed inaccuracies with low concentrations with the analog signal and truncated hard accelerations that are not seen in the recorded PEMS4 digital signal. UCR does not have the optional digital interface for PEMS4, so the data must be time-aligned and joined with the MEL data if the digital files are to be used. These data are not currently available, but are planned for future publications.

3.6 TSI DustTrak PEMS5

PEMS5 was operated by UCR following typical operating procedures developed over the years of operation in the MEL. PEMS5 is operated with weekly zero calibrations and requires weekly cleaning as per manufacturer's recommendations. UCR performs the cleaning and zero calibration procedure during routine propane verifications and maintains logs on the PEMS5 performance. PEMS5 was inspected less than five days prior to testing. PEMS 5 is typically calibrated on Arizona road dust. The MEL has found calibrations on diesel exhaust provide a better span value. The current span calibration for the DustTrak is from MEL PM mass data from 2005, with weekly zero calibrations, but no adjustments. Adjustments are not made since the instrument span value is stable and appears to still be appropriate. The PEMS5 zero was checked daily and was not adjusted between tests, similar to the operation for PEMS4.

3.7 MEL Operation

The MEL was operated using procedures planned for the subsequent PM MA correlation at SwRI. The MEL primary tunnel flow rate was set to 2700 standard cubic feet per minute (scfm) and the secondary tunnel was set to provide a secondary dilution of 2.27. The nominal expected exhaust flow was estimated at 1000 scfm at full load. Thus, the primary dilution tunnel achieved a minimum DR of 2.7. This combined with the fixed secondary dilution ratio of 2.27 gave a minimum overall PM dilution of 2.27 * 2.7 = 6.0.

The PM mass collection for the MEL is defined by the filter media (Pall teflo 2 µm pore), sample temperature (47°C), backing screen (ambient backing screens), flow rates (50 cc/s), and other conditions (2 sec residence time). Future upgrades are in progress, and the MEL is expected to operate at face velocities of 90 – 100 cc/s (47°C) by doubling its filter sample volume flow rate. These face velocities will be similar to those to be used by SwRI in the main PM MA program. The filter stabilization process is at different conditions compared to the QCM real-time environment. The Teflon filter is stabilized at 1065 conditions of 21°C dry bulb and 9.5°C dew point temperature (45% relative humidity) for a minimum of 1 hour and up to 72 hours.

A standard zero span calibration was performed every hour and before each test throughout the correlation. Typically, the MEL performs an daily audit check to verify proper calibration gaseous operation, but this was not performed due to the level of complexity with the PM instruments and because the PEMS1 and PEMS2 manufacturers did not plan on providing gaseous PEMS data. The MEL did not fill or analyze bags for ambient level concentrations. The MASC decided to use default ambient concentrations for background corrections. The default concentrations came from averages from the audits for nominal concentrations found on previous studies for these types of driving routes.

In an attempt to synchronize signals between the MEL and multiple PEMS, the MEL provided a forced event five volt signal to each PEMS that corresponded to when the MEL was sampling on the gravimetric filters. This essentially acted as a forced NTE event. The signal transitioned from 0 volts to five volts to identify the start of the forced filter event. The transition from five volts back to 0 volts indicated the end of the forced NTE event and the end of the MEL filter sample. For the MEL, four forced events were performed for each test run, with each forced event sampled on a separate filter. Each test run lasted about one hour. At the end of each test run, the filters were removed and replaced with new filters for the next test. An automated zero span was also performed on the MEL while the filters were being changed and PEMS manufacturer verified proper PEMS operation. This procedure was repeated for the whole test day. Typically 5 runs per day were performed.

Figure 3-9. MEL Driver's Aid Interface

3.8 Test Routes

The PEMS were tested over several different routes during the on-road testing. These routes were designed to provide some differing environmental conditions, but at the same time be conducive to operation in the NTE-zone. The routes include some that were previously used in the gas-phase measurement allowance program [Miller et al. 2007, 2008] and some that were new for this test program.

Route 1 – Riverside Local Freeways

Route 1 was a local loop on the freeways in the local Riverside area, as shown in Figure 3-10. This is approximately a 50 mile loop that was conducted after the initial installation of the PEMS to insure that the PEMS were operating properly prior to going on the other routes. The route was repeated 4-5 times depending on the needs in operating the PEMS.

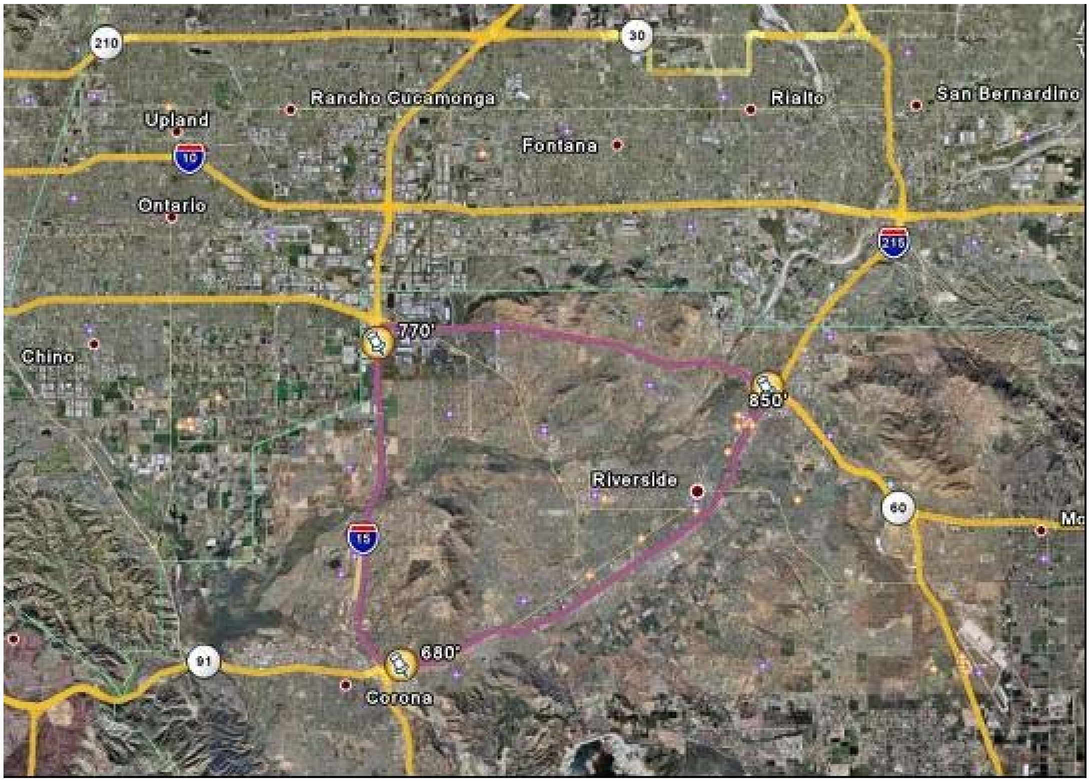


Figure 3-10. Riverside Local Freeway Route.

Route 2 – Riverside to San Diego Round Trip

The second route for the on-road testing consisted of driving from Riverside to San Diego and then returning to Riverside. This route utilizes Interstate-15 (I-15) and I-5, which are two of California's major freeways. This route is shown in Figure 3-11. Driving on this route is more rural with possible congestion around the San Diego region and around the Riverside area on the return trip. This route also included some power line crossings and potholes which contributed to road vibrations. This route has many elevation changes and uphill grades, which ensured a sufficient amount of operation in the NTE control zone of the engine. The total trip distance is approximately 200 miles.

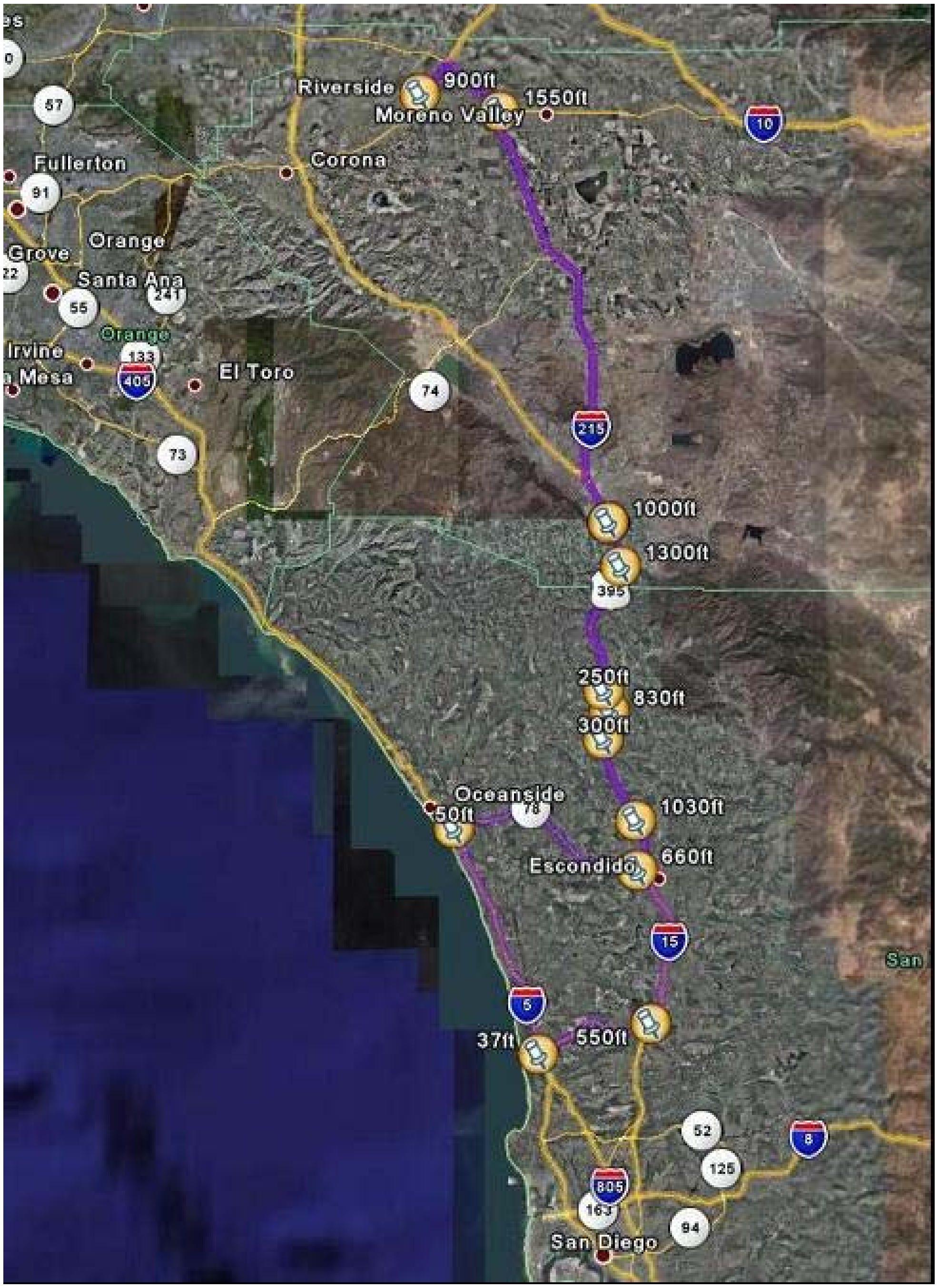


Figure 3-11. Riverside to San Diego Route

Route 3. Riverside to Palm Springs/Indio, CA

The 3rd route was a round trip to Palm Springs/Indio, CA and back. This route is shown in Figure 3-12. This route travels along the I-10 freeway and includes varying elevations throughout the trip. This route is commonly used by interstate truck traffic heading to Arizona and other areas. Traffic is relatively free flowing on this route over most of the duration of the travel.

Figure 3-12. Riverside to Palm Springs/Indio, CA Route

Route 4. Riverside toward Baker, CA and over the Baker grade

The final route consisted of driving along I-15 towards Baker and the Las Vegas state line. This route is shown in Figure 3-13. This route is commonly used by vehicles traveling from Southern California to Las Vegas, NV. The Baker grade is also reportedly used by different engine manufacturers for performance testing. The route has many elevation changes, providing a sufficient amount of operation in the NTE control zone of the engine, and reaches an elevation above 5000 feet. The total trip distance is approximately 240 miles.

Figure 3-13. Riverside to Baker/State Line Route.

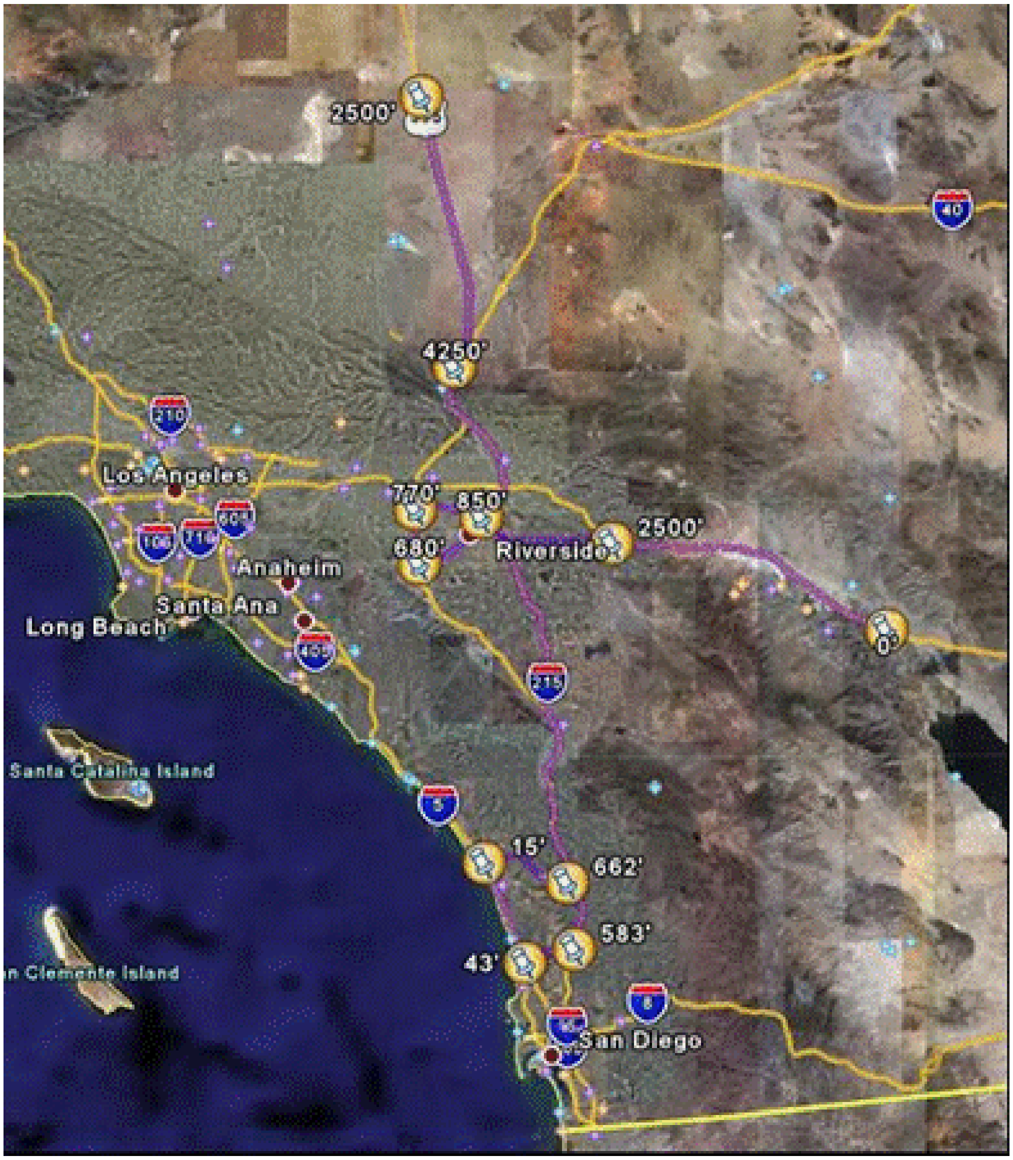


Figure 3-14 Overview of all routes relative to Riverside and LA area.

4.0 On-Road Testing – Experimental Results

The experimental results and cross comparisons between the different PM PEMS and the MEL are presented in the following section. This section covers only PM emissions, since other gas-phase emissions were not emphasized in the program or were not provided by the instrument manufacturers.

4.1 NTE Event Summary and Data Collection

Data for each instrument was collected over a series of NTE events over the different testing days. The results presented in this report are based on a subset of the actual data collected. Table 4-1 shows a breakdown of the NTE events attempted and the percentage of events for which bsPM data were provided or are reported. The data are separated for the testing sessions for PEMS1/PEMS3 and PEMS2/PEMS3.

Instrument	NTE events Attempted	NTE events Submitted	% reported
PEMS1/PEMS3 Tests			
PEMS1	70	62	89%
PEMS3	52	48	92%
PEMS4	70	70	100%
PEMS5	70	70	100%
PEMS2/PEMS3 Tests			
PEMS2	92	46	50%
PEMS3	100	56	56%
PEMS4	100	100	100%
PEMS5	100	100	100%

Table 4-1. Data Summary of NTE Events.

4.2 Measurements of Brake Horsepower

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 4-1 through Figure 4-3 show the correlation between the hp calculated by the MEL and the different PEMS. The correlation plot represents a filtered set of data in which only NTE events that "matched" between the MEL and PEMS are included. In this case, matching NTE events are ones where the identified NTE events have a similar start time between the MEL and PEMS2 and a duration that is the same within 4 seconds. Overall, the hp correlations were relatively good for each of the PEMS. PEMS2 showed the best correlation. PEMS 1 showed a generally good correlation, with a few outlier points. These outlier points were removed for the subsequent emissions analyses to provide the best comparison of pure PM measurements. The nature of these outlier events was not investigated, but could be attributed to the level of software development for the system. PEMS3 showed a good correlation also, but with slightly greater scatter compared to PEMS2.

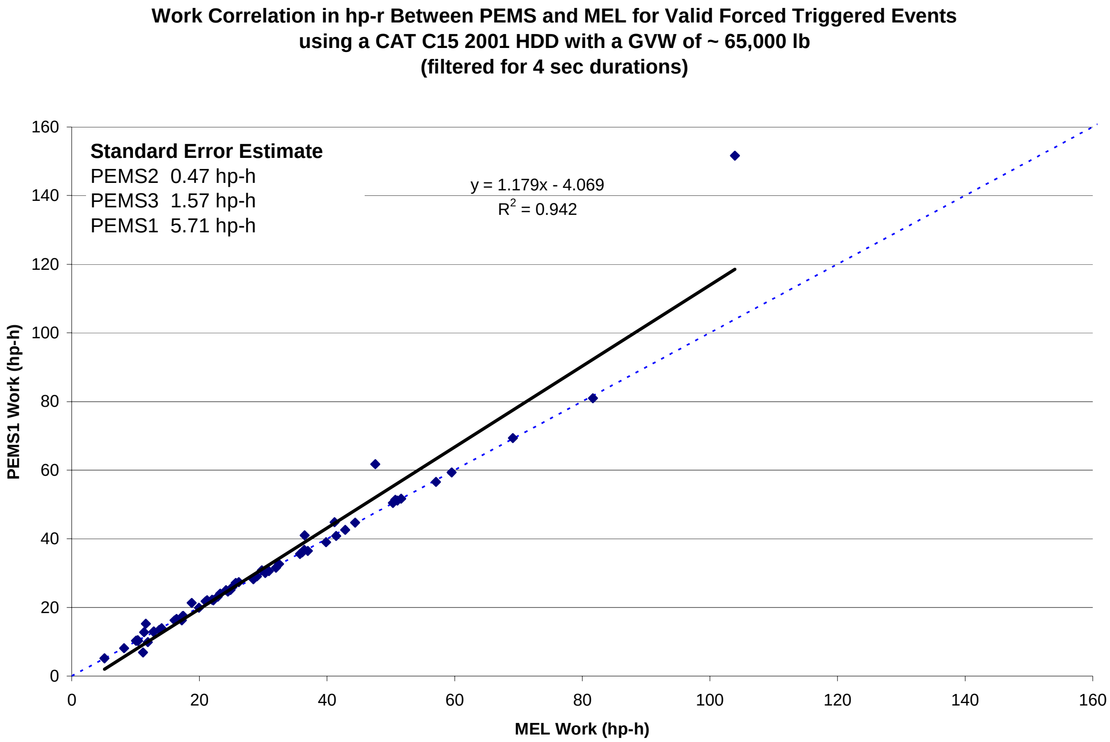


Figure 4-1. Work Correlation between MEL and PEMS1

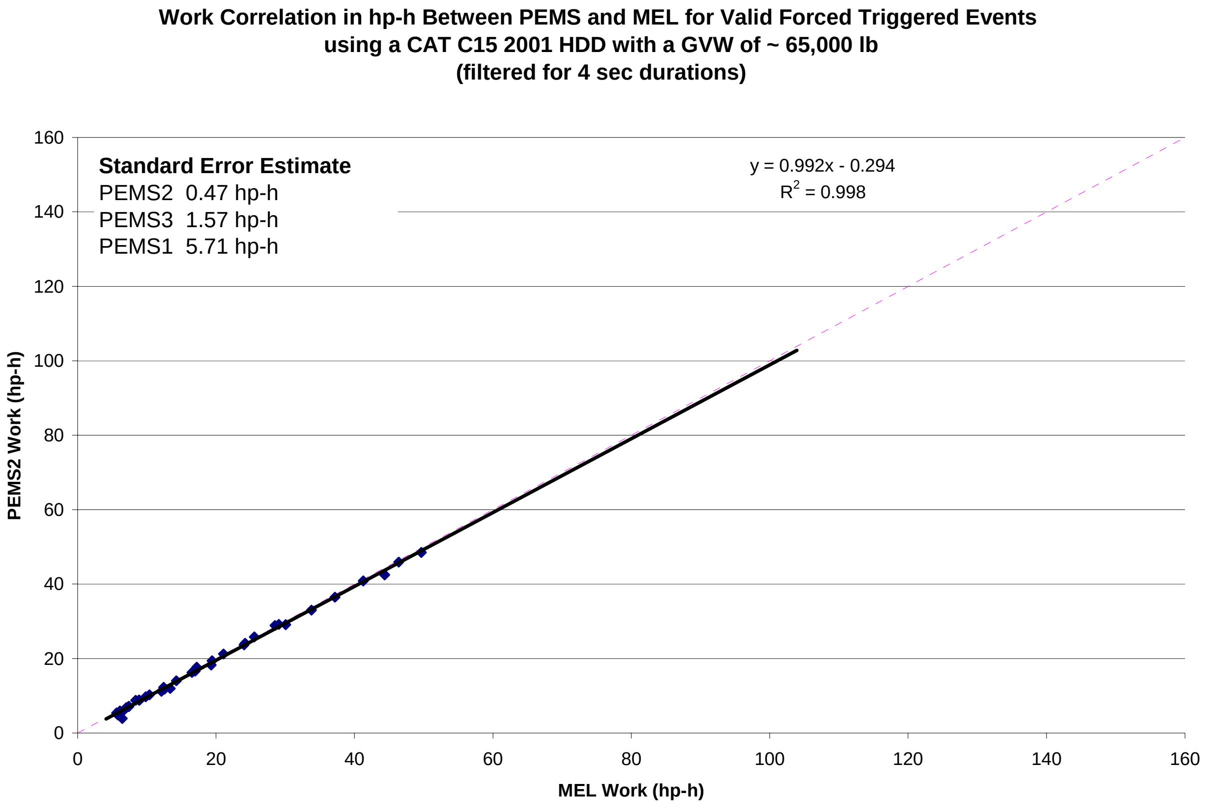


Figure 4-2. Work Correlation between MEL and PEMS2

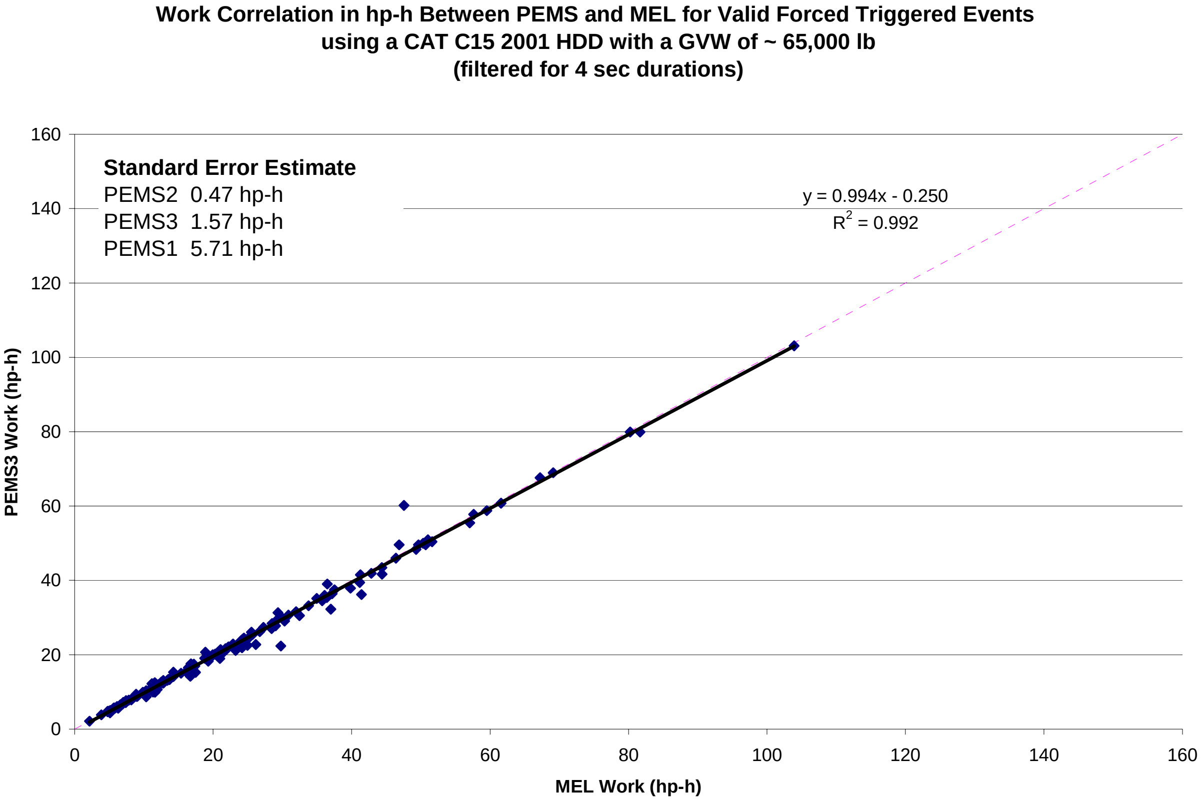


Figure 4-3. Work Correlation between MEL and PEMS3

The average hp-h levels for each of the individual “NTE” events is provided in Figure 4-4. As shown, the triggered NTE events spanned a range of hp-h levels. The values fell predominately into the NTE region, which is represented by the data above the line in the figure. These data show the triggered NTE events provided a reasonable representation of actual operation within the NTE zone.

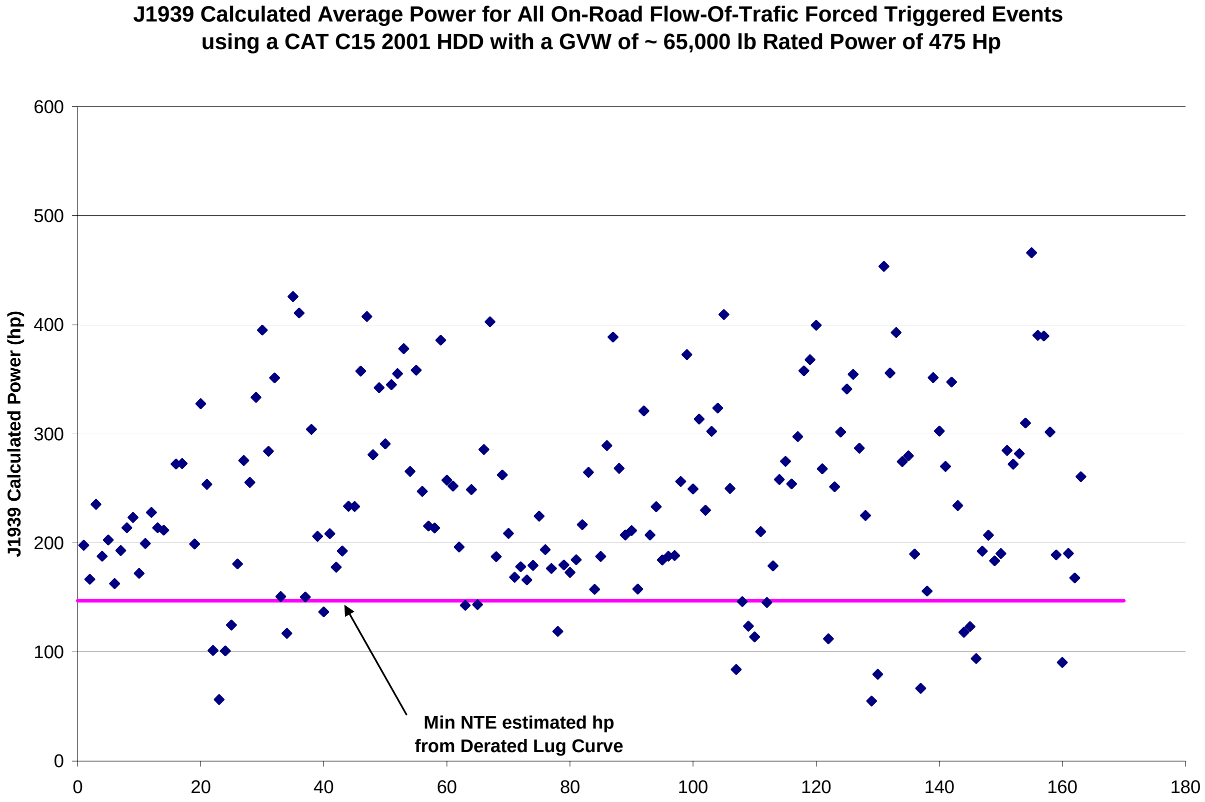


Figure 4-4. Average Power for Forced NTE Triggered Events

4.3 PM Filter Mass Results

It is important to understand the filter mass results to provide a perspective in interpreting the PM emissions results. As discussed above, the filter masses were targeted to be between 50 and 200 µg during the triggered NTE events. The filter masses for each NTE event are presented in Figure 4-5, along with the corresponding test durations and PM emission rates in g/hp-h. The results show that the filter masses ranged from approximately 50 µg to over 400 µg. The data show that most of the test filter mass values are within the targeted 50-200 µg range, with nearly all filter mass values below 300 µg. In many cases, the higher filter weights are associated with longer test durations.

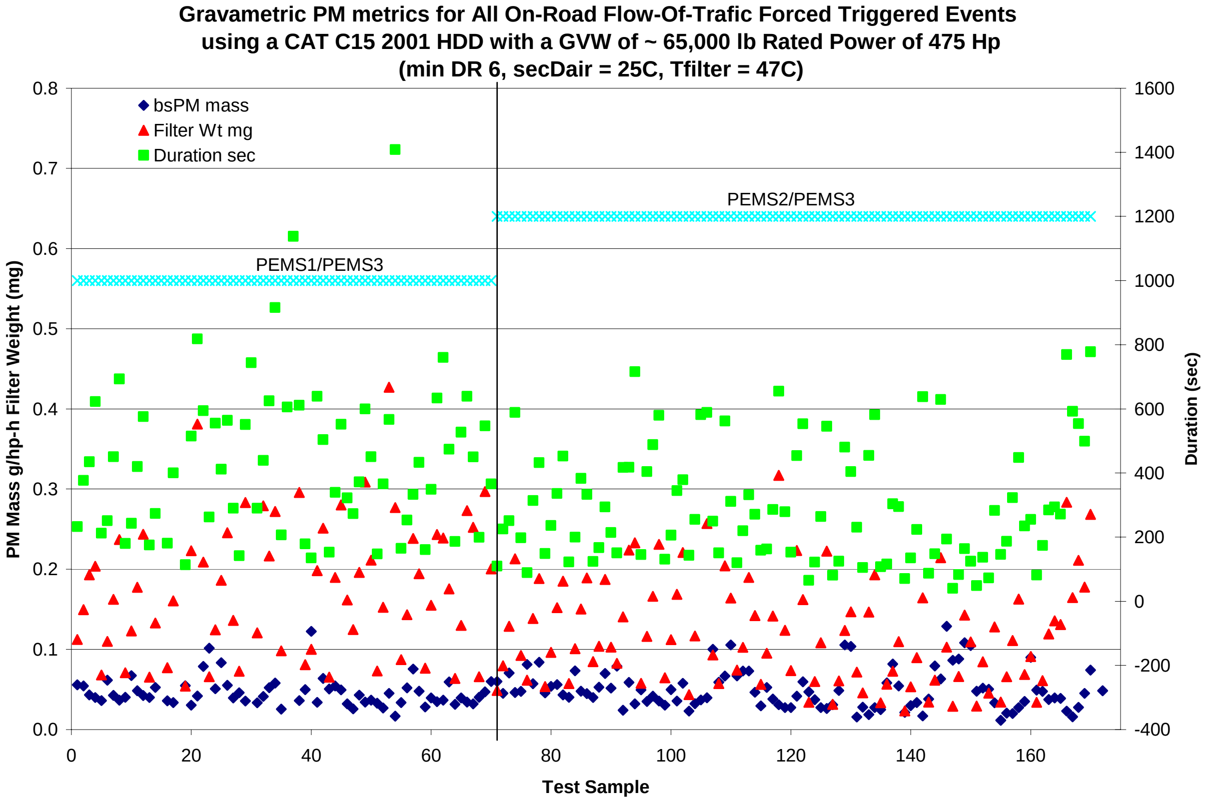


Figure 4-5. Filter Mass, Test Duration, and PM Emission Level for the Individual Triggered NTE Events for the MEL.

A comparison of filter weights for different brake-specific PM emission levels is provided in Figure 4-6. The highest filter weights on this graph are generally associated with PM emission levels in the 0.2 to 0.6 g/hp-h range. This indicates that these could be longer tests, with lower average brake horsepower levels. A wider range of PM emission levels is found for the corresponding lower filter mass samples. This indicates a range of shorter duration samples with varying average brake horsepower levels.

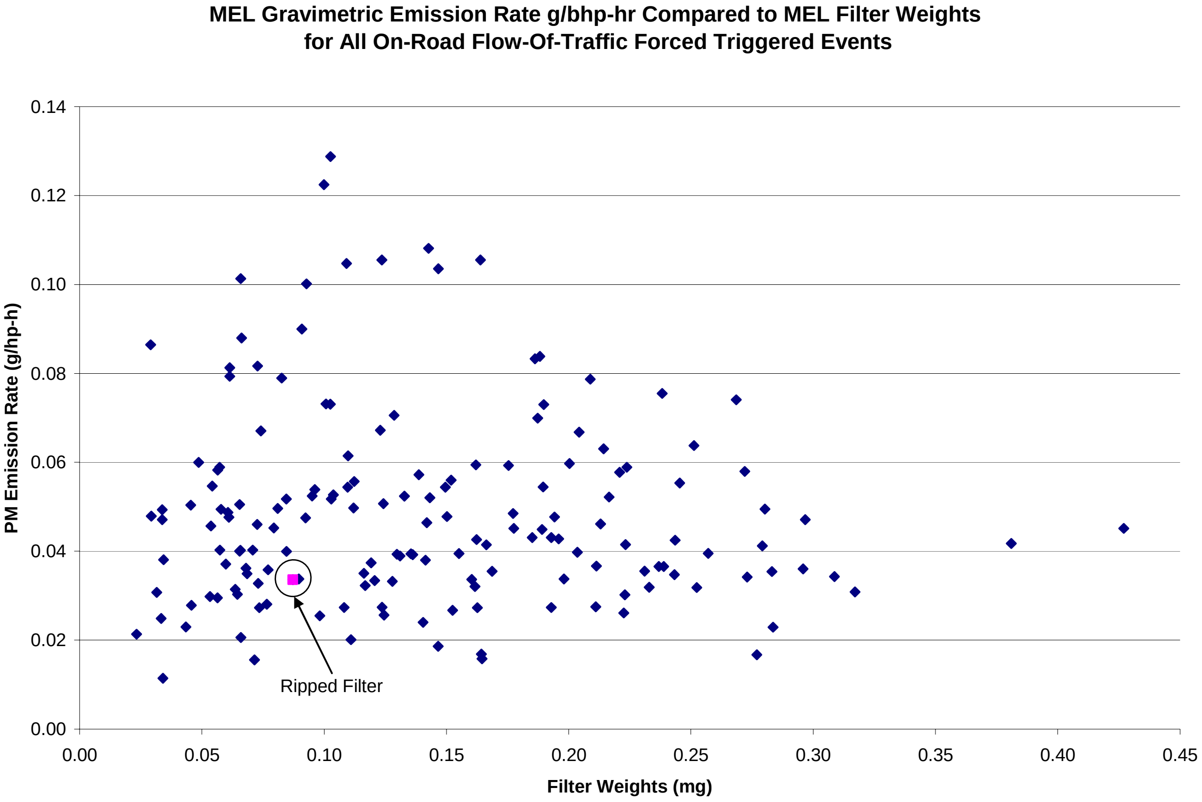


Figure 4-6. PM Emission Level (g/hp-h) as a Function of Filter Weight for the MEL.

Figure 4-7 shows a different perspective of PM filter weights as a function of descending PM emission rate. This Figure shows that the range of PM filter masses is relatively consistent over the PM emission rate range. The NTE events with the highest PM emission rates generally had lower average hp-hr levels, indicating points either just at or below the NTE power threshold.

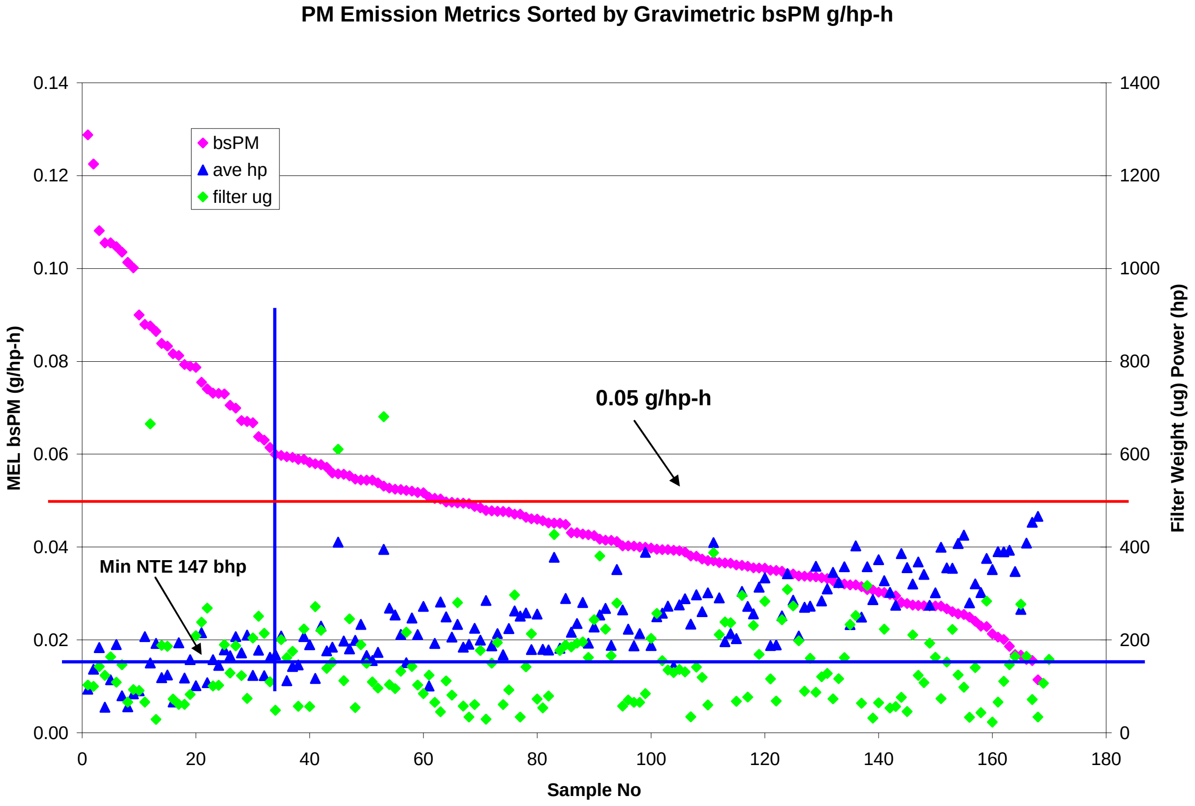


Figure 4-7. Filter Weights in Order of Descending PM Emission Rate (in hp-h)

4.4 PM Emission Results

PEMS 1 PM Results

The PM results for PEMS1 are compared with those of the MEL in Figure 4-8 on a g/hp-h basis and in Figure 4-9 on a g/hour basis. For these Figures, all the collected data that was provided by the PEMS1 manufacturer was included, with each data point representing a single NTE event. In looking at these two Figures, the correlation between PEMS1 and the MEL was poor on both a g/hp-h and g/hour basis, with R^2 values of 0.013 and 0.03, respectively. An additional g/hp-h correlation comparison was made with the outlier work values removed (any work values that differed from the MEL values by greater than 50%). This correlation was also equally poor. Discussions with the PEMS1 instrument manufacturer indicated that the instrument was not operating optimally during the initial days of testing. To evaluate the instrument performance under the more optimal operating conditions, an additional correlation was made utilizing only the results from only the final day of testing. These results are shown in Figure 4-10. The results show an improved correlation at $R^2 = 0.56$, with a systematic positive bias in the measurement, as indicated by the slope of 1.2.

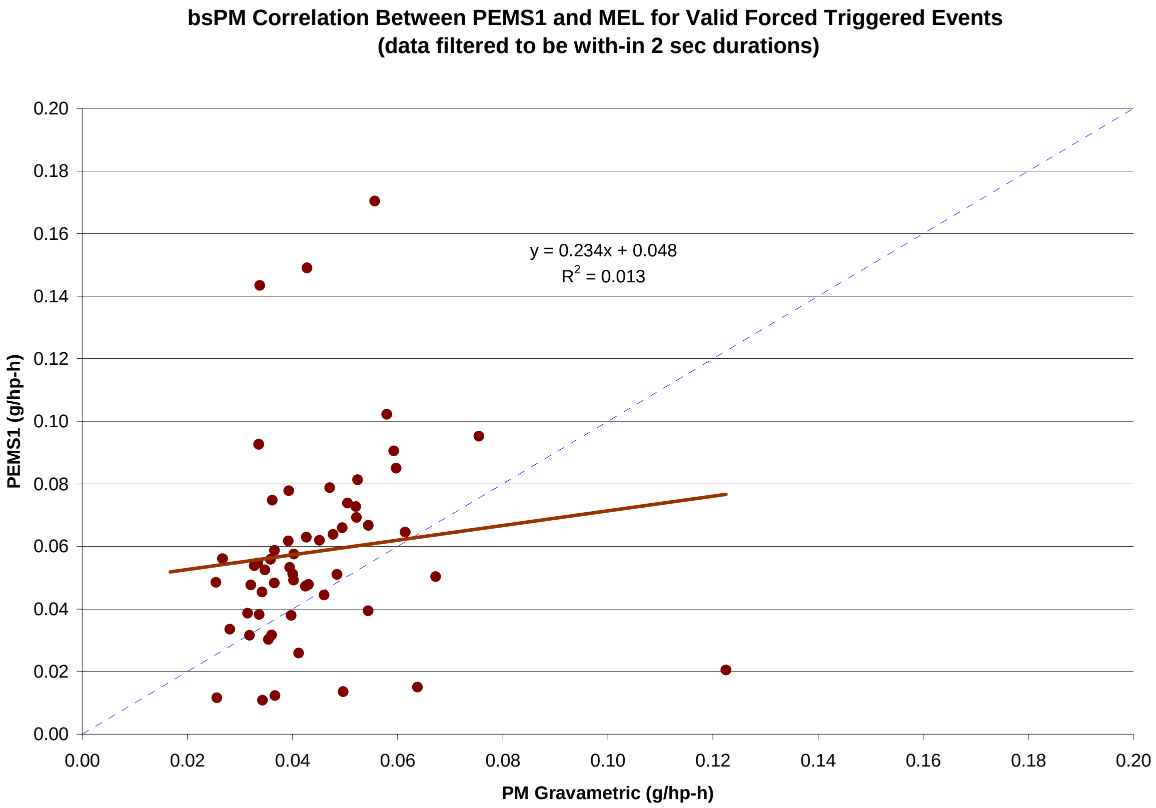


Figure 4-8. Correlation between the MEL Gravimetric and PEMS1 PM Measurements on a g/hp-h basis

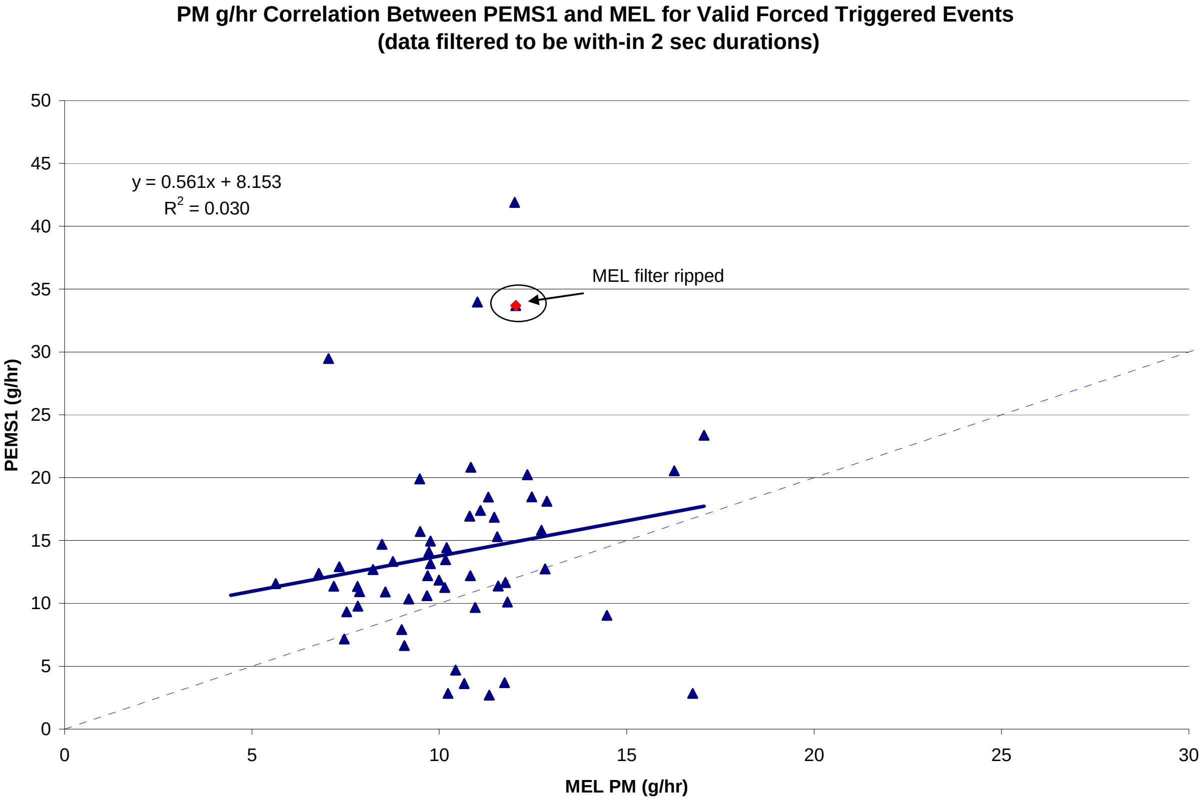


Figure 4-9. Correlation between the MEL Gravimetric and PEMS1 PM Measurements on a g/hr basis

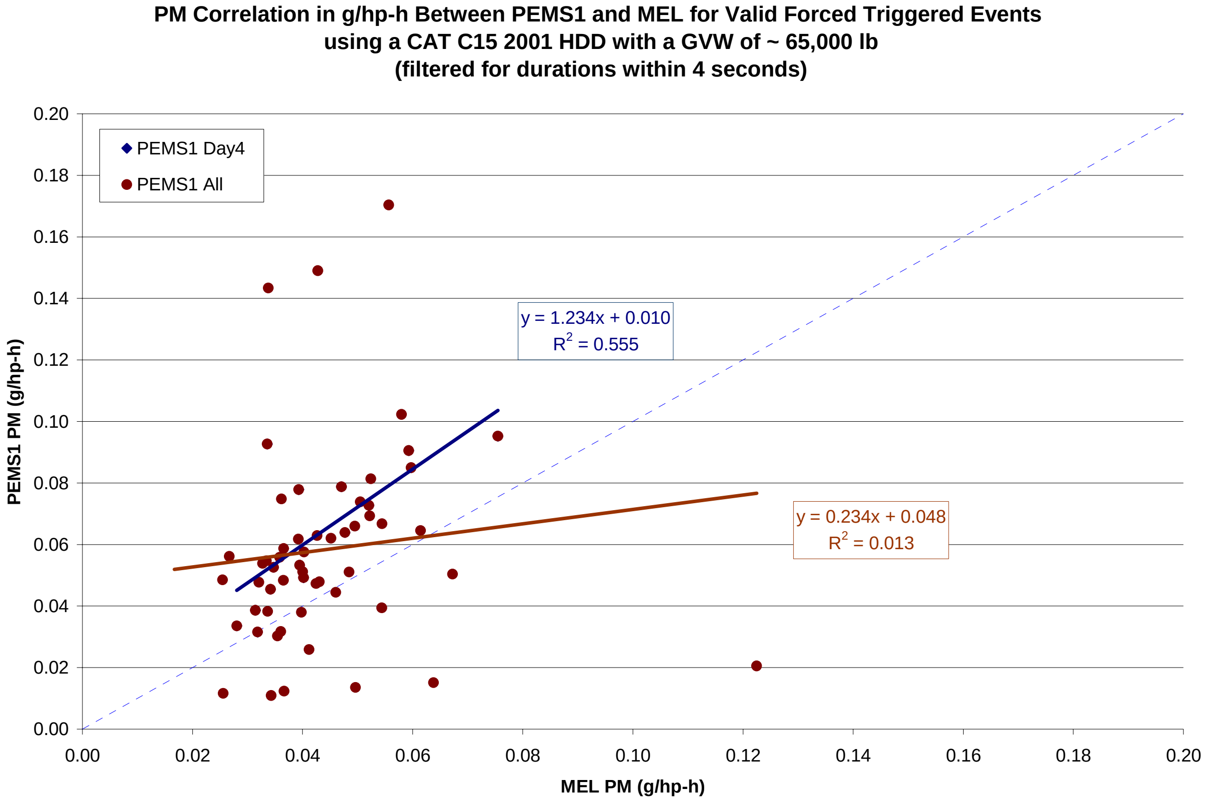


Figure 4-10. Correlation between the MEL Gravimetric and PEMS1 PM Measurements on a g/hp-h basis utilizing only Data from the Fourth Day of Testing

PEMS 2 PM Results

The PM correlation results for the subset of data provided by PEMS2 is provided in Figure 4-11. These data represent approximately 60% of the data collected in the field. The results showed a correlation of R^2 = 0.57 and a slope that is greater than one (1.51). It should be noted that the data in the Figures relating to PEMS2 are all based on the original data set provided to CE-CERT. Subsequently, as of the November 2008 MASC meeting, the PEMS2 manufacturer reported a change in the QCM sensitivity that would have the effect of increasing the PM mass by 1.5 times, as discussed in Section 3.4. The data in this report were not updated to reflect this increase in PM mass due to program timing and an allocation of resources to the main PM MA program. As such, the PM masses reported for PEMS2 should be 1.5 times higher than those provided in the Figures.

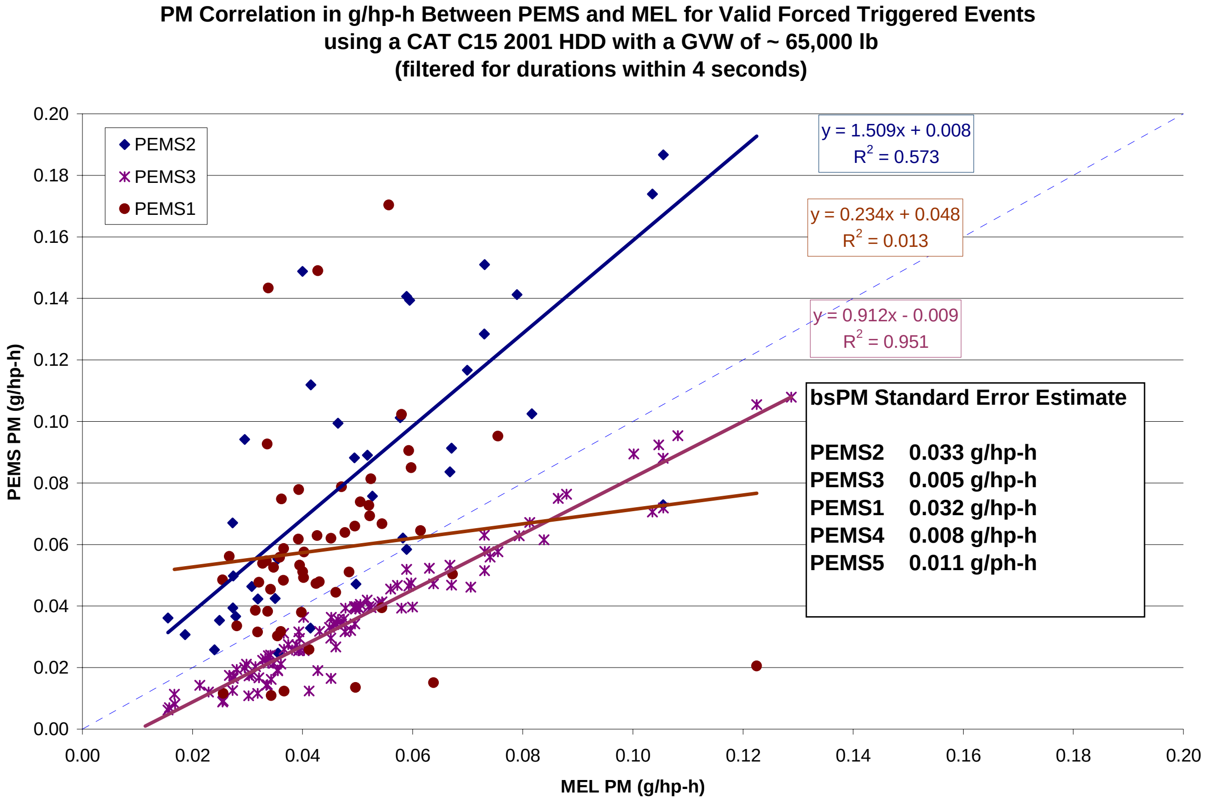


Figure 4-11. Correlation between the MEL Gravimetric and PEMS2 PM Measurements on a g/hp-h basis

PEMS 3 PM Results

The PM correlation results are presented in Figure 4-12 for PEMS3 on a g/hp-h basis. The data show that there is a good correlation between the MEL PM gravimetric values and the PEMS3 PM measurements, with an R^2 = 0.95. The slope (0.91) and intercept of the line indicate that PEMS3 is biased low compared to the MEL. This is not unexpected since the PEMS3 measurement technology is designed to measure elemental or soot carbon instead of total PM.

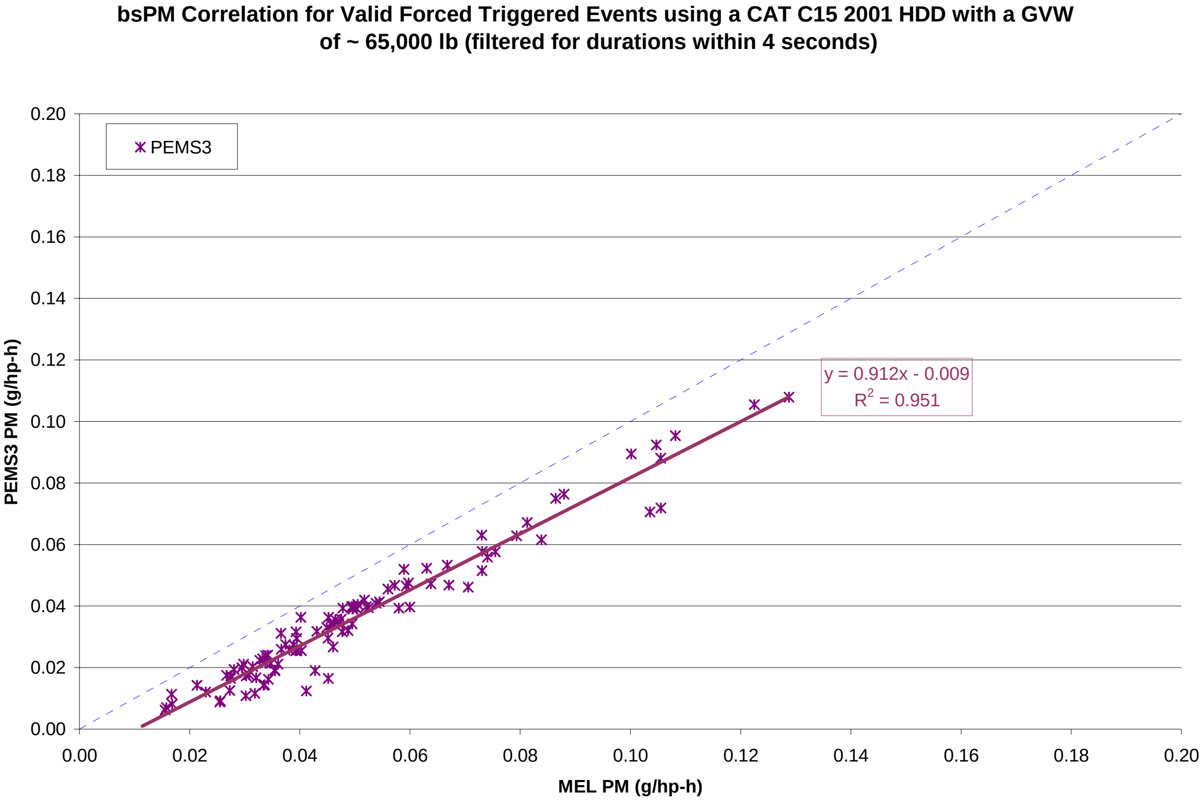


Figure 4-12. Correlation between the MEL Gravimetric and PEMS3 PM Measurements on a g/hp-h basis

The instrument manufacturer for PEMS 3 provided some additional analysis as part of this program, in an effort to better incorporate the soluble organic fraction (SOF) to allow measurement of total PM with their instrument. A summary of the instrument manufacturer's data is included here for completeness. Their analysis essentially utilizes a correction factor based on the soot, THC concentration, and sampling conditions to estimate the SOF contribution to the PM. This analysis is based on previous work by Clerc and Johnson (1982). The analysis also accounts for thermophoretic losses and sulfate contribution. The results utilizing the data correction method are presented in Figure 4-13. The data correction was only calculated for the tests conducted with the Sensors system. These results show a good correlation with the MEL gravimetric PM values ($R^2 = 0.94$), and essentially eliminate the bias seen in Figure 4-12.

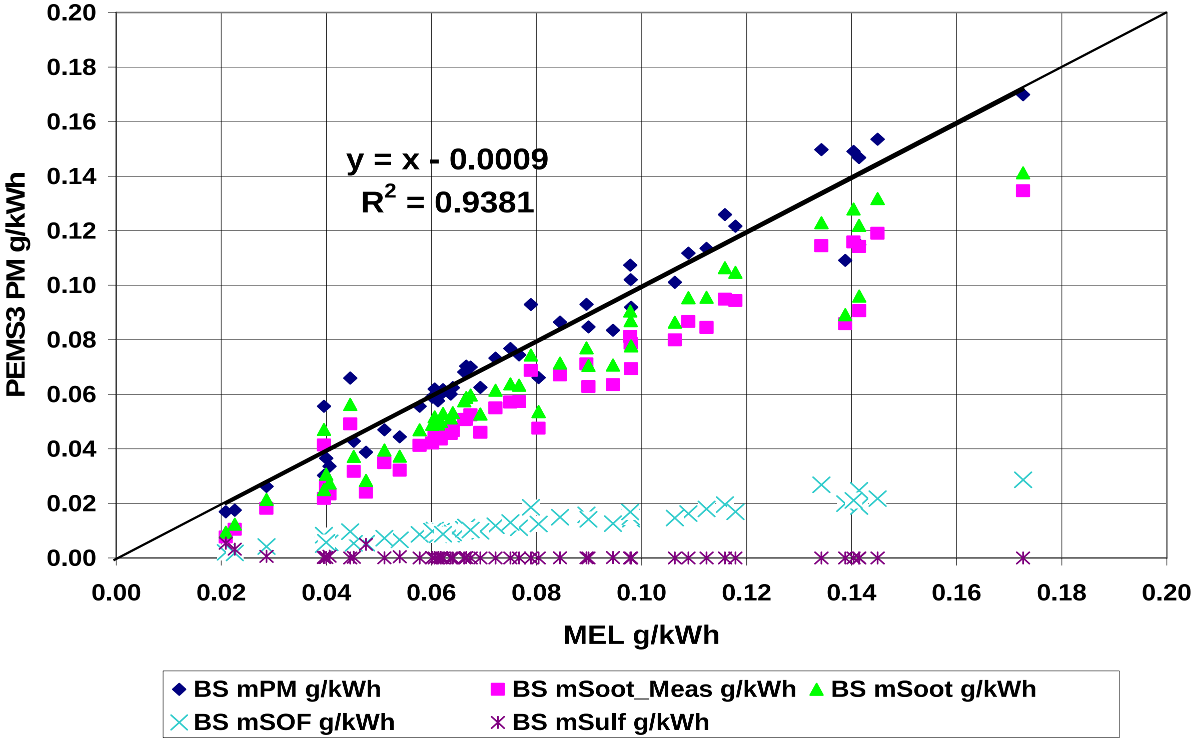


Figure 4-13. Correlation between the MEL Gravimetric and PEMS3 PM Measurements on a g/hp-h basis after Application of the data correction method

PEMS 4 and PEMS 5 PM Results

The PEMS 4 instrument was operated over three different dilution ratios (DR = 70, direct DR =1, and DR=2.3 (off the secondary)). Figure 4-14 shows the correlation between the MEL and PEMS4 for each of the dilution ratios. The correlation coefficients R^2 vary from 0.65 to 0.98. The measurements for PEM4 tend to show a bias low compared with the PM filter mass. The slopes on the lines vary from 0.78 to 0.90. Further analysis is needed to determine if the differences between the different testing conditions are statistically significant.

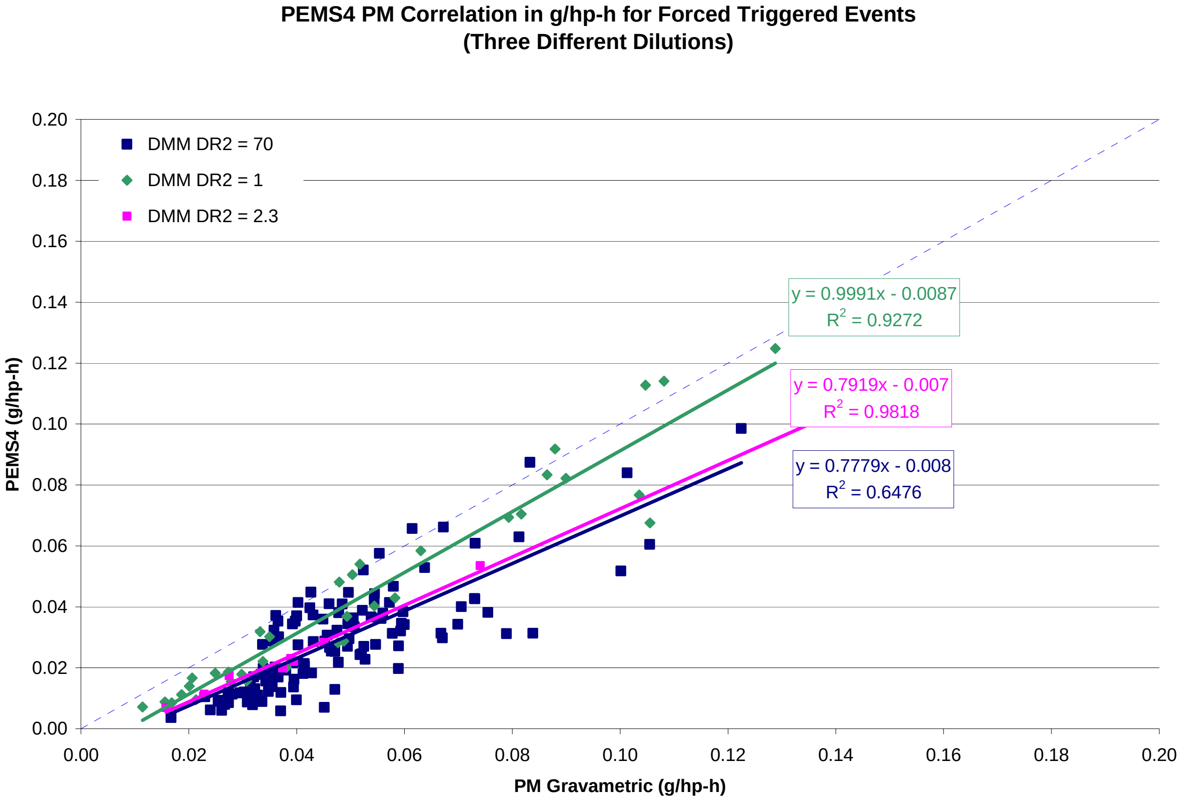


Figure 4-14 Correlation between the MEL and PEMS 4 PM Measurement on a g/hp-h basis

The PM correlations for the combined data for all DRs for PEMS4, along with data from PEMS1 through PEMS5, are shown together in Figure 4-15 for comparison. The results for PEMS4 show that the instrument shows some correlation with the MEL gravimetric PM measurement (R^2 = 0.70), but the values are biased low relative to the MEL PM measurements.

PEMS5 is an internal UCR instrument that is regularly operated in the MEL. This instrument is calibrated against the PM filter masses in the MEL. Not surprisingly, this instruments shows a reasonable correlation (R^2 = 0.86) with the MEL PM gravimetric values and a good slope value. In typical service using the manufacturer’s calibration, it is expected that this instrument would have a much greater bias relative to standard gravimetric PM values.

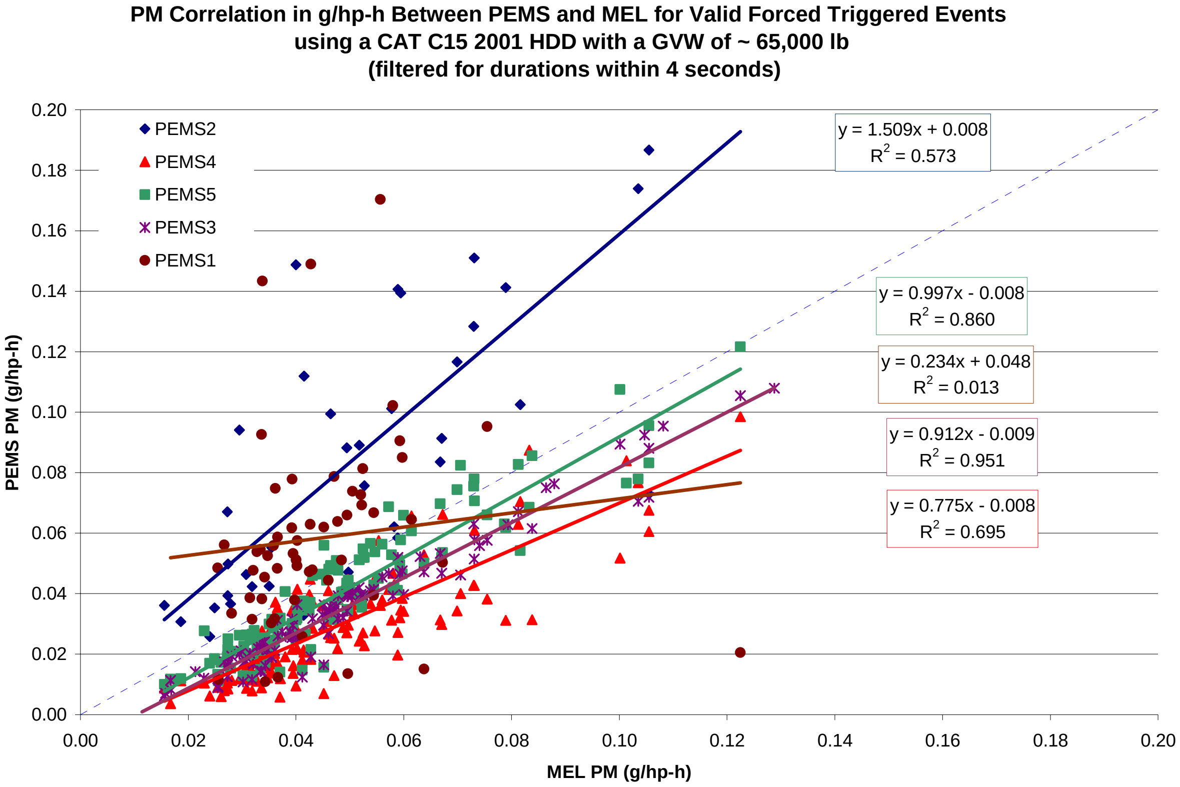


Figure 4-15. Correlation between the MEL Gravimetric and All PEMS PM Measurements on a g/hp-h basis

PM Deltas between PEMS and MEL

The deltas in the PM measurements between the PEMS and the MEL are shown in Figure 4-16. The data provide some indication of the absolute deviations found during the testing. It should be noted that these values represent preliminary data and are not meant to be indicative of any values that would be related to the actual PM measurement allowance.

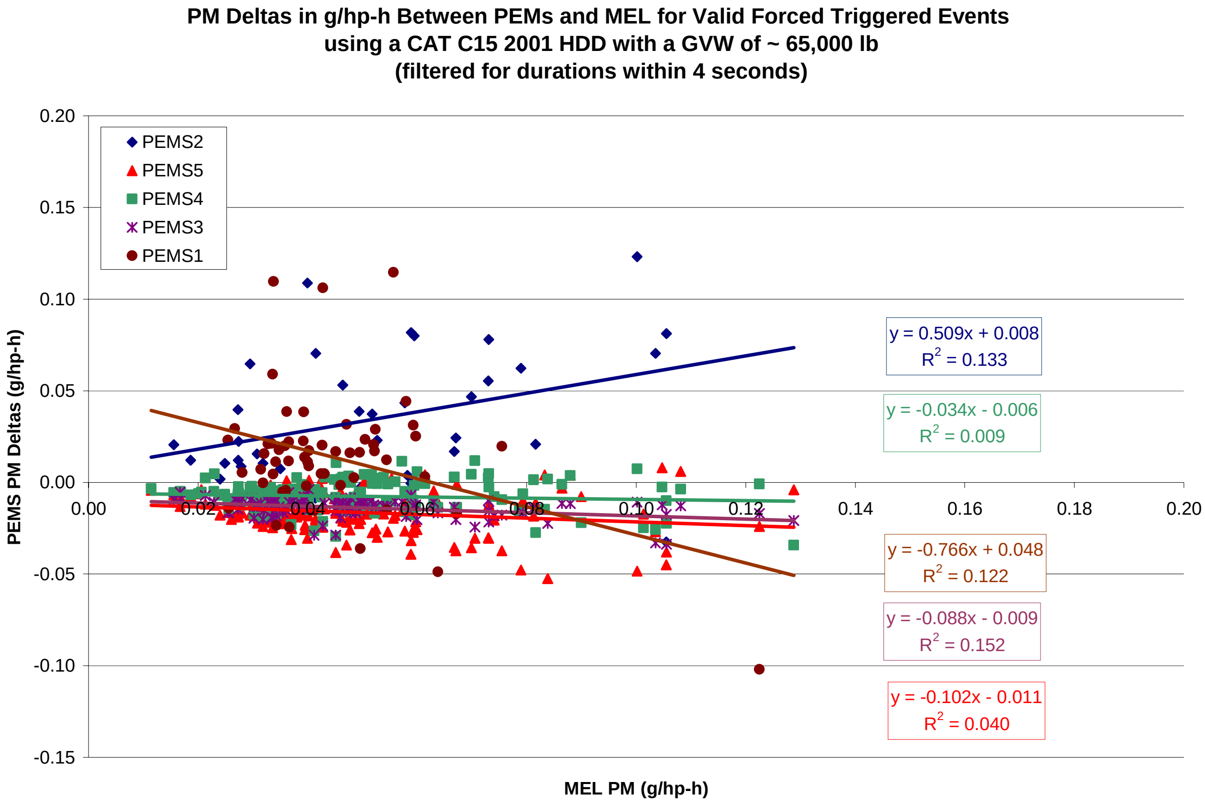


Figure 4-16. PM Deltas as a function of MEL PM Values

4.5 Fuel Consumption Results

Fuel consumption results provide some measurements that can be compared with external values to provide some measure of the overall accuracy of emissions measurements. In this test, the MEL fuel consumption measurements, as determined via carbon balance, were compared with those obtained from the ECM. The correlation between these independent measurements is shown in Figure 4-17. The results show a good correlation between the two readings, with the ECM fuel consumption readings biased slightly high compared to the MEL measurements. This level of agreement is similar to that found in previous MEL studies [Cocker et al., 2004a]. This good correlation is an indicator that the on-road emissions masses are reliable and consistent within expectations.

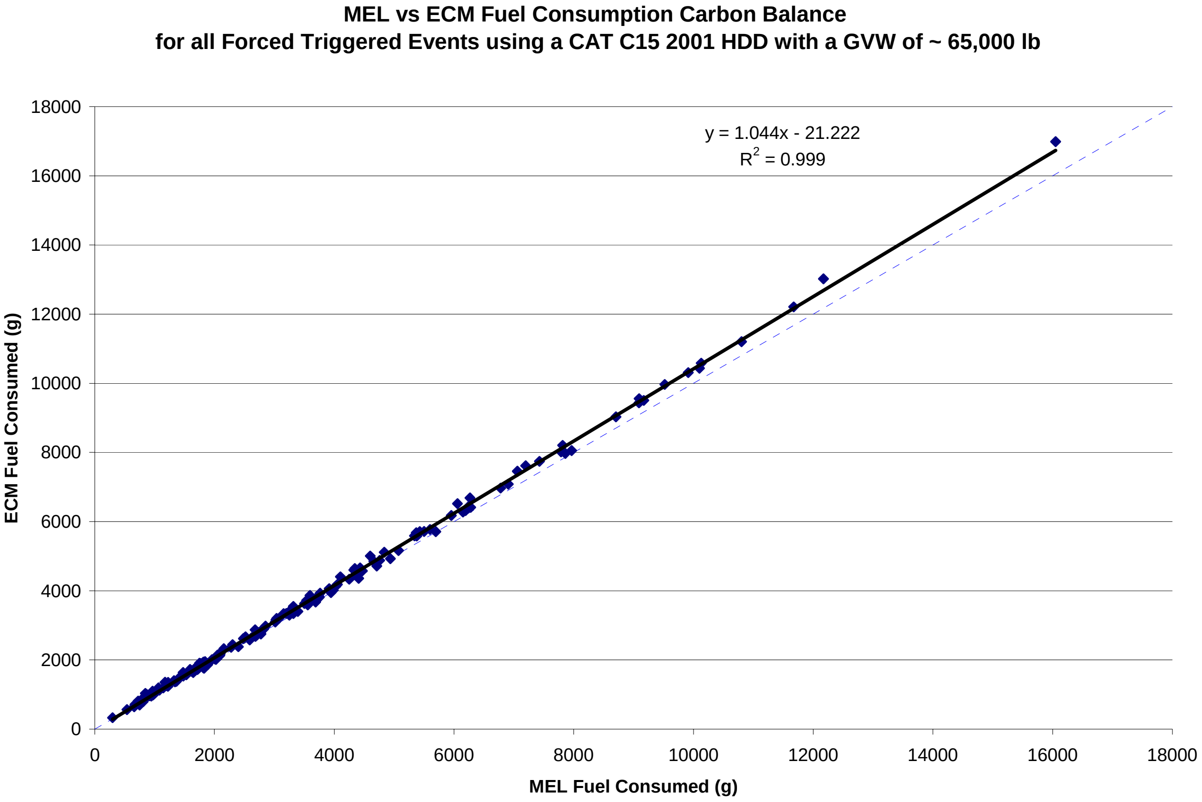


Figure 4-17. Fuel Consumption Correlation between the MEL Carbon Balance Measurements and the ECM Readings.

4.6 Other PM Comparisons

One additional observation of note was made during the on-road testing. PM and NO_x emission rates and the associated humidity correction factor for individual NTE events are provided in Figure 4-18. During one of the testing segments, conditions with a relatively high humidity were found. Under these conditions, a significant shift in both PM and NO_x emission levels was observed. These shifts were in opposite directions, with NO_x levels decreasing while PM levels increased, consistent with a NO_x-PM tradeoff. This indicates that environmental conditions encountered during on-road testing can have an important impact on PM emissions as well as NO_x emissions.

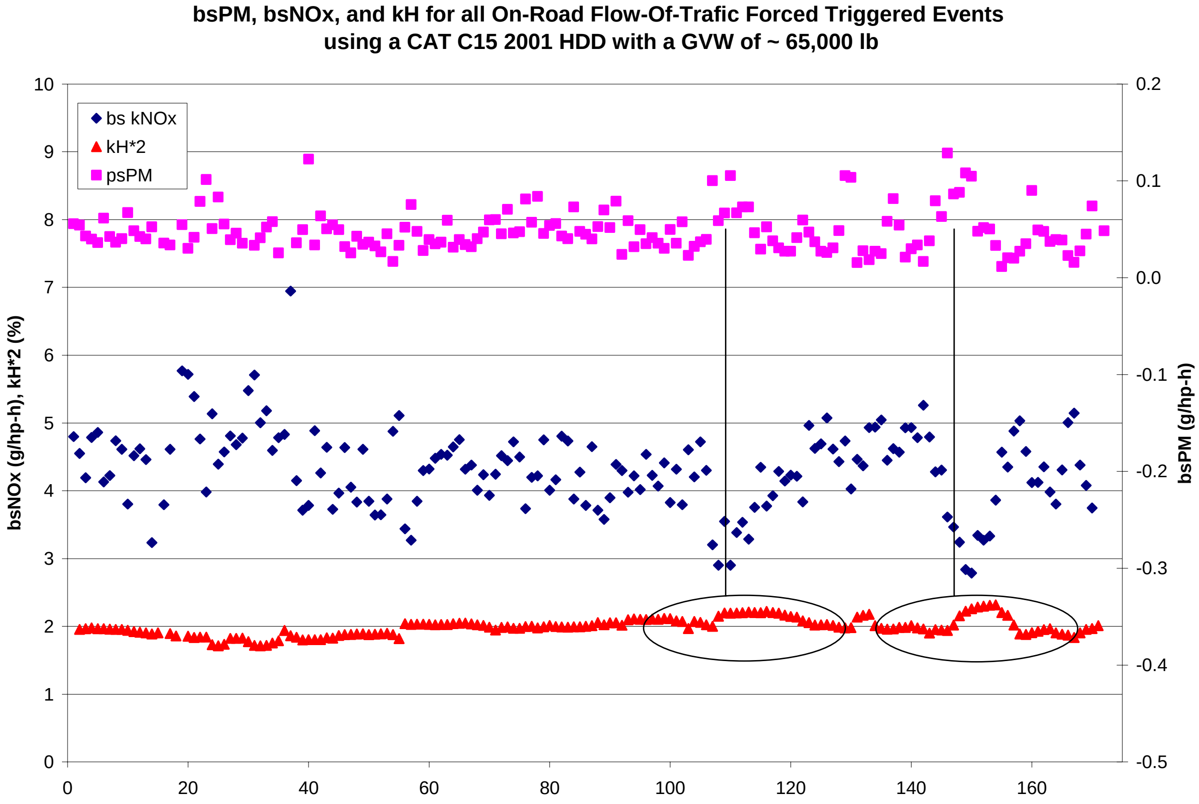
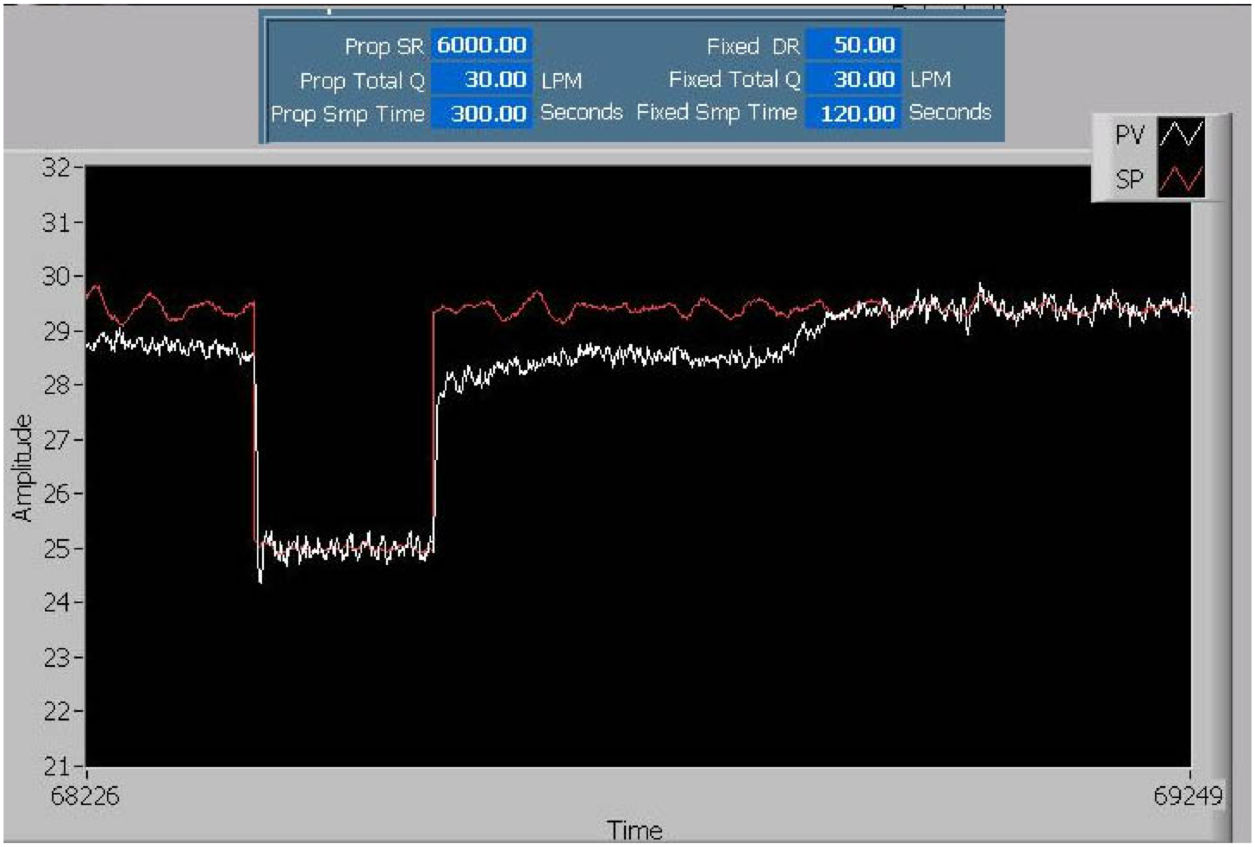


Figure 4-18. PM and NO$_x$ Emission Rates and the Associated Humidity Correction Factor for Individual NTE Events.

5.0 Lessons Learned and Operational Issues

In this section PEMS problems are discussed. Since UCR did not operate or process the raw data, the problems presented here do not completely characterize what would be expected during MA and MA validation. UCR staff did not operate the PEMS1 and PEMS2 instruments and did not have access to PEMS1 and PEMS2 low level data to see complete system behavior. During a similar in-use PM PEMS study where UCR staff operated the PEMS2 equipment, several additional sources of operational errors and possible biases were discovered [Durbin et al. 2009]. These include potential issues with post processor validation, crystal drift, signal spikes, sampling delay, and zero offsets in the pressure transducers. These results will be presented in greater detail elsewhere [Durbin et al. 2009]. The summary of problems presented here focuses primarily on observations made from the current study with feedback from the PEMS manufacturers, discussions during post-test MA meetings, and some UCR observations.

PEMS1 had several problems that prevented higher data collection efficiencies, as described in the results section. The problems covered several of the PEMS1 main components, such as the dilution air system, gravimetric filter box system, and the EAD system. The dilution air system problems included failed air compressor, faulty piezo valve connector, dilution system control adjustment, faulty regulator, and overheating. The dilution control problem can be seen by the need for dynamic pressure adjustment, as shown by the deviation between the dilution air set point (SP) and measured value (PV) in Figure 5-1. No UCR analysis was performed to document the effect the dilution control had on the bsPM correlation.



Prop SR 6000.00
Prop Total Q 30.00 LPM
Prop Smp Time 300.00 Seconds
Fixed DR 50.00
Fixed Total Q 30.00 LPM
Fixed Smp Time 120.00 Seconds

Figure 5-1 PEMS1 partial flow dilution air control during in-use correlation

The filter box system problems were a result of removing the gravimetric filter from the holder. When the filter was being removed the vacuum from the CVS pulled the filter the reverse way possibly sucking off mass from the filter surface. Typical vacuum issues are also found within the MEL secondary filter system, but the holders are disconnected from the CVS before they are opened to ambient to prevent this suction problem. If the CVS was not connected and the filter was attempted to be removed by an operator slight positive pressure in the exhaust (such as filter removal during an idling engine) could cause mass to deposit on the filter. PEMS1 manufacturer is making the necessary improvements to prevent suction or depositing type problems experienced during this study.

The EAD system had technical issues such as overheating and signal communication problems. The overheating issue was expected given the ambient temperatures during testing were around 35°C and it is estimated local instrument temperatures at the level of the roadway were in excess of 45°C during parts of the test day. The TSI EAD manual recommends operating the EAD instrument with an ambient temperature range from 10°C to 40°C. There were no instrument constraints on vibration and/or shock. The signal communication problems appeared to be a result of the level of commercial availability and these problems should be worked out with future versions of PEMS1. There were two specific communication problems encountered during the correlation that would cause the PEMS1 manufacture to invalidate some results. One problem was a loss of the EAD RS 232 serial communication and the other was signal quality for the analog communication with the EAD analog out. The errors caused data processing difficulties due to time alignment and/or data invalidation. It is expected that this type of problem will be resolved for future versions of the instrument.

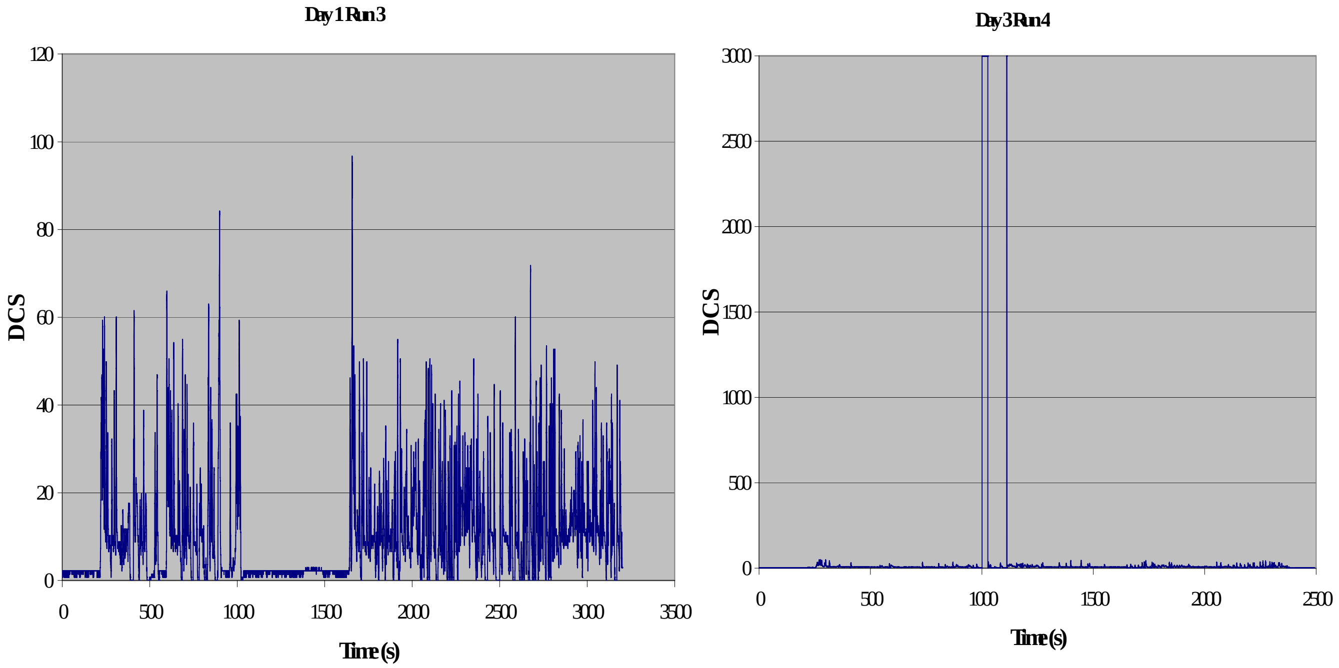


Figure 5-2 PEMS1 EAD real time signal a) typical valid measurement b) during a communication problem

PEMS2 also had several problems that prevented providing more than 50% of the sampled data. Some of the sampling issues were a result of lack of in-use operational experience and problems with not performing routine checks on startup for both the PM and gaseous PEMS combined. For example, one time the Semtech DS data card filled up and all the data on that test and the tests to follow were lost. Another time the Semtech DS was restarted during a test which caused a power surge thus resetting the PPMD system which caused the PPMD to go into standby mode (the power surge could have been prevented with a parallel connection to the battery). In standby mode, the PPMD stops collecting PM data until the PPMD is set back to proportional mode. Another time a couple data points were discarded due to a test run ending before the final event of that test had time to get a final stabilized mass. Several times the crystals were not responding or frozen. These problems were fixed by PEMS2 operators using a low level data interface configuration utility. Daily operation of the PPMD required some type of low level configuration by PEMS2 manufacturer. The PPMD at the time of testing and at the time of a subsequent study [Durbin et al. 2009] was not at a level of commercial availability where it could be operated from generic, stand-alone software.

Proportional exhaust flow sampling requires some type of sample flow measurement and control to maintain proportionality to the exhaust flow. PEMS2 uses low pressure drop sensors to monitor and control flow across a series of sample tubes to maintain proportionality. One problem that results from CVS correlations is the negative pressure imposed on the PPMD inlet sample. Figure 5-3 shows the PEMS2 inlet sample differential pressure with and with out the CVS during an outbound test (without CVS) and a return bound test (with the CVS). The CVS causes a 1 kPa negative pressure suction on the PPMD sample system during low power conditions (non NTE operation). Negative pressure is not a behavior that PEMS systems will experience in an typical in-use exhaust, but any errors associated with the CVS should be considered in the correlation. Data with negative pressure will cause ambient air to dilute the sample concentration due to a bypass setup of their sample probe. It is also important to point out that negative pressure only occurs at low work conditions (i.e., not while in the NTE zone). During low work the dilution ratios are high and the PM mass rate in g/s is low. Problems associated with CVS negative pressure should be minimal especially if the % of low power sample time is low.

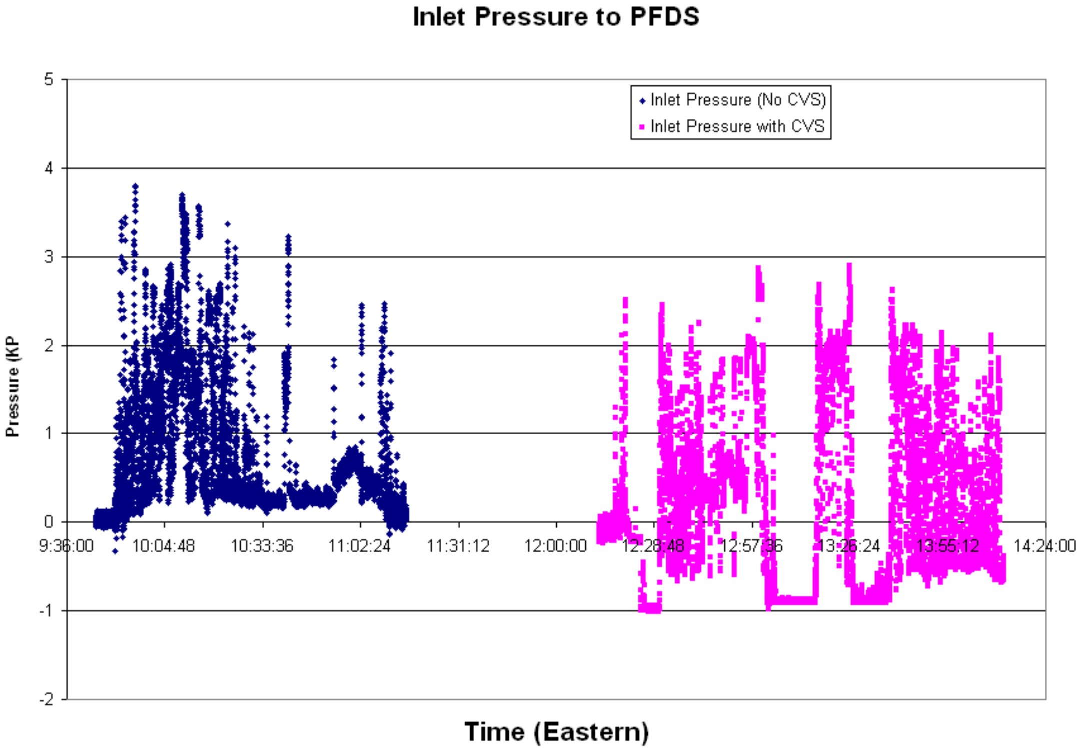


Figure 5-3 PEMS2 Sample inlet to proportional sampler with and with out CVS during (day 6)

Several discussions about PEMS2 dilution, crystal operation, and NTE triggering occurred between the EMA/EPA and PEMS2 during this study. These discussions caused PEMS2 operators to try different settings in the field. Some data loss and correlation variability could be a result of the different configurations attempted. The data on day 1 was not provided since the QCM was overloaded for most of the tests. Based on conversations with the PEMS2 manufacturer, ungreased crystals with 0.2 µg QCM weights are considered overloaded for dry soot engines, such as the engine tested here. A listing of the configurations used for each test day is provided in the following.

- Day 1: Single dilution, nominal QCM flows. (overloaded crystals)
- Day 2: Secondary 50:1 dilution
- Day 3: Secondary 50:1 dilution cont.
- Day 4: Secondary 10:1 dilution, 0.25 LPM flowrate; combined crystals (5 min max each)
- Day 5: Single dilution, 0.25 LPM flowrate, combined crystals. Data collected differently, causes PPMD post-processor to crash. Will fix ASAP.
- Day 6: Same as Day 5 with Actual NTEs. Data processed but not analyzed in detail. Real-time NTE flag dropped out erroneously on many occasions.

PEMS2 also had many software-related problems in providing the data quickly to UCR and to the MASC. Several of the problems were attributed to using the session manager according to the PEMS manufacturer. During a similar UCR study with PEMS2, several issues were discovered in trying to post process the PM PEMS data for forced events [Durbin et al. 2009].

Due to the nature of this study, with the forced NTE events, the switching behavior of either PEMS1 or 2 when they encounter a rapid succession of shorter NTE events could not be evaluated. The ability to handle such rapid switching will depend on a number of factors including the volume of the sampler and valve switching control and algorithms. PEMS2 employs a special logic scheme that requires the crystal to not be resampled for a period of at least 300 seconds from the time of the previous sample. This can cause NTE events to be missed during a typical sampling day. Data from the in-use validation testing for the gas-phase MA program was examined to evaluate the potential impact of this algorithm on losing NTE events. The gas-phase MA data showed that of the time spent in the NTE control zone, more than 70% was for durations of less than the 30 seconds needed to produce a valid NTE event (Miller et al. 2007, Johnson et al. 2007). In other words, only 30% of the time spent in the NTE zone results in a fully valid 30+ second NTE's. If it is assumed the PEMS2 waits 2 seconds before an NTE is considered valid, then based on the gaseous MA NTE data, approximately half the NTEs (or 250 of 450 events) will be missed assuming 7 crystals are in the rotation. If only 5 crystals are properly operating, the fraction of PM NTE events drops to ~25%, or a capture rate of 120 out of 450 events. It should be noted that since the gas-phase MA program routes were designed to emphasize operation in the NTE zone, it is possible that a lower percentage of NTE events would be missed during more average typical driving. It is also unclear that this procedure has been correctly employed since crystal reuse during a separate but related study showed that resampling periods on the same crystal were separated by as little as 100 seconds [Durbin et al. 2009].

PEMS3 problems were primarily electronics overheating issues. This PEMS was located closest to the engine heat and just below the exhaust system. As a result, the temperatures of the electronics exceeded internal limits and the instrument would shut down. PEMS3 technicians requested some additional dilution air to cool the electronics internal to the instrument. These modifications were made after the first day of testing by PEMS3 manufacturer. The amount of dilution air cooling was limited to the supply capability of the MEL compressor. It was soon discovered the MEL could not maintain proper flow control on its PM system and thus had to limit this cooling air to PEMS3. PEMS3 manufacturer kept a close eye on the instrument temperature and the data presented is considered valid. The PEMS3 manufacturer attempted to sample 152 samples and provided data on 104 forced events.

PEMS4 and PEMS5 are integrated with into the MEL air conditioned laboratory and were not subjected to similar in-use conditions since these instruments are part of the long term MEL operation. No operational issues were experienced and full capture of these PEMS data was achieved as expected from UCR previous experience with PEMS4 and PEMS5.

The MEL had some operational issues during the beginning of the test program while sampling with PEMS. One of the main PC cards dislodged and caused loss of data on parts of two runs (loss of two forced events). Another problem was a filter was removed from the holder and a small tear was noted and this data point was flagged as invalid. Of the 170 filters sampled, not valid data was collected for 3 filter samples, for a test efficiency of 98%.

6.0 Examination of Sources of Error for PM MA Test Plan Development

An important objective of this study was to identify possible sources of error for the different PM PEMS for consideration in the development of the test plan for the PM MA program. Although this effort focused on field testing and operational experience, there are other more scientifically fundamental differences that can be considered in the development of the Test Plan for the Measurement Allowance program. In this Appendix, we examine some of the more fundamental theoretical issues with the different instruments investigated. These sources of error were not investigated or evaluated in this study, but are only provided for possible consideration in the MA program development.

These potential sources of bias/errors include fundamental scientific issues, issues for comparing the PM PEMS results with those from the gravimetric filters, and NTE operation issues. These issues are based on a combination of fundamental theoretical consideration in conjunction with experience gained through the field operation of the units during this and other associated PM PEMS programs.

6.1 Potential Errors or Biases for PEMS1

The following is a list of possible special sources of biases/errors based on the EAD principal of operation and sampling control methods for the gravimetric filter. There are three primary sources of error, those that are fundamental to the EAD signal generation (diffusion charging characteristics), those that are fundamental to the integration of the EAD signal and correlation to gravimetric filter mass, and those that are associated with NTE operation (i.e., controlling the operation of loading a PM filter). The operational issues are discussed in the main text, so this Appendix focuses on the two other sources of error.

Fundamental sources of error in electrometer detection:

- The EAD measurement is a combination of diffusion charging (unipolar charging) and electrometer detection. This behavior is an electrical signal proportional to diameter ($d^{1.133}$) (TSI manual) down to 10 nm in diameter. Based on EAD response curves reported in prior studies [Jung and Kittelson, 2005; Fissan et al., 2007; TSI manual], the EAD's response to a 10 nm particle is 7 % of its response to a 100 nm particle. More than a couple of orders magnitude higher concentration of small particles at above 10 nm size (since EAD's response drops significantly below 10nm) could have an electrical signal comparable to that from particles with a large diameter (relatively higher mass) (see the Fuchs area curve in Figure 5 of Jung and Kittelson [2005]). This high concentration of small particles could bias the EAD electrical signal high thus causing the PM to have both positive and negative errors depending on the filter calibration.
- Although diffusion charging is affected by dielectric properties of the aerosol below 40 nm, none of the prior studies that have characterized the EAD have reported a material dependency for this instrument for particles between 10 and 40 nm [Jung and Kittelson, 2005; Fissan et al., 2007; TSI manual]. Thus, the compositional differences between EC/OC, sulfate, and trace elements should not have an effect on the EAD signal.
- While the gravimetric method measures particle mass which is proportional to particle volume (d_p^3), the diffusion charger responds to particle surface area (d_p^2) in the free

molecular regime and d_p^1 in the continuum regime). The combustion aerosol from diesel combustion lies in all three regimes. Two prior studies [Jung and Kittelson, 2005; Fissan et al., 2007] have characterized the EAD up to 150 nm, where the most of particle number exists, and their calibration curves ($d_p^{1.13}$) match well with that of manufacturer that covers a wider range up to 1 um size. Unless the particle size distribution is similar in all operational conditions, it is expected that the calibration between gravimetric instrument with the diffusion charger is not simple. The advantage of adopting diffusion charger is that its response matches well with particle lung deposition characteristics [Fissan, 2007]. Historically, most of health effect studies were done using gravimetric method and the gravimetric method will stay as an important metric. However, the reactions that cause adverse health effects are probably more related to the surface area of the particle, thus there should be good correlation with the response of diffusion chargers. Also of note is the European PMP, which measures "solid" particle number counts (d_p^0). The response of the EAD ($d_p^{1.13}$) could be a better metric for regulation and health effect studies.

- Particle losses in diffusion chargers can increase due to the particles added electrical mobility. This source of error is greatest for small particles (<20 nm) and low for large particles. This bias will have minimal mass effect since small particles have little weight and large particles dominate the mass. This impact is accounted for already in the $d_p^{1.13}$.

Fundamental sources of error in calibrating the EAD signal with the gravimetric filter in order to correlate with reference methods on a brake specific basis:

- Possible correlation errors both positive and negative if there is a shift in particle diameter during EAD integration periods.
- Short NTE events could show EAD spikes on transient exit due to possible nucleation on rapid deceleration [Lui et al. 2007]. The nucleation event appears to occur seconds after a rapid deceleration (such as switching gears). This could be seen in in-use NTE operation but maybe not during contrived engine dyno testing.
- Long gravimetric sampling intervals of short high frequency filter "on/off" events could cause EAD integration bias due to particle size differences during transient operation vs steady operation. If the filter integration period captures a lot of rapid transients, the EAD signal calibration could be influenced by possible high nucleation events from the sudden deceleration [Lui et al. 2007]. The amount of nucleation seems to also be a function of the soot concentration, where less soot (less bypass) causes higher nucleation behavior.

6.2 Potential Errors or Biases for PEMS2

The following is a list of possible special sources of biases/errors based on the QCM principal of operation and sampling control methods for NTE events. There are three primary sources of error, those that are fundamental to the QCM principal of operation (aerosol physics), those that are fundamental to the correlation of QCM-derived mass and gravimetric filter mass, and those that are associated with NTE operation (i.e., controlling the operation of loading the crystal). The operational issues are discussed in the main text, so this Appendix focuses on the two other sources of error.

Fundamental sources of QCM mass errors/biases.

- Particle charging in electrostatic precipitators has an upper efficiency of 95% for a particle diameter (Dp) between 10nm<Dp<2500nm (PEMS2 manual). This efficiency could directly bias the PEMS2 mass low relative to the MEL. Others have show that the charging efficiency falls below 95% for particles less than 10 nm and greater than 50 nm [Saiyasitpanich et al. 2006]. Charging efficiency is dependent on particle size and number of charges in a particle for a given electric field strength.
- Particle composition should not impact particle charging or particle to surface precipitation [Matter et al. 1998, Hinds 1982], as discussed in section C.1. There has been some indication that corona charging can change gas phase composition thus possibly changing particle absorption/adsorption behavior [Volckens and Leith 2002]. This behavior could have the effect of adding mass or removing mass depending on the dominate mechanism and composition. This overall behavior is not a strictly positive or negative bias and should be minimal.
- Although the particles will be charged properly and precipitate on the surface as explained above, it is well understood that dry soot doesn’t stick as well as organic carbon and thus there may be some negative mass biases depending on the PM composition due to over saturating at low mass loadings. The 2000 Caterpillar engine tested was a dry soot engine. The PEMS2 manufacturer recommended greasing the crystals to increase the PM loading capabilities (1 µg). The PEMS2 manufacturer made greasing a standard practice for their instrument. Issues associated with greasing can include contaminating contacts or over greasing.
- Vehicle vibration should not be a source of bias because the base crystal resonance frequency is 5-10 kHz, which is well above road, tire, and engine vibration. In addition pre- and post-test 30 second averaging should eliminate any possible spikes due to in-use vibration. Thus, no fundamental QCM bias is expected from vibration, but there may be some practical design bias attributed to vibration as explained in the application sources of error.
- The quartz crystal and PM may resonate at different frequencies and/or the PM particles may be sheared off. If long shaped PM agglomerations form on the surface where the PM acts as a lever arm and oscillates at a different frequency. This will change the correlation between frequency and mass loading (not expected for DPF level emissions) and thus bias the PEMS low. If long shaped agglomerations form on the surface they can also be sheared off and will also bias the PEMS2 low. Both behaviors are more likely to happen near the 0.03 g/hp-h threshold compared to properly working DPF out exhaust levels. Both behaviors would bias PEMS2 lower then the reference method.
- Conversion from frequency to mass makes an assumption on the sensitivity of the quartz crystal and other properties such as crystal density, resonant frequency, and shear velocity. The assumptions that go into the conversion from frequency to deposited mass should be understood. This uncertainty could be both a positive and negative mass error. The calibration across different crystals could also be examined.

Fundamental sources of correlation errors/biases for QCM vs. filter mass

- The organic carbon partitioning adsorption artifact will be higher on Teflon filters compared to a quartz crystal surface. This effect will be greater at DPF emission levels. Greasing the quartz crystal surface may change the organic partitioning between ungreased and greased. In all cases it is expected the QCM mass will be biased low relative to the Teflon filter.

- The different residence time and dilution methods (single stage vs. double) between the reference method and the PEMS may cause nucleating sulfate particles to be in the gas phase for the PEMS and in particle phase for the reference method (assuming PEMS residence time is shorter as expected due to proximity, flow rates, and miniaturization). This behavior will bias the PEMS mass low relative to the reference method for nucleating particles.
- The physical proximity of the PEMS2 sampling to the exhaust compared to the reference method could be a source of positive bias. PEMS2 is located much closer thus thermophoretic, diffusion and impaction losses should be lower for the PEMS compared to the full flow CVS reference systems. The miniaturization of the PEMS and small sample flow (~ 400 cc/s) could cause higher temperature gradients and thus higher thermophoretic losses. It is unclear if this type of bias will be positive or negative

Regeneration is potentially a serious problem for all PEMS, including the PEMS1 gravimetric filter reapportionment method. Fortunately in-use regulations exclude regeneration operation, thus it is only important for the PEMS to not be sampling during regenerations. The reliability and reporting of the J1939 signal when the engine is in a regeneration mode should be investigated.

During regeneration, large nucleated sulfate particle could significantly affect the gravimetric mass, as measured by PEMS1. The problem with sulfate mass is that typically with each unit of sulfate mass is an associated unit of water mass that must be accounted for properly. The water mass will not be accounted for by particle size with the real time EAD signal unless some empirical relation is considered by PEMS1. If sulfate mass reaches the QCM, the mass may not match the gravimetric method due to water absorption at different conditioning temperatures and RH.

7.0 Summary and Conclusions

Federal and state regulators are currently implementing a compliance program to measure in-use emissions within the Not-To-Exceed (NTE) control area of the engine map using PEMS. This program was conducted as a preliminary or pilot study to the main PM measurement allowance program where the "allowance" will be determined for compliance purposes when PM PEMS are used for in-use testing. The main goal of this work was to provide preliminary measurements from PM PEMS to assess the accuracy of PM measurements under in-use conditions and provide a basis for the development of the more comprehensive PM Measurement Allowance program.

For this pilot program, PM PEMS were directly compared with the UCR Mobile Emissions Laboratory (MEL), which is a full 1065 compliant constant volume sampling system with gravimetric PM measurements that is fully operational under on-the-road driving conditions. Measurements were made from a class 8 truck over a series of different on-road driving conditions. The on-road driving courses included segments near sea level, in coastal regions, in desert regions, and on longer uphill inclines. Measurements were made with 5 different PM PEMS, including the two primary PM PEMS being considered for the PM measurement allowance program. A 1065 audit for PM measurements was also conducted on the MEL as part of this program.

This report describes the on-road comparisons between the UCR MEL and the PM PEMS and the associated 1065 audit of the MEL. The results of this study are summarized below as follows:

- Forced NTE events were utilized to target filter masses between 50 and 200 µg. The results show that the filter masses ranged from approximately 50 µg to over 400 µg, with most of the test filter mass values within the targeted 50-200 µg range.
- The correlation for primary PEMS1 was poor when averaged over all the data (R^2=0.013). The PEMS manufacturer indicated that the instrument was not operating optimally during the initial days of testing. The correlation improved to R^2=0.56 with a slope of 1.23, indicating a bias toward higher masses, when only the final or best day of testing was considered.
- The correlation for primary PEMS2, based on the original data provided, was R^2=0.57 over the range of test conditions utilized, with a slope of 1.51, indicating a bias toward higher masses. <u>It should be noted that subsequently, the PEMS2 instrument manufacturer indicated a change in the QCM instrument sensitivity that would further increase the bias by a factor 1.5 times. The original data were not updated in the present report for this change.</u>
- PEMS3 (the photoacoustic monitor) was not a full system and operated in conjunction with PEMS1 and 2 to obtain gas-phase measurements and horsepower information. PEMS3 showed a good correlation with MEL gravimetric PM measurements (R^2=0.95), but was biased low relative (slope = 0.91) to the MEL PM measurements. The low bias is not unexpected since this instrument is designed to only measure black carbon or soot. The manufacturer performed a separate analysis utilizing a correction factor to account for SOF using the hydrocarbon and soot concentrations and the sampling conditions, thermophoretic losses, and sulfate. With the application of this correction factor, the good

correlation was maintained, but the bias was eliminated. PEMS3 experienced some issues with electrical overheating due to the proximity of the instrument placement to the engine.

- Two other PM-only PEMS were evaluated. These PEMS are both used in semi-regular operation in the MEL. One of these PEMS showed a reasonable correlation (R^2=0.70) with the MEL PM measurements, with a low bias. The second instrument is regularly calibrated against MEL gravimetric PM measurements, so did not represent an independent measure of PM. Nevertheless, with the appropriate calibration factors applied, this instrument showed a reasonable correlation (R^2=0.86) with no appreciable bias.
- PEMS1 experienced various problems with the main system components, including the dilution air, filter box, and EAD. The EAD system had technical issues such as overheating and signal communication problems. The filter box experienced some issues with the vacuum from the CVS that should be considered for the main PM MA program.
- PEMS2 had several problems related to lack of in-use operational experience and not performing routine checks that limited data collection to only 50%. The operation of the PEMS2 software required low level configuration and direct operation by the PEMS manufacturer. There were also issues relating to the post-processing of the data. PEMS2 also experienced some issues with the vacuum from the CVS that should be considered for the main PM MA program.
- Since forced NTE events were used, the switching behavior of either PEMS1 or 2 when they encounter a rapid succession of shorter NTE events could not be evaluated. The ability to handle such rapid switching will depend on a number of factors including the volume of the sampler and valve switching control and algorithms. PEMS2 employs a special logic scheme that requires the crystal to not be resampled for a period of at least 300 seconds from the time of the previous sample. This can cause NTE events to be missed during a typical sampling day.
- In addition to the operational issues identified for PEMS1 and 2, some additional consideration could be given to fundamental operational differences for the instruments and their correlation with filter mass. For PEMS1 with the EAD, this could include the impact of particle size on the charging efficiency, the difference between gravimetric methods that are proportional to particle volume and diffusion charging that is proportional to surface area, particle losses, or nucleation impacts. For PEMS2 with a quartz crystal microbalance, this could include the charging efficiency and deposition efficiency on the crystal surface and the quartz crystal calibration. Other factors to consider in comparing both PEMS with the constant volume sampler (CVS) gravimetric PM measurements include artifacts, differences in residence time or dilution methods, and the proximity of sampling points from the exhaust and any associated losses.
- The MEL passed all audit checks and the system was found to be in compliance with 40CFR Part 1065.

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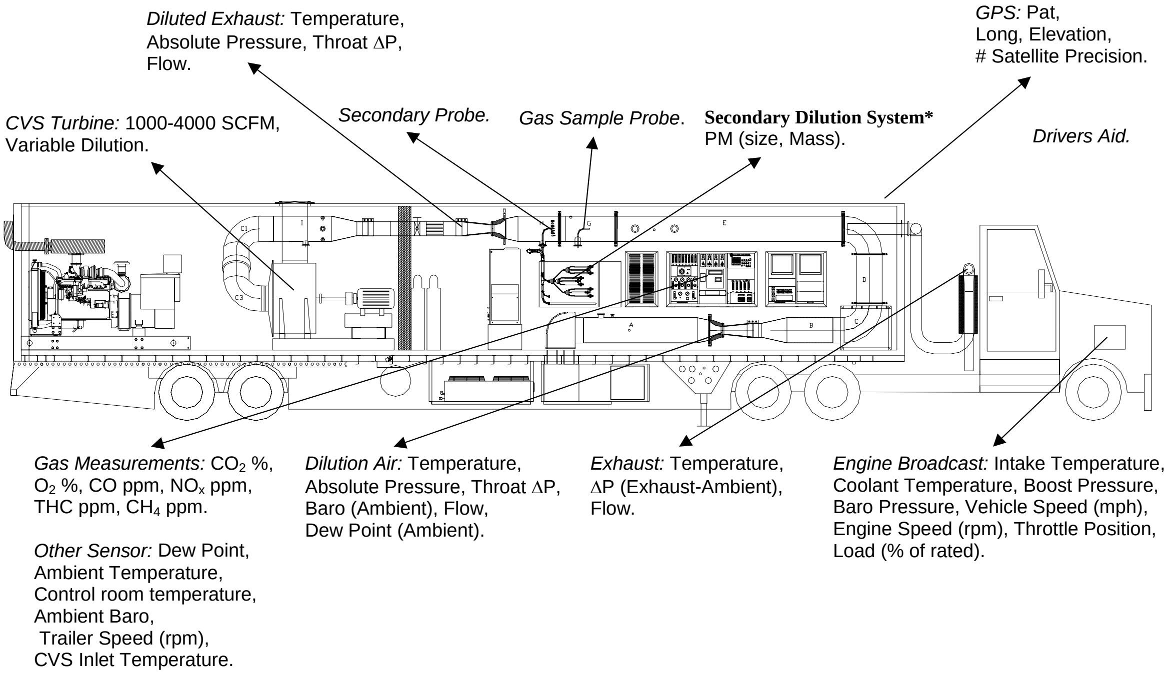
Appendix A – Background Information on UCR's Mobile Emission Lab

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 600 hp. 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	10/30/100/300/1000 & 5000 (ppmC)	HFID

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).

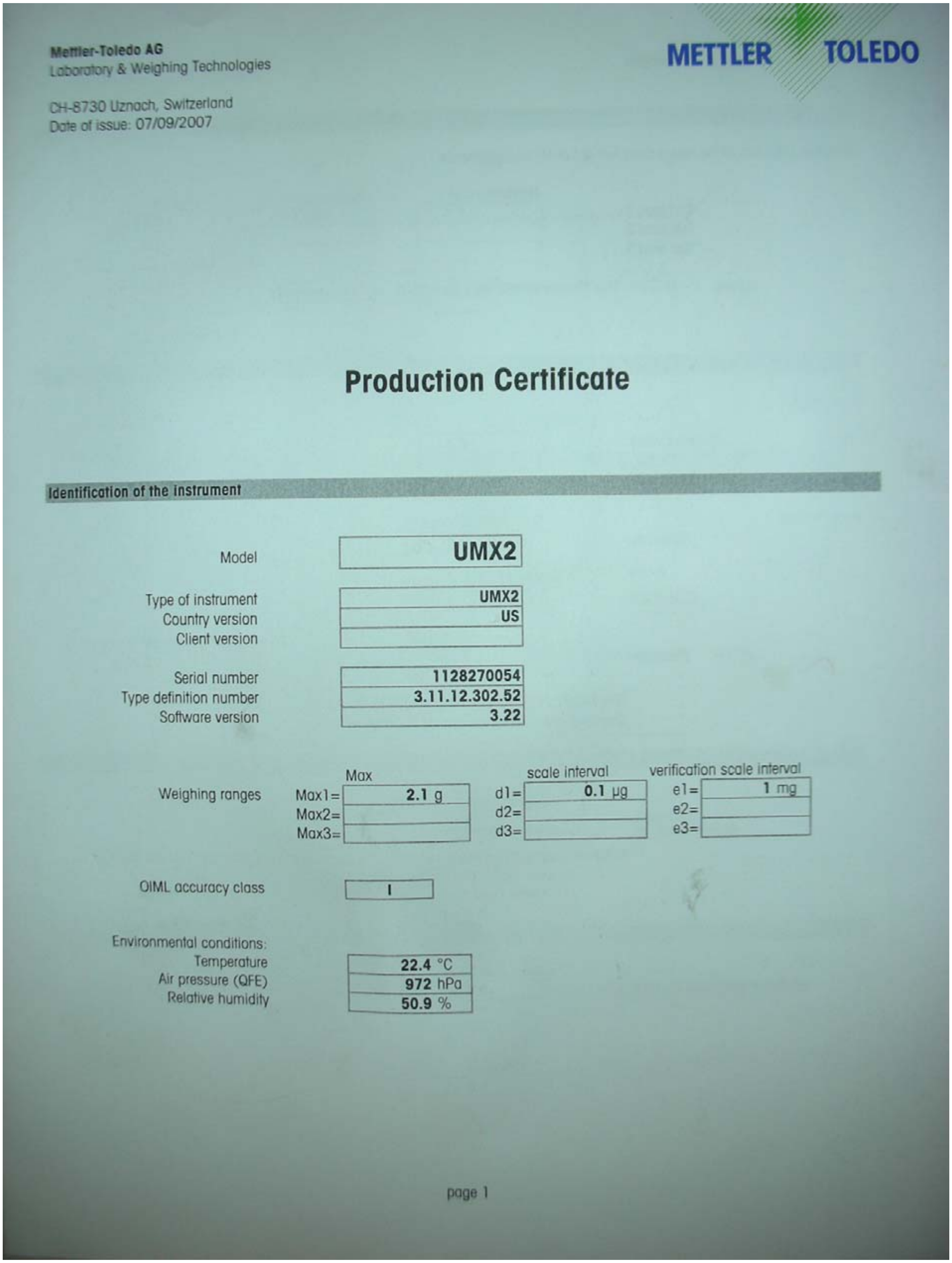
Tests	**Raw C3H8 g**	**Dil C3H8 g**	**CVS DF**	**Raw C3H8 est**	**Diff**
1	**2522**	**608**	**4.11**	**2499**	**-0.9%**
2	**2485**	**598**	**4.10**	**2454**	**-1.2%**
3	**2462**	**601**	**4.13**	**2484**	**0.9%**
ave	**2490**	**602**	**4.12**	**2479**	**-0.4%**
stdev	**30**	**5**	**0.01**	**23**	
COV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



Mettler-Toledo AG
Laboratory & Weighing Technologies

CH-8730 Uznach, Switzerland
Date of issue: 07/09/2007

METTLER TOLEDO

Production Certificate

Identification of the instrument

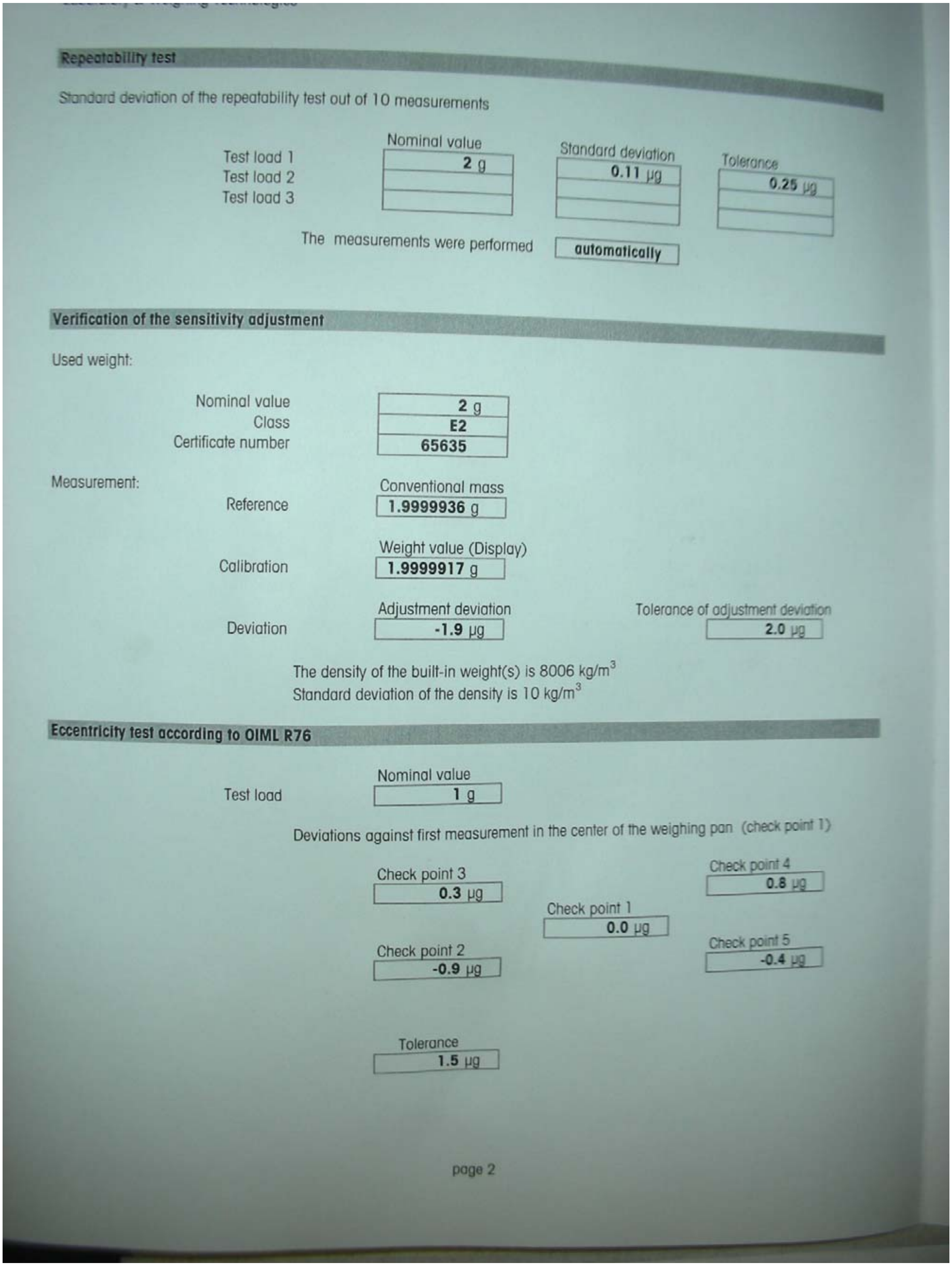
Model	**UMX2**
Type of instrument	**UMX2**
Country version	**US**
Client version	
Serial number	**1128270054**
Type definition number	**3.11.12.302.52**
Software version	**3.22**

Weighing ranges		Max		scale interval		verification scale interval
	Max1=	**2.1** g	d1=	**0.1** µg	e1=	**1** mg
	Max2=		d2=		e2=	
	Max3=		d3=		e3=	

OIML accuracy class	**I**

Environmental conditions:	
Temperature	**22.4** °C
Air pressure (QFE)	**972** hPa
Relative humidity	**50.9** %

page 1



Repeatability test

Standard deviation of the repeatability test out of 10 measurements

	Nominal value	Standard deviation	Tolerance
Test load 1	**2** g	**0.11** µg	**0.25** µg
Test load 2			
Test load 3			

The measurements were performed **automatically**

Verification of the sensitivity adjustment

Used weight:

Nominal value	**2** g
Class	**E2**
Certificate number	**65635**

Measurement:

Reference	Conventional mass **1.9999936** g	
Calibration	Weight value (Display) **1.9999917** g	
Deviation	Adjustment deviation **-1.9** µg	Tolerance of adjustment deviation **2.0** µg

The density of the built-in weight(s) is 8006 kg/m^3
Standard deviation of the density is 10 kg/m^3

Eccentricity test according to OIML R76

Test load — Nominal value **1** g

Deviations against first measurement in the center of the weighing pan (check point 1)

Check point 3: **0.3** µg
Check point 4: **0.8** µg
Check point 1: **0.0** µg
Check point 2: **-0.9** µg
Check point 5: **-0.4** µg

Tolerance: **1.5** µg

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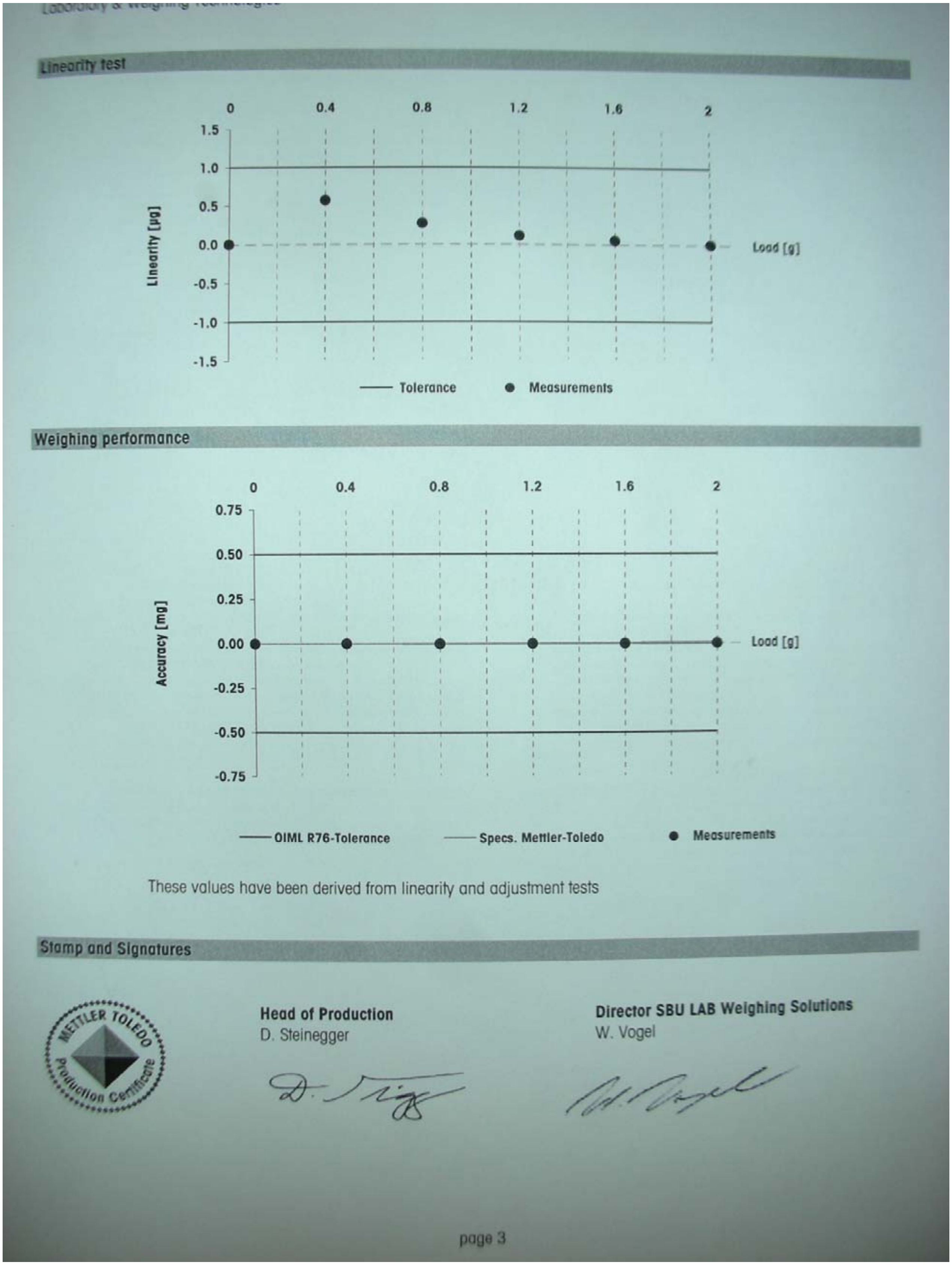

Linearity test

Weighing performance

These values have been derived from linearity and adjustment tests

Stamp and Signatures

Head of Production
D. Steinegger

Director SBU LAB Weighing Solutions
W. Vogel