Title
PM PEM’s On-Road Investigation – With and Without DPF Equipped Engines

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Disclaimer

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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 three different Class 8 tractors representing three different engine manufactures. One truck had a 2000 Caterpillar engine without a DPF and the other two were equipped with OEM DPFs, one from Cummins and the other from Volvo. Each of the 2007 vehicles was modified to vary their emission levels using regeneration, ECM recalibrations, and a DPF bypass. The on-road driving courses included segments near sea level, in coastal regions, in desert regions, and on longer uphill inclines.

The goal was to test the 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 bsPM level varied from 0.1 g/hp-h to 0.0003 g/hp-h over the different vehicles and operating conditions where one vehicle had high EC, one had high OC, and another had a substantial amount of sulfate. In addition to varying composition and bsPM level, one of the vehicles showed a significant reduction in particle size thus challenging the PM PEMS measurement systems.

PM measurements in real-time were made with a variety of different PM instruments from manufacturers preparing for the PM Measurement Allowance program, including a Horiba OBS-TRPM system, a Sensors SemtechDS PPMD (QCM), and an AVL Photoacoustic MicroSoot Sensor, 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.

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
DOC	diesel oxidation catalyst
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 Manufacturers 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 now in progress.

The main objective of this program and an associated earlier program 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. These programs were conducted as preliminary investigations 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. For these two pilot programs, PM PEMS were directly compared with the UCR Mobile Emissions Laboratory (MEL) under on-the-road driving conditions. The MEL is a full 1065 compliant constant volume sampling system (CVS) with gravimetric PM measurements. Measurements were made from three class 8 trucks over a series of different on-road driving conditions. Measurements were made with 5 different PM PEMS, including the two primary PM PEMS being considered for the PM measurement allowance program.

PM 1065 Audit

This program did not ask for an audit of the UC Riverside PM components, but as part of a recent program the UCR's MEL under went 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 for a previous version of a similar program and four were selected for 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 can provide the comprehensive data collection required for in-use testing, but only when coupled with the primary system from PEMS1 or PEMS2, as such was considered an alternate system. 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	SemtechDS PPMD (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 Matrix

Testing for this program was conducted on three different vehicles using different combinations of the 5 PEMS. One vehicle was used for the previously sponsored study and two vehicles were used for this study. The MEL trailer itself provided the load for the on-road testing for all test vehicles. The gross vehicle weight of the tractor and trailer is 65,000 lbs

The first 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 other two test vehicles used for this program were tractors equipped with a 2007 Cummins ISX450 and a 2007 Volvo D13F-485 diesel engine. Both engines were certified to the 2007 model year level which is 0.01 g/hp-h PM and a NMHC + NO_x level between 1.45 and 1.3 g/hp-h. To meet these standards both vehicles utilized original equipment manufacturer (OEM) diesel particulate filters (DPF) with active particulate matter loading management.

The testing performed for this project utilized different combinations of PEMS and different models or particular PEMS for the different vehicles. PEMS1 was only tested on the first vehicle. Several different models of the PEMS2 and PEMS3 systems were used with the different vehicles, which are a, b, and c in the table. PEMS 1-3 all sampled from the raw exhaust, while PEMS4 and 5 were sampled from the MEL CVS system with varying levels of additional dilution.

Test Count	Test Days	Raw Sampled Instruments		CVS Diluted Insturments		Engine	Nominal PM g/hp-h	Notes	Total Filters
Test 1	4	PEMS1	PEMS3a	PEMS4	PEMS5	2000 Caterpillar C15	0.05	OEM	70
Test 2	6	PEMS2a	PEMS3a	PEMS4	PEMS5	2000 Caterpillar C15	0.05	OEM	96
Test 3	4	PEMS2b	PEMS3b	PEMS4	PEMS5	2007 DPF Cummins ISX 450	<0.01	Regen ECM Mods	28
Test 4	4	PEMS2c	PEMS3c	PEMS4	PEMS5	2007 DPF Volvo D13	<0.01	Regen/ECM Mods Bypass	39

Table ES-3. Test matrix of instruments, vehicles, and emissions level

In order to vary the PM level, the Engine Manufacturers Association (EMA) committee recommended varying the concentration utilizing forced regenerations and filter bypass. The 2000 Caterpillar vehicle had no aftertreatment system and was not modified in its operation. The Cummins engine was modified by forcing regenerations and by changing Electronic Control Module (ECM) calibrations. During the Volvo testing, forced regenerations, ECM modifications, and varying levels of bypass were all used.

On-Road Testing Results

The filter masses for this program were targeted to be between 50 and 200 μg during the manually triggered events. This was a filter loading level deemed to be reliable for gravimetric weighing accuracy with out overloading some the PM PEMS systems. The distribution of filter masses is shown by the histograms in Figure ES-1, where the results for the filters pooled together are in the top left figure then the other histograms show the results for the three vehicles individually. 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 where the 2007 filter weights had less loading compared to the uncontrolled 2000 engine.

The corresponding PM emissions levels for each vehicle varied and provided comparisons from 0.1 g/hp-h to .00003 g/hp-h, see Table ES-4. The Caterpillar averaged 0.043 which is just above the in-use NTE standard of 0.03 g/hp-h and for the DPF-controlled engines averaged 0.0026 and 0.0057 for the Cummins and Volvo, respectively. The composition and particle size of the particles also varied from vehicle to vehicle, with one vehicle having high EC (2000 Caterpillar), one having high sulfate (2007 Cummins), and another having a substantial amount of OC (2007 Volvo).

	MEL Level g/hp-h		
Manufacture	ave	max	min
CAT 2000*	0.0431	0.108	0.01143
Cummins 2007	0.0026	0.010	0.00003
Volvo 2007	0.0057	0.040	0.00083

Table ES-4. Average, Maximum and Minimum PM Emission Levels for the three test vehicles.

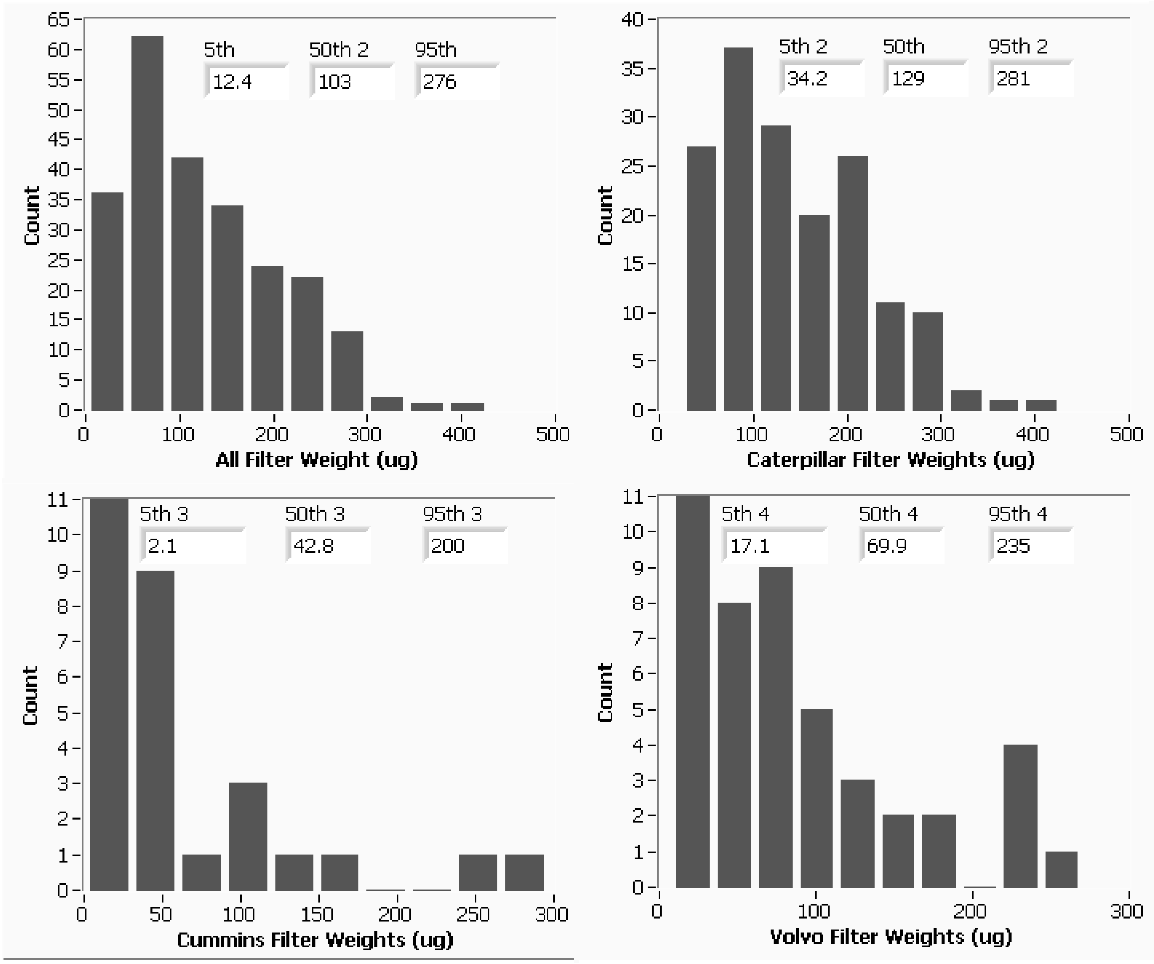


Figure ES-1. Histogram of event filter weights for all test engines and for each engine individually.

The results presented in this report are based on a subset of the actual data sampled. The need to use a smaller data set is due to PEMS operational issues, which ranged from environmental conditions to instrument operation and data processing. Table ES-5 shows a breakdown of the forced events attempted and the percentage of events for which bsPM data were processed and reviewed. Processed data is data that was provided by the manufacturer as-is or processed using the PEMS post processors. During the time UCR operated the PEMS2 system, it was discovered that some data that was validated by post processor had to be invalided upon UCR review (thus the name reviewed). A deeper look at the signals used to calculate PEMS2 bsPM uncovered some system issues that were not obvious at the time of testing. The reviewed data is data that UCR examined and found to be reliable using good engineering judgment.

There is a strong correlation to instrument maturity and the percentage of data yield, where PEMS1 was the least developed at the time of testing and PEMS3 the most. PEMS4 and 5 showed the highest data yield, but these instruments were in the MEL and were not subjected to the same harsh environment as PEMS1, 2 and 3. As such, the PEMS4 and 5 data yield is offered as a point of reference. The PEMS1 system showed the lowest overall data yield mostly because at the time of testing the system was very preliminary. PEMS1 provided results on 62 of 70 forced events, but only 16 of the data points were considered best-cases by the manufacturer. The manufacturer felt that the PEMS performed best on the final day of testing, thus the PEMS1 data yield was 23% for their best-case and 88% for what was submitted. PEMS2, which has had more time being evaluated at different levels of commercial availability, showed a data yield from 40% to 64%. PEMS3 showed the highest data yield of the PEMS sampled in the harsh environment with a yield from 65% to 100%. The lower 65% data yield on the Caterpillar testing was attributed to the instrument being placed too close to the engine exhaust, where temperatures could be 40°C higher than experienced by the other PEMS. The PEMS3 was located away from the exhaust during the Cummins and Volvo test and, as such, their data yield improved to 100% and 93%, respectively.

It is important to note that the measurement data results represent a snap shot of the PEMS development at the time of testing. Development of the PEMS generally is continuing on an ongoing basis. Nevertheless all PEMS were considered to be commercially available at the time of testing. PEMS1 at the time of testing was only available from the manufacturer.

Test Vehicle	PEMS	Sampled	Processed	Reviewed	% Reviewed
Caterpillar	1	70	62	16	23%
Caterpillar	2a	94	38	38	40%
Caterpillar	3a	152	99	99	65%
Caterpillar	4	170	170	170	100%
Caterpillar	5	170	170	170	100%
Cummins	2b	28	22	18	64%
Cummins	3b	28	28	28	100%
Cummins	4	28	28	28	100%
Cummins	5	28	28	28	100%
Volvo	2c	39	21	19	49%
Volvo	3c	45	42	42	93%
Volvo	4	45	45	45	100%
Volvo	5	45	45	45	100%

Table ES-5. PEMS Data Summary of Forced Events for all test vehicles.

The correlation between the PM PEMS and MEL PM gravimetric measurements is shown in Figures ES-2-4, respectively, for the 2000 Caterpillar, 2007 Cummins, and 2007 Volvo. The comparisons relating to each PEMS and vehicle are discussed in greater detail below.

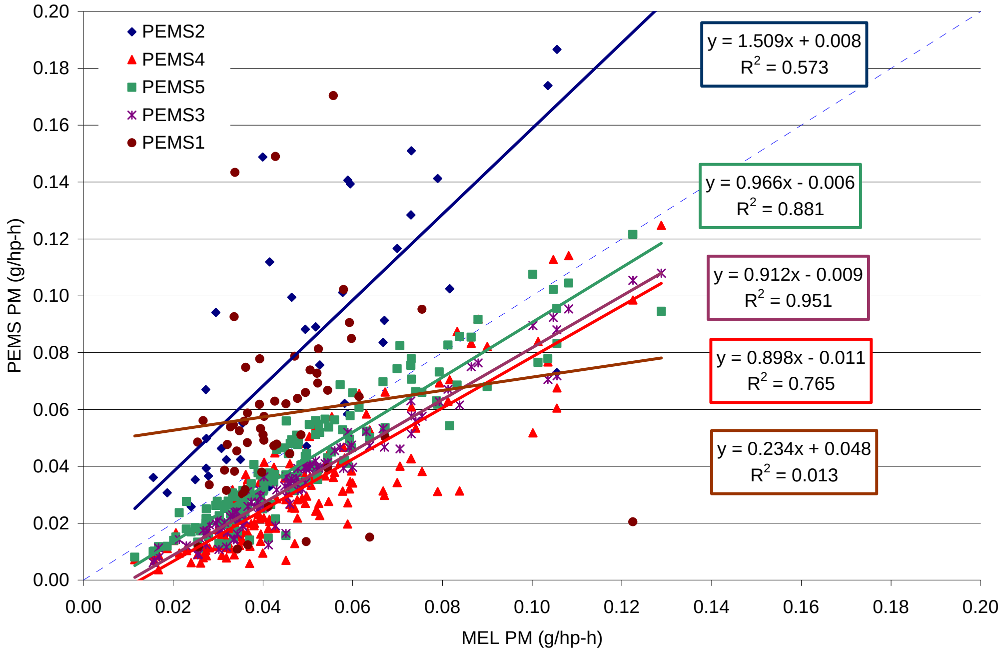


Figure ES-2. bsPM Correlation between the MEL and PEMS emissions level (Caterpillar)

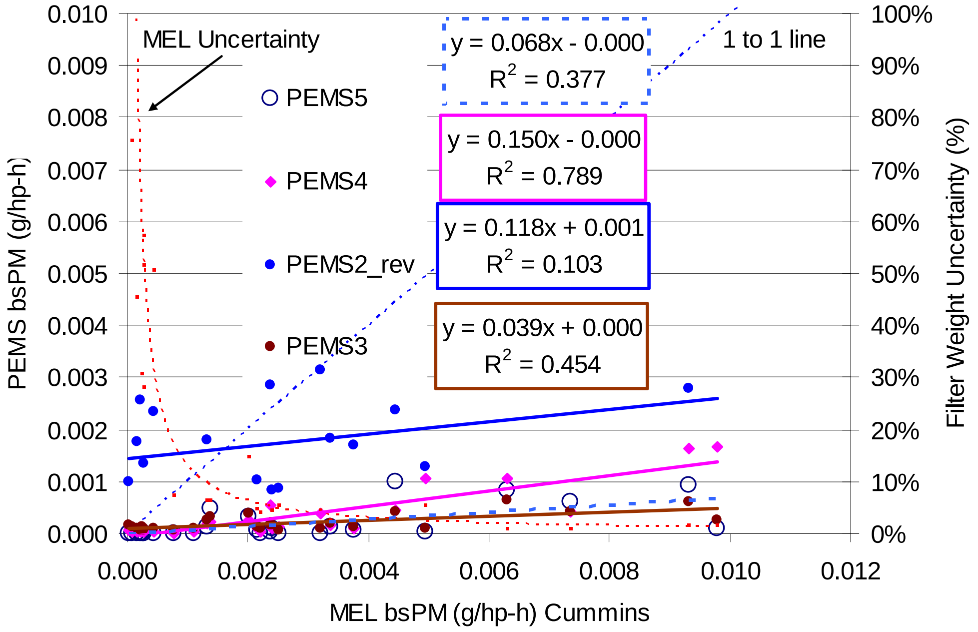


Figure ES-3. bsPM Correlation between the MEL and PEMS (Cummins)

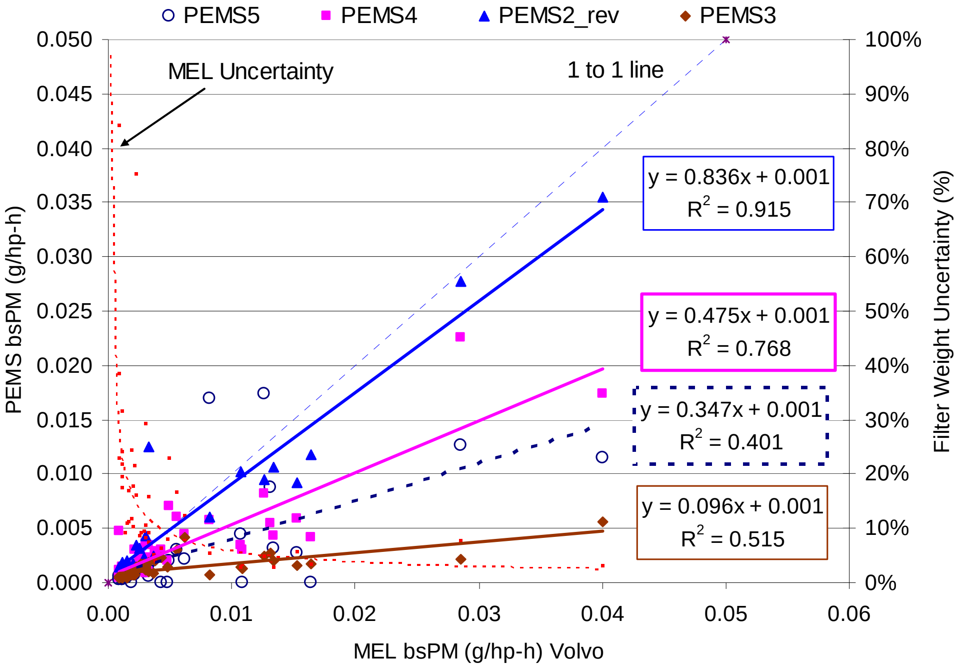


Figure ES-4. bs PM Correlation between the MEL and PEMS (Volvo)

PEMS1 was tested only on the 2000 Caterpillar vehicle. The correlation for PEMS1 on this vehicle 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 the final day of testing is presented in Figure ES-5.

PEMS2 was tested on all three vehicles. For the 2000 Caterpillar vehicle, the correlation for 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. For the 2007 Cummins vehicle, PEMS2 showed a poor correlation (R^2 = 0.1), low slope (0.1), and positive zero intercept (0.001 g/hp-h). For the 2007 Volvo vehicle, PEMS2 showed better results with a correlation of R^2 = 0.9, a slope of 0.84, and positive zero intercept of 0.001 g/hp-h.

<u>It should be noted that subsequently, the PEMS2 instrument manufacturer indicated a change in the QCM instrument sensitivity that would increase all the PEMS2 data by a factor 1.25 times. The original data were not updated in the present report for this change.</u> This new factor would make the PEMS2 correlation worse for the Caterpillar tests, but improve it for both the Cummins and Volvo tests.

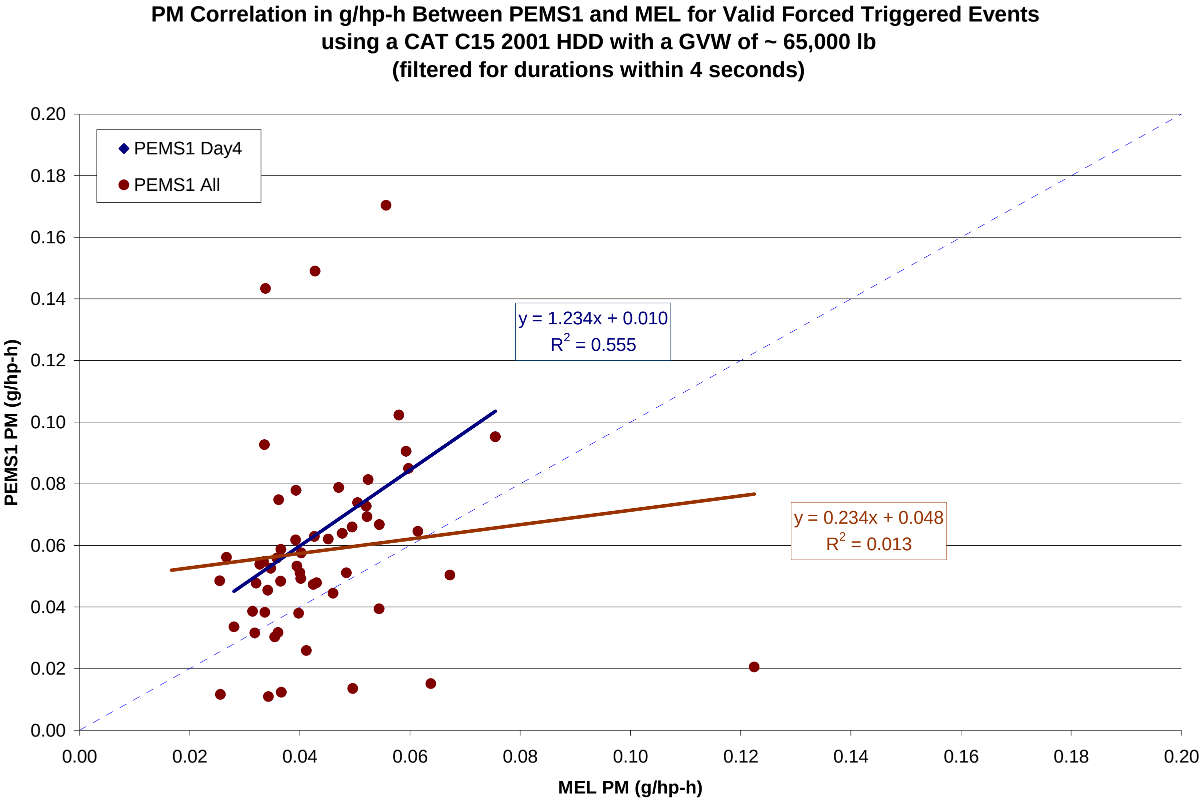


Figure ES-5. Correlation between the MEL Gravimetric and PEMS1 PM Measurements on a g/hp-h basis for all data and data from the fourth day of testing.

PEMS2 showed both good and poor correlations. The poor correlation for the Caterpillar data has been suggested to be due to operational issues and does not necessarily reflect the capability of the instrument when following a fixed set of operational conditions. The Cummins tests were operated following a fixed set of conditions, but still showed a poor correlation where only 10-20% of the mass was detected. It is suggested that the poor correlation could be due to the PM composition (sulfate) and/or particle size (< 30 nm). Assumptions about water association with sulfate mass between the reference and the PEMS can account for some of this difference, but would not be enough to account for the poor correlation The Volvo correlation was good and would improve if the 1.25 sensitivity factor was employed. It is interesting that the Volvo tests had only trace amounts of sulfate and was dominated by organic PM with a particle size that was centered from 60-100 nm. This suggests that the particle size, composition, or bsPM level of the Cummins tests was a challenge for eh PEMS2 measurement system.

PEMS3 was tested on all three vehicles. For the non-DPF equipped, 2000 Caterpillar vehicle, 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 performance of PEMS3 for the DPF-equipped, 2007 Cummins and Volvo vehicles was much worse. For the Cummins vehicle, the correlation was R^2 = 0.45, the slope was 0.04, and the zero intercept was 0.000 g/hp-h. For the Volvo vehicle, the correlation was R^2 = 0.52, the slope was 0.1, and the zero intercept was 0.001 g/hp-h. The composition of the PM was predominantly sulfate for the Cummins vehicle and OC for the Volvo vehicle. The low correlations and biases for these vehicles is consistent with the PEMS3 instrument not being effective for DPF-equipped vehicles where particles that are predominantly not EC in nature (e.g., sulfate or OC).

The manufacturer performed a separate analysis utilizing a total PM model to account for SOF using the hydrocarbon, soot concentrations and the sampling conditions, sulfate using catalytic conditions, and thermophoretic losses. With the application of this model for the 2000 Caterpillar, the good correlation ($R^2 = 0.94$) was maintained, but the bias was essentially eliminated. The model improved the Volvo correlation, which was predominantly OC PM, with an R^2 increasing from 0.52 to 0.82 and the slope from 0.1 to 0.6, but still showed a negative bias. For the 2007 Cummins, the model improved the slope somewhat from 0.04 to 0.34, but was still biased negatively. Also, the correlation did not significantly improve ($R^2 = 0.43$). Since the composition of these particles was predominantly sulfate (Cummins) and organic (Volvo), additional information is probably needed to improve the model to account for the contribution of sulfate and SOF.

Two other PM-only PEMS were evaluated (PEMS4 and PEMS5). These PEMS are both used in semi-regular operation in the MEL. PEMS4 showed a reasonable correlation of R^2=0.77 and a slope 0.9 for the 2000 Caterpillar. For the 2007 Cummins vehicle, PEMS4 showed a good correlation with an R^2 of 0.8, but a slope of only 0.15, indicating this PEMS had difficulty with quantifying the mass levels for this vehicle. For the 2007 Volvo vehicle, PEMS4 showed a good correlation with an R^2 of 0.77 and a slope of 0.48, indicating the PEMS had some correlation with the MEL but underestimated the PM mass by more than 50%.

PEMS5 showed a good correlation of R^2=0.88 and a slope near unity of 0.97 for the 2000 Caterpillar. This correlation is due in large part to the fact that this instrument calibrated against MEL gravimetric PM measurements, so it does not represent an independent measure of PM. For the 2007 Cummins vehicle, PEMS5 showed a poor correlation with an R^2 of 0.38 and a slope of only 0.07. Similarly, for the 2007 Volvo vehicle, PEMS5 showed a poor correlation with an R^2 of 0.4 and a slope of 0.35. This indicates that PEMS5 has difficulty with quantifying the PM mass levels for DPF-equipped engines and tends to underestimate the mass for these engines. Thus, the calibration that works effectively at the higher PM mass levels is not effective at low PM mass levels or when particles size drops significantly.

Figure ES-6 shows all the PEMS bsPM deltas on the y-axis and the MEL bsPM level on a log x-axis. Note that this also includes only data considered to be valid, as explained above. The MEL uncertainty line is added to the right y-axis to show the same relative uncertainty in measurements as a function of the measured MEL level. The read lines represent, respectively, a positive 100% bias and a negative 100% bias. These data show there is a lot of data spread from all instruments, with PEMS1 and 2 showing mostly a positive bias and PEMS3, 4, and 5 showing mostly a negative bias.

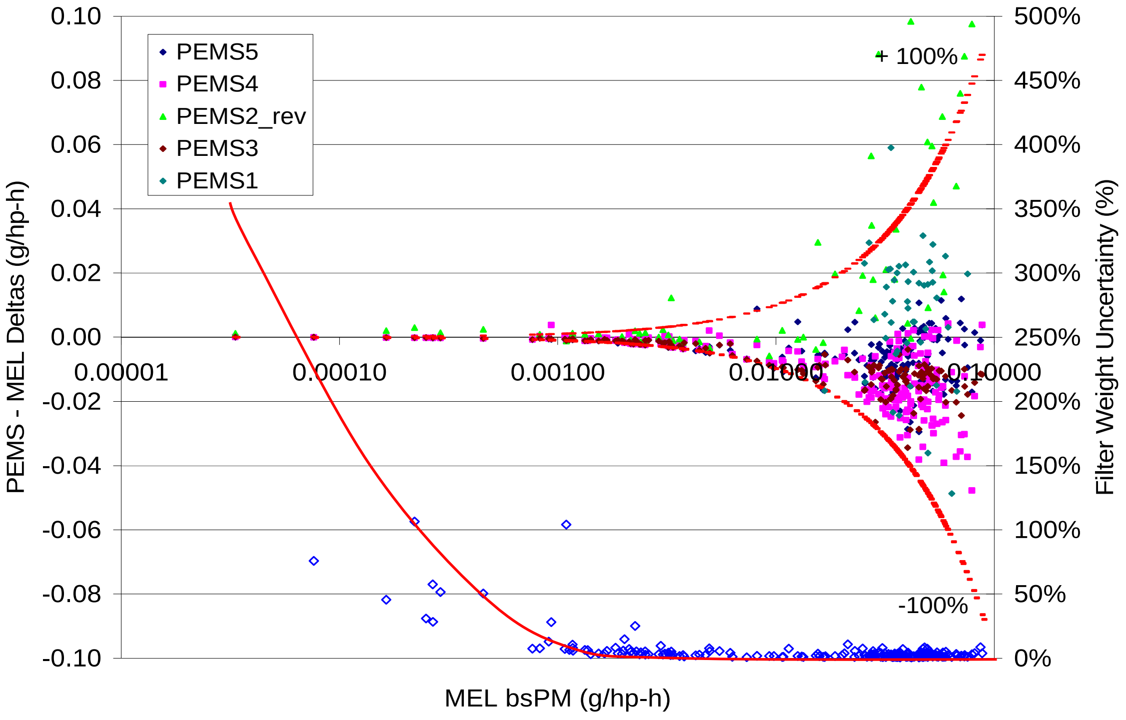


Figure ES-6. bsPM Deltas as a function of the MEL bsPM emission level (All Test Engines)

Table ES-6 lists the 90% confidence interval values at the 0.03 g/hp-h level in units of g/hp-h and the bias that is estimated at the 0.03 g/hp-h level. Based on these values, the 95th and 5th percentile confidence limits are estimates. These confidence limits include the bias which would serve to shift the 90% confidence limit higher or lower depending on the direction of the bias. The 5th and 95th percentile confidence limits thus represent the range of values that could equate to values representing a failure at the 0.03 g/hp-h level.

	Values at the 0.03 g/hp-hr Level			
PEMS ID	90% Interval	Bias	95th	5th
n/a	g/hp-h	g/hp-h	g/hp-h	g/hp-h
PEMS1	0.053	0.014	0.068	-0.039
PEMS1 day4	0.029	0.016	0.045	-0.013
PEMS2	0.040	0.028	0.068	-0.011
PEMS2_DPF	0.006	0.002	0.007	-0.004
PEMS3	0.008	-0.010	-0.001	-0.018
tPEMS3	0.009	0.001	0.010	-0.008
PEMS4	0.015	-0.011	0.004	-0.026
PEMS5	0.011	-0.006	0.005	-0.016

Table ES-6. Predicted future value based on 90% confidence intervals and mean reference bsPM for all valid PEMS data

These results show that PEMS1 and 2 have the widest confidence interval of 0.05 and 0.04 g/hp-h, respectively. PEMS3, 4, and 5 have the lowest intervals at around 0.01 g/hp-h. PEMS1 and 2 overestimate bsPM as seen by the positive bias. The PEMS2 bias increases with increasing level. PEMS3, 4, and 5 underestimate the bsPM, as seen by the negative bias. The bias for PEMS3 and 4 increases slightly with the reference level while for PEMS5 the slope was closest to zero. The total PM approach for tPEMS3 showed that the model improved the PM response to a very slight positive bias with a slight positive slope suggesting the total PM model is increasing with level. The reader should be warned that PEMS3 data looks good, but could easily underestimate when the composition of the PM changes from EC dominated to sulfate or OC dominated. The PEMS3 model was only able to achieve approximately 50% of the reference mass for both the Cummins (sulfate dominated) and the Volvo (OC dominated) test vehicles.

In general PEMS3 had the lowest overall confidence interval with a slightly negative bias. If the modeled PEMS3 data is considered, their confidence interval changes from negative to slightly positive. PEMS1 and 2, which are the two main candidates for the MA program, had the largest confidence intervals where PEMS2 was slightly better. If the subset of the data is considered, then PEMS2 would have the lowest confidence interval and a slightly positive bias of all the PEMS.

Lessons Learned from In-Use Operational Experience and Elements for Possible Consideration in the Main PM Measurement Allowance Program

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 a number of problems both when operated by the manufacturer and when operated by UCR. During the tests where the instrument was operated by the manufacturer, some of the problems related to lack of in-use operational experience and not performing routine checks that limited data collection. The operation of the PEMS2 software at that point 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. During the portion of the testing when UCR operated PEMS2, several additional issues were identified, ranging from startup difficulties that on average took over 4 hours, problems with sensors, faulty parameters in the code causing incorrect control, condensation in sample lines, frozen crystals still being used in sampling mode, unstable crystals thus loss of data and valve switch timing issues. Problems with the post processing were also identified, including issues with crystal stability, valve switching, data filtering, work integration and final emissions calculations.

PEMS3 experienced some issues with electrical overheating due to the proximity of the instrument placement to the engine for some tests. Also, for one engine, the 2007 Volvo, PEMS3 experience considerable system noise, the source of which was not fully identified.

Since Forced 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 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.

In summary, the overall experience in operating and processing the PM PEMS data was difficult due to the level of commercial availability of some PEMS. PEMS3, 4, and 5 are more commercially available and thus had fewer operational issues and thus provided more consistent PM results. PEMS1 and 2 required additional effort to prevent data loss, data integrity, and data accuracy.

Given the operational issues and measurement inaccuracies, that can exceed 100% at the relevant emissions levels, it is suggested that in addition to the MA rigorous evaluation of the sources of measurement error there should be an evaluation of the PEMS operational and data processing issues. It is expected that there will be some improvement in the PEMS operations as a result of the MA program, but the main focus of the MA program is on measurement error identification and not operational reliability.

A new program with a focus on operating the PM PEMS in such a way that the PEMS will detect issues with their instruments that affect bsPM could be conducted based on expectations from PM measurement practices. For example, a frozen crystal, bad parameters, sample flows, audit calibrations, and other details would be identified by the PEMS. The PEMS would then inform the user of some alarm condition for troubleshooting. This alarm would warn the user so that a day of testing is not lost and/or a day of inaccurate measurements are not submitted to the compliance office at EPA.

Such a program exists at EPA and is part of their verification new environmental technology and is called EPA's Environmental Verification Technology Program (ETV) [http://www.epa.gov/etv/]. The goal of this program is to create an objective and fair evaluation of new environmental test equipment. The ETV program should include an evaluation of operating procedures to evaluate the ability of the PEMS to detect a failure/drift and should be designed to evaluate all operations that will affect their bsPM emissions.

1 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 defines 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 the 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 in progress.

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 several 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 results presented in this report combine the results from a previous funded project by the EPA/CARB and EMA [Durbin et al 2009] with this EMA only funded work. The combined results provides a larger set of consistent data and allows for a more robust analysis of general trends including results for engines without PM aftertreatment and with PM aftertreatment. This will help with the understanding of in-use PM PEMS operation relative to a reference system over varying concentrations

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 PM 1065 Audit

2.1 1065 Audit Overview

The MEL under went a 40CFR Part 1065 self-audit for PM criteria selected by the MASC. The audit was performed under the associated MASC PM pilot program (Durbin et al 2009). The results from this audit are provided here since the data is still relevant. 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 coefficient of determination (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				**Slope**			**Intercept**			**SEE**			r^2		**Overall**
Name	Units	Date	Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	Value	Criteria	Pass/Fail	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 evaluated 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 tunnel blank weight 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 maximum 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 On-Road Testing– Experimental Procedures

Comparisons were made between the UCR MEL and the PEMS under in-use conditions designed to evaluate PM PEMS performance during NTE-type operation and provide a variety of environmental conditions, including variations in temperature, elevation, etc. The experimental procedures such as test vehicles, configurations, modifications, and test routes are described in this section.

3.1 Test Matrix

The testing performed for this project and the previous project covered various PEMS manufacturers, different serial number PEMS from the same manufacturer, different test vehicles and modifications to the engine PM emissions systems, as shown in Table 3-1. There were three PEMS2 and PEMS3 serial numbers tested, which are denoted with subscripts a, b, and c. There was only one PEMS1, 4, and 5 Tested. PEMS1, 2, and 3 were sampled off the vehicles raw exhaust and PEMS 4, and 5 sampled out of the MEL primary dilution tunnel. The testing effort for PEMS1 was four days where PEMS2 and 3 was over 14 days. The reason for the difference in testing effort between PEMS 1 and the remainder is a result of the additional funding by the EMA for PEMS2, 3, 4, and 5. Test 1 and 2 were funded by both EPA/CARB and the EMA. PEMS1 was not evaluated on the two trap equipped 2007 diesel engines.

Test Count	Test Days	Raw Sampled Instruments		CVS Diluted Insturments		Engine	Nominal PM g/hp-h	Notes	Total Filters
Test 1	4	PEMS1	PEMS3a	PEMS4	PEMS5	2000 Caterpillar C15	0.05	OEM	70
Test 2	6	PEMS2a	PEMS3a	PEMS4	PEMS5	2000 Caterpillar C15	0.05	OEM	96
Test 3	4	PEMS2b	PEMS3b	PEMS4	PEMS5	2007 DPF Cummins ISX 450	<0.01	Regen ECM Mods	28
Test 4	4	PEMS2c	PEMS3c	PEMS4	PEMS5	2007 DPF Volvo D13	<0.01	Regen/ECM Mods Bypass	39

Table 3-1 Test matrix for previous and current PM PEMS in-use evaluations

One of the primary goals of this combined effort was to evaluate the PM PEMS for varying PM emissions levels. In order to vary the emission levels, one non-diesel particulate filter (DPF) vehicle near the in-use NTE standard of 0.03 g/hp-h was selected and two DPF-equipped vehicles certified at the 2007 PM standard of 0.01 g/hp-h were selected.

Typical model year (MY) 2007 engines have PM emission levels at 0.001 g/hp-h. The 0.001 g/hp-h is a difficult level to measure during short NTE like events and is even a challenge for current gravimetric systems during the 20 minute certification test interval. In order to prevent having all the DPF comparisons at the 0.001 g/hp-h level, the engine's PM emission control systems were modified. Three approaches to change the PM level were used; ECM recalibrations, DPF forced regenerations, and DPF bypass, as listed in Table 3-1. These modifications were typically performed in combinations to significantly change the PM emission level. The ECM recalibrations and regenerations were performed on both MY 2007 engines and the bypass was used only on the Volvo engine. During the Volvo testing, different levels of bypass were also attempted, as described in more detail in the Volvo test vehicle section.

3.2 Test Vehicles

Three heavy duty diesel vehicles were selected for the two programs. The vehicles selected comprised one non-DPF diesel engine and two OEM DPF diesel engines. The non-DPF engine was a 2000 Caterpillar and the two DPF-equipped diesel engines were a 2007 Cummins and a 2007 Volvo. The MEL trailer itself provided the load for all the on-road testing. The gross vehicle weight of the tractors and trailer were around 65,000 lbs for all the in-use testing performed. The vehicles are described in more detail in this section.

3.2.1 Caterpillar 2000

The first 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 UCR truck had a mileage of approximately 18,000 miles at the time of testing. The engines peak torque is 1650 ft-lb at 1200 rpm and rated power is 475 Hp at 1800 rpm. The engine was certified to the 2000 MY level which is 0.1 g/hp-h PM and a 4 g/hp-h NO_x. The manufacturer's certification data shows 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 PM emissions levels from an aftertreatment system would have been too low to adequately represent levels near the in-use NTE standard of 0.03 g/hp-h. The lug curve used to calculate the NTE thresholds and associated data are provided in Figure 3-1 and Table 2-1, respectively.

Based on the certification data, the Caterpillar engine could have more than twice the PM compared to the in-use NTE standard of 0.03 g/hp-h. The Typical load for the FTP is lower than for in-use driving and thus it was expected that the actual in-use PM would be lower for this vehicle and actually closer to the in-use NTE PM standard. During the Caterpillar testing, the average PM level measured was 0.043 g/hp-h with a single standard deviation of 0.02 g/hp-h. Thus, the Caterpillar test engine provided a very reasonable in-use evaluation of the PM PEMS systems around the in-use NTE standard.

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

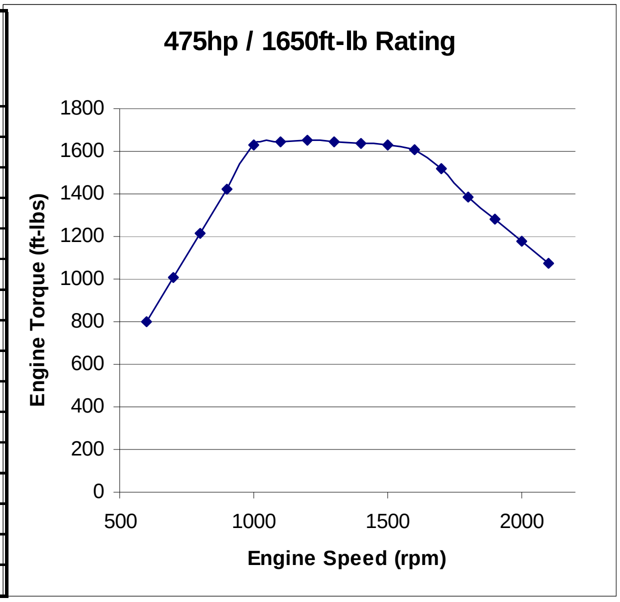


Figure 3-1 and Table 3-2 Caterpillar C-15 lug curve

3.2.2 Cummins 2007

The second test vehicle was a MY 2008 Prostar tractor equipped with a 2007 Cummins ISX450 diesel engine. The vehicle mileage was 17,500 at the time of testing. The engine's peak torque is 1650 ft-lb at 1200 rpm and rated power is 450 Hp at 1800 rpm. The engine is certified to the 2007 MY level, which is 0.01 g/hp-h PM and a 1.45 g/hp-h NMHC + NO_x. To meet the PM standards, the vehicle incorporated an original equipment manufacturer (OEM) diesel particulate filter (DPF) with an active PM regeneration management system. The vehicle was operated with its original ECM and a modified ECM that allowed control of the DPF regeneration times. The lug curve used to calculate the NTE thresholds and associated data are provided in Figure 3-2 and Table 3-3, respectively.

Updated Lug Curve 2/25/2008		
rpm	torque	hp
600	918	105
700	1020	136
965	1265	232
1050	1450	290
1100	1550	325
1150	1650	361
1200	1650	377
1300	1650	408
1400	1650	440
1500	1612	460
1600	1526	465
1700	1421	460
1800	1313	450
1900	1210	438
2000	1107	422
2100	1004	401
2130	973	395
2131	0	0

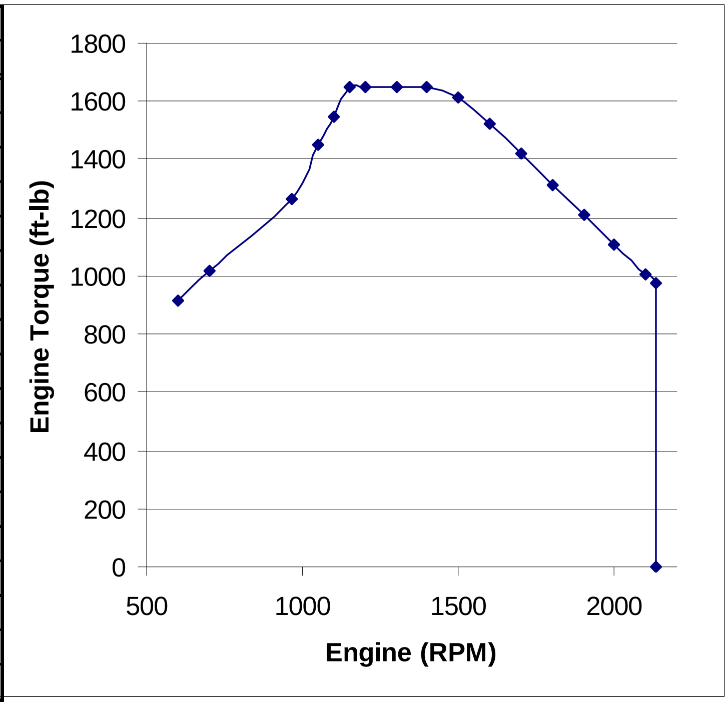


Table 3-3 and Figure 3-2 Cummins ISX 450 Lug Curve used in NTE threshold analysis

The Cummins first day of testing was performed with the engine running in its original equipment condition (i.e., no regenerations and with a stock ECM). On test days 2, 3, and 4, the emissions were modified by varying the fraction of regeneration time using a modified ECM with a different calibration. The regeneration for the DPF was performed using proprietary tools provided by Cummins. This involved setting a soot loading term in the engine control module. The soot loading term would then trigger the ECM into a regeneration enable mode. The only difference between this type of regeneration and a real one is the amount of soot on the filter. Typical regenerations are also accompanied by engine tuning to increase exhaust temperature such as advancing fuel injection and reducing EGR in addition to injecting fuel into the exhaust next to the turbo charger.

Figure 3-3 shows the percent of time spent with the regeneration enabled as a function of test number. It can bee seen that UCR operators attempted to vary the percentage of time in regeneration enabled from 0 to 100% of the time. It should be noted that having the regeneration enabled does not necessarily indicate that a regeneration is occurring, it only represents a request that a regeneration is needed. Hence, a test where the regeneration is enabled for 100% of time, does not indicate that a regeneration is occurring over the entire period of the test. Rather the active regeneration only occurs when the appropriate conditions occur, such as elevated exhaust temperatures. It was found that several operating conditions can prevent true active regenerations, which is discussed in more detail in the results section. UCR used a condensation particle counter (CPC) to identify when an active regeneration was present. Results from the CPC instrument will be described in more detail in the results section.

The Cummins emissions modifications (regeneration and ECM recalibrations) increased the bsPM emissions and significantly affected the range of NO_x emissions. The bsPM levels were increased from around 0.0005 g/hp-h with no regenerations to a maximum of 0.01 g/hp-h with regenerations. PM composition analysis showed that the PM was dominated by sulfate particles and OC with only trace amounts of EC. The $bsNO_x$ emissions for the Cummins engine ranged from 0.75 g/hp-h to 6 g/hp-h, which is described in more detail in the results section. The modified ECM calibration was used for all Cummins testing, except for the first day, where the stock ECM was used. In general, the Cummins regeneration approach to increase bsPM was successful, but regeneration and ECM recalibrations did not reach the desired in-use emissions of 0.03 g/hp-h.

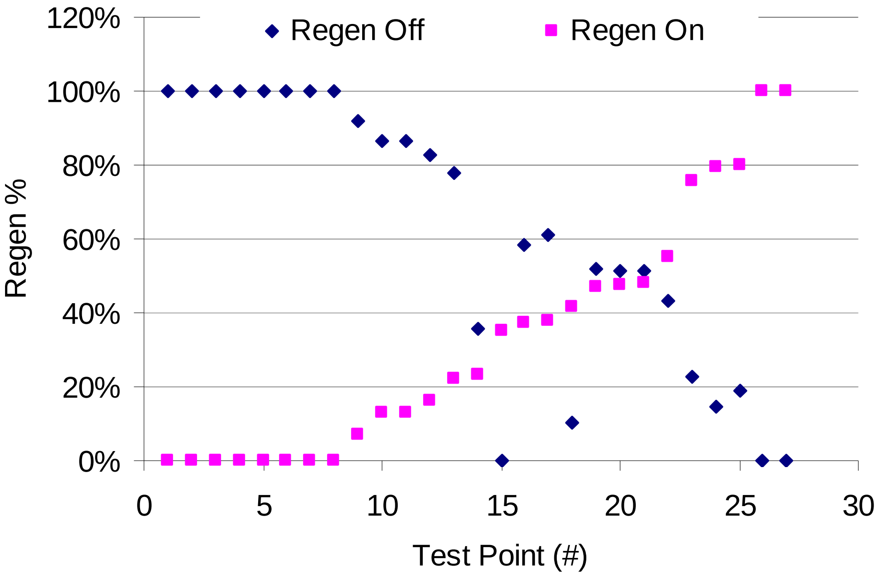


Figure 3-3 Cummins ISX 450 regeneration percentages for each test point

3.2.3 Volvo 2007

The third test vehicle was a MY 2008 Volvo tractor equipped with a 2007 Volvo D13F-485 diesel engine. The engine has a displacement of 12.7 liters, a peak horsepower power of 485 Hp at 1900 rpm, and has a flat peak torque of 1690 ft-lb from 1050 to 1500 rpm. This engine was certified at the 0.01 g/hp-h PM and a 1.3 g/hp-h NMHC + NO_x standard and used a DPF to meet this PM standard. The vehicle had only 500 miles at the time of testing, but the DPF was considered sufficiently degreened for the PM PEMS comparison study. The lug curve used to calculate the NTE thresholds and associated data are provided in Figure 3-4 and Table 3-4, respectively.

Volvo D13 Recommended Lug Curve		
RPM	Torque ft-lb	Hp
650	934	115.6
700	969	129.2
800	1239	188.7
900	1414	242.3
950	1472	266.3
1000	1530	291.3
1050	1693	338.5
1100	1693	354.6
1150	1693	370.7
1200	1693	386.8
1300	1693	419.1
1400	1693	451.3
1500	1693	483.5
1600	1591	484.7
1700	1497	484.6
1800	1414	484.6
1900	1338	484.0
1950	1222	453.7
2000	1112	423.5
2050	1000	390.3
2100	847	338.7
2149	525	214.8
2150	0	0.0

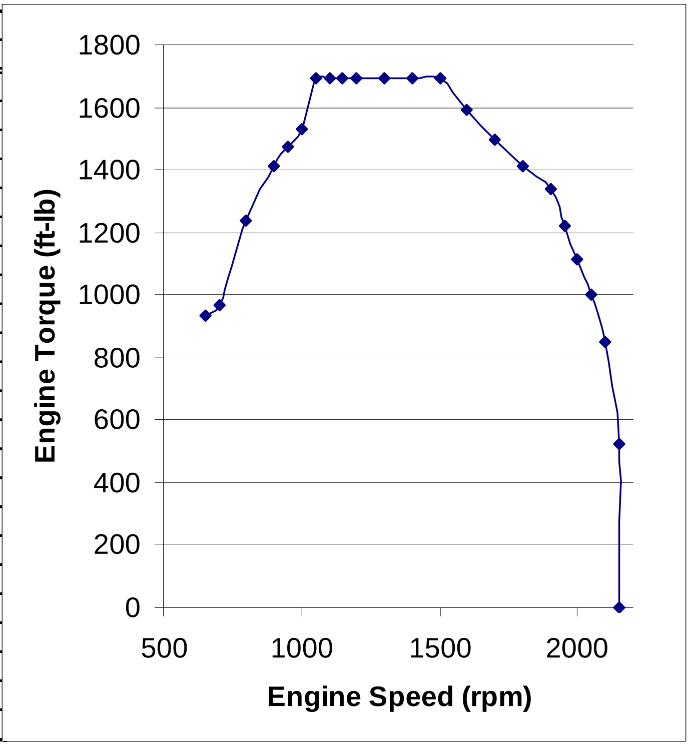


Figure 3-4 and Table 3-4 Volvo D13 lug curve used for NTE threshold and data analysis.

The PM emissions system modifications varied the most for the Volvo test vehicle. The modifications included varying levels of aftertreatment bypass, several ECM recalibrations, and various fractions of forced regenerations. The idea behind bypassing the aftertreatment system was to increase the tailpipe PM emissions rate, but at the same time it was desired to simulate a failed aftertreatment system. The PM aftertreatment system is typically composed of a Diesel Oxidation Catalyst (DOC) and a DPF where the DOC removes typically the volatile fraction of PM referred to as organic carbon (OC) and the DPF typically removes the elemental carbon (EC) based particles. The ideal bypass system thus is one that only bypasses the soot (i.e., bypass the DPF) and removes the soluble PM (i.e., don’t bypass the DOC) especially during regenerations where larges amounts of HC’s could be present from the filter maintenance procedures employed by the ECM. Bypassing only the DPF is difficult on production vehicles where several aftertreatment sensors are required for proper DPF soot management. Thus the best solution is to install a separate DOC in the bypass leg while maintaining some level of controlled back pressure to the original DPF system.

Due to timing and cost constrains, the bypass was not installed with a DOC or a system to maintain back pressure. As a result of bypassing the entire aftertreatment system, high concentrations of HC’s were measured during regenerations which led to a large fraction of the PM being organic. The Volvo’s PM emissions was dominated by OC mass with EC mass typically less than 25% and only trace amounts of sulfate PM. The low sulfate measurements for the Volvo tests were very different compared to the Cummins PM. More detail on the PM fraction is explained in the results section for all the test vehicles

Three bypass settings were attempted, with each day having some level of DPF bypass (i.e., there were no tests performed with the stock system). The bypass settings are listed in Table 3-5. The first bypass setting was through two separate bypass tubes. One tube was ½ inch in diameter with a 0.020 inch wall thickness and the other tube was ¾ inch in diameter with a 0.065 inch wall thickness. All the tubes were attached to the exhaust system through 90 degree pipe-to-Swagelok fittings. Bypass setting two was with only one ½ inch diameter with a 0.020 inch wall thickness tube. Bypass setting three was setup with two 1 inch diameter tubes with a 0.065 inch wall thickness tubing, and with 1" pipe-to-Swagelok fittings for connection to the exhaust.

Setting	Tube 1	Tube 2
Bypass 1	1/2x0.020 with two 90's pipe fittings fittings	3/4x0.065 two 90's and pipe fittings
Bypass 2	1/2x0.020 with two 90's pipe fittings fittings	
Bypass 3	1"x0.035 with two 90's pipe fittings fittings	1"x0.035 with two 90's pipe fittings fittings

Table 3-5 Volvo bypass conditions for three different levels of bypass

Three ECM configurations were specially prepared for the Volvo test vehicle to provide a traverse of NOx/PM over the range of interest for this program, see Table 3-6. The ECM #1 had the lowest PM emissions and ECM #3 had the highest expected PM emissions. The NO_x emissions were highest with ECM #1 and lowest with ECM #3 and are estimated to be between 1.3 to 0.7 g/hp-h based on estimates from the in-use testing.

Test Date	Bypass Setting	ECM Calibration	Regenerations
3/20/2008	setting 1	ECM 1	none
3/25/2009	setting 1	ECM 2	varies
3/26/2009	setting 2	ECM 3	varies
3/27/2009	setting 3	ECM 3	varies

Table 3-6 PM emission modifications to the Volvo test engine

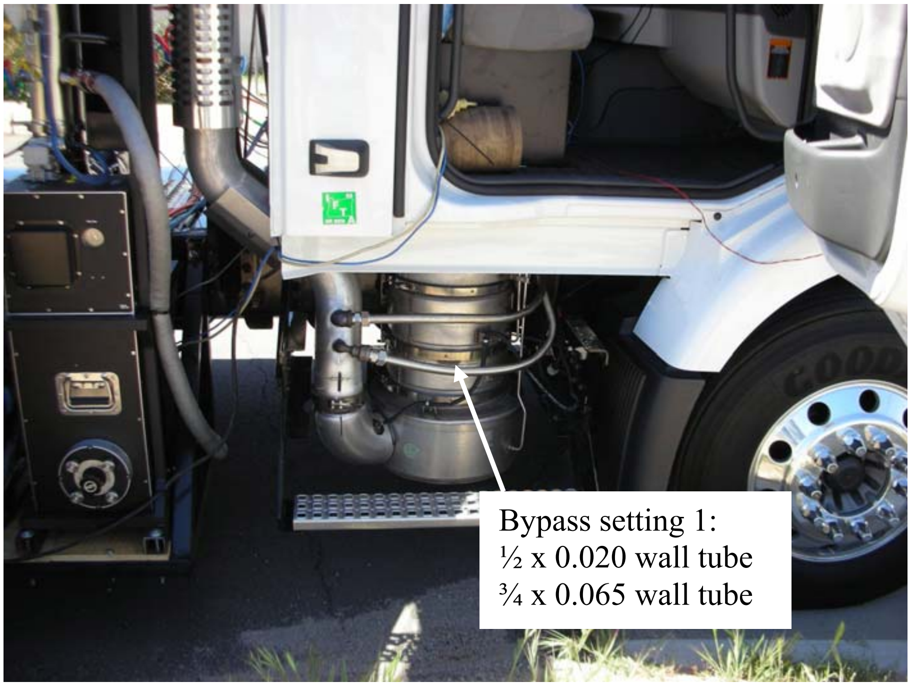


Figure 3-5 DPF bypass configuration for Volvo test vehicle with PEMS2 and 3

In addition to ECM calibrations and bypass settings, regenerations were also varied for all test days except for the first day. Regenerations were performed using Volvo proprietary tools with similar control methods as the Cummins testing. Figure 3-6 shows the percent of regeneration as a function of test point. There was less regeneration activity for this test engine compared to the Cummins. Half of the test points show that there was no attempted regeneration. The highest regeneration for a single test was around 90%. The regeneration enabled status does not indicate an active regeneration as will be discussed in the results section.

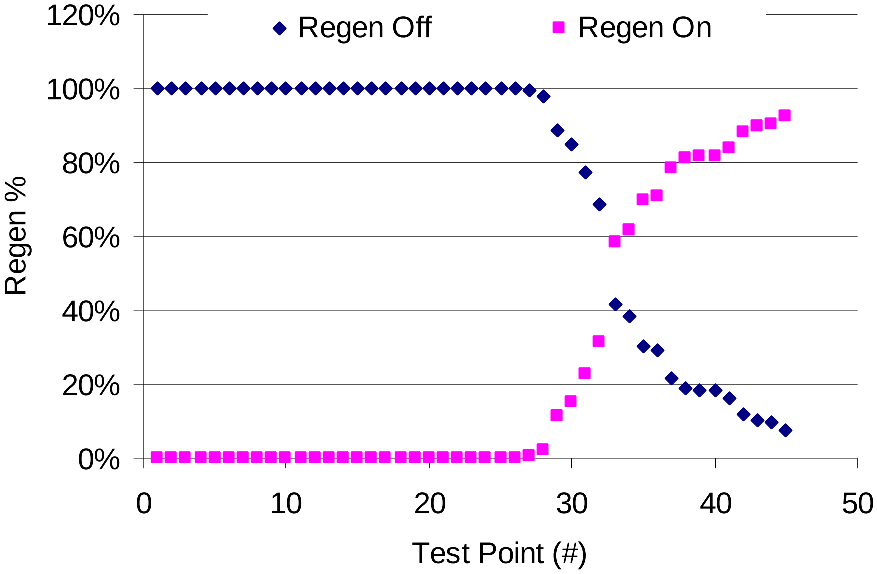


Figure 3-6 Volvo D13 regeneration percentages for each test point

The Volvo emissions modifications (bypass, regenerations, and ECM recalibrations) increased the bsPM emissions and varied the NO_x emissions significantly. The highest bsPM emissions with 0% regeneration were 0.006 g/hp-h and the highest bsPM emissions with regeneration, ECM modifications, and bypass was 0.04 g/hp-h. The $bsNO_x$ emissions varied from 0.7 g/hp-h to 7 g/hp-h for the forced events. In general, the bypass seemed to increase the bsPM slightly, but the combination of bypass, regeneration, and ECM recalibration increased the bsPM to a level that exceeded the desired 0.03 g/hp-h emission level.

3.3 PEMS Description

A total of five PEMS systems were tested as part of these two programs. These five PEMS represent different levels of technology and technological advancement with respect to meeting the in-use testing requirements. The PEMS are listed in Table 3-7 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 the MEL reference system on diesel exhaust 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.

Three different units with different serial numbers of PEMS2 and PEMS3 were used during the in-use vehicle studies. The idea behind using several PEMS2 and PEMS3 instruments with different serial numbers was to investigate unit-to-unit differences. The Caterpillar test engine used the first serial number PEMS described PEMS2a/PEMS3a, the Cummins test engine used PEMS2b/PEMS3b and the Volvo test engine used PEMS3c/PEMS3c (see Table 2-1 for PEMS usage). The first serial number denoted with the subscript “a” was provided by the PEMS2 and PEMS3 manufacturers and the following two PEMS serial numbers “b” and “c” were provided by EMA members. The EMA provided units were supplied from the PEMS2 consortium members, where “b” came from Navistar and the “c” came from PACCAR. The gaseous parts of PEMS2 were provided by Caterpillar and both had undergone a full 1065 audit at the PEMS2 manufacturing facility prior to testing. The PACCAR PM PEMS was used on the Cummins test engine and the Navistar International PM PEMS was used on the Volvo test engine. The PEMS3a was supplied by the PEMS manufacturer and PEMS3b and 3c were supplied by Caterpillar.

PEMS #	Manufacturer	Unit/Model	Gases	PM
1	Horiba	OBS-TRPM system	X	X
2a,b,c	Sensors	PPMD (Sensors Inc. QCM)	X	X

3a,b,c	AVL	Photoacoustic Microsoot Sensor		X
4	Dekati	Dekati Mass Monitor		X
5	TSI	DustTrak		X

Table 3-7. PEMS Included in the On-Road Testing Program

3.3.1 PEMS1

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. For the measurement of PM, 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 with an EAD, and thus the EAD signal is weighted proportionally by exhaust flow. 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 signal 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 of diameter to the power of 1.133 ($D^{1.133}$). The EAD signal is then converted from length to mass units by assuming an effective 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 filter sample volume flow rate was doubled which increased the face velocities to ~95 cc/s for the Cummins and Volvo testing, where PEMS1 was not tested. The higher face velocities are similar to those being used by SwRI in 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.

3.3.2 PEMS2

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 at the time of this testing reported the QCM sensitivity at 125 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 125/100 to correct for this parameter change. This will have the effect of increasing the PM mass by 1.25 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 1.25 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.

3.3.3 PEMS3

PEMS3 only measures the PM concentration and thus requires 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. PEMS3 is simpler system from an operational standpoint and is more commercially mature compared to the full PEMS system. PEMS3 a more straight forward measurement system due to its relative simplicity and commercial availability, however, the measurement principal primary responds to soot concentration. PEMS3 uses the photoacoustical measurement principal, which provides a PM measurement that more directly corresponds to soot or EC as opposed to PM 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, which is composed of many parts including, soot or elemental carbon (EC), organic carbon (OC), ash or inorganics, nitrate particles and sulfate particles (and associated water mass with each unit of sulfate mass). The PEMS3 manufacturer 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. 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.

3.3.4 PEMS4 & PEMS5

PEMS4 measures PM mass concentrations through a combination of an electrical mobility diameter via particle charging and an aerodynamic diameter via inertial impaction over six stages of electrometers [Lehmann, et al., 2004]. PEMS4 was operated by UCR following the recommended operating procedures provided by the manufacturer (DMM manual). A technical description of the measurement principal is provided in Appendix C.

PEMS5 utilizes an optical scattering measurement technique. 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.

3.4 PEMS Installation

3.4.1 2000 Caterpillar

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.

Installation PEMS1/PEMS3a/2000CAT

PEMS1 and PEMS3a were operated simultaneously. PEMS1 was only tested with the Caterpillar 2000 test engine. PEMS1 is a full PM and gaseous system and thus required space for all its components. As such, the PEMS1 installation included units both inside the MEL as well as outside mounted to the truck. Figure 3-7 shows the PEMS1 equipment mounted inside the air-conditioned, vibration isolated mobile laboratory trailer and Figure 3-8 through Figure 3-10 show the PEMS1 and PEMS3a 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 PEMS3a 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 PEMS3a dilution cell, heated transfer line, soot detector and sample conditioner.

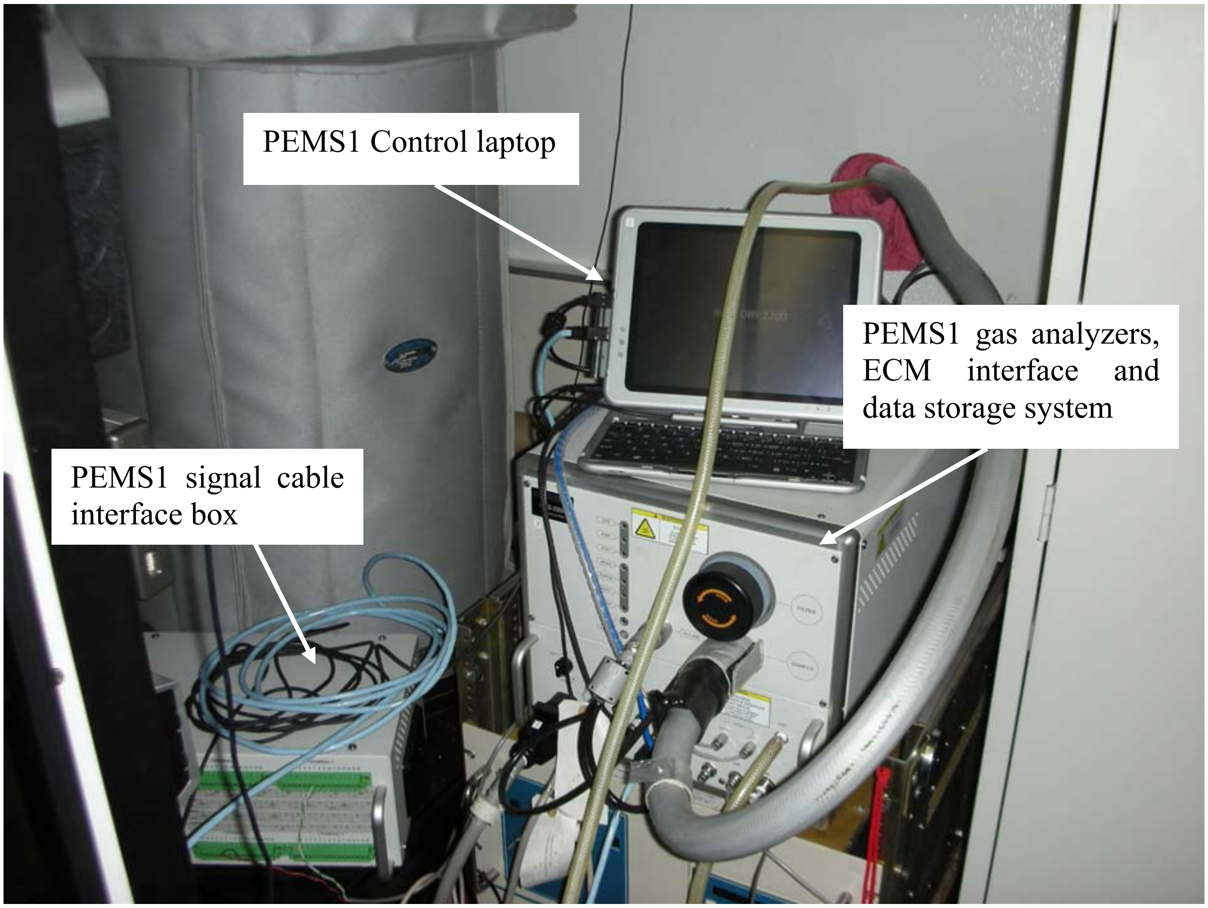


Figure 3-7 PEMS1 installation inside the MEL trailer

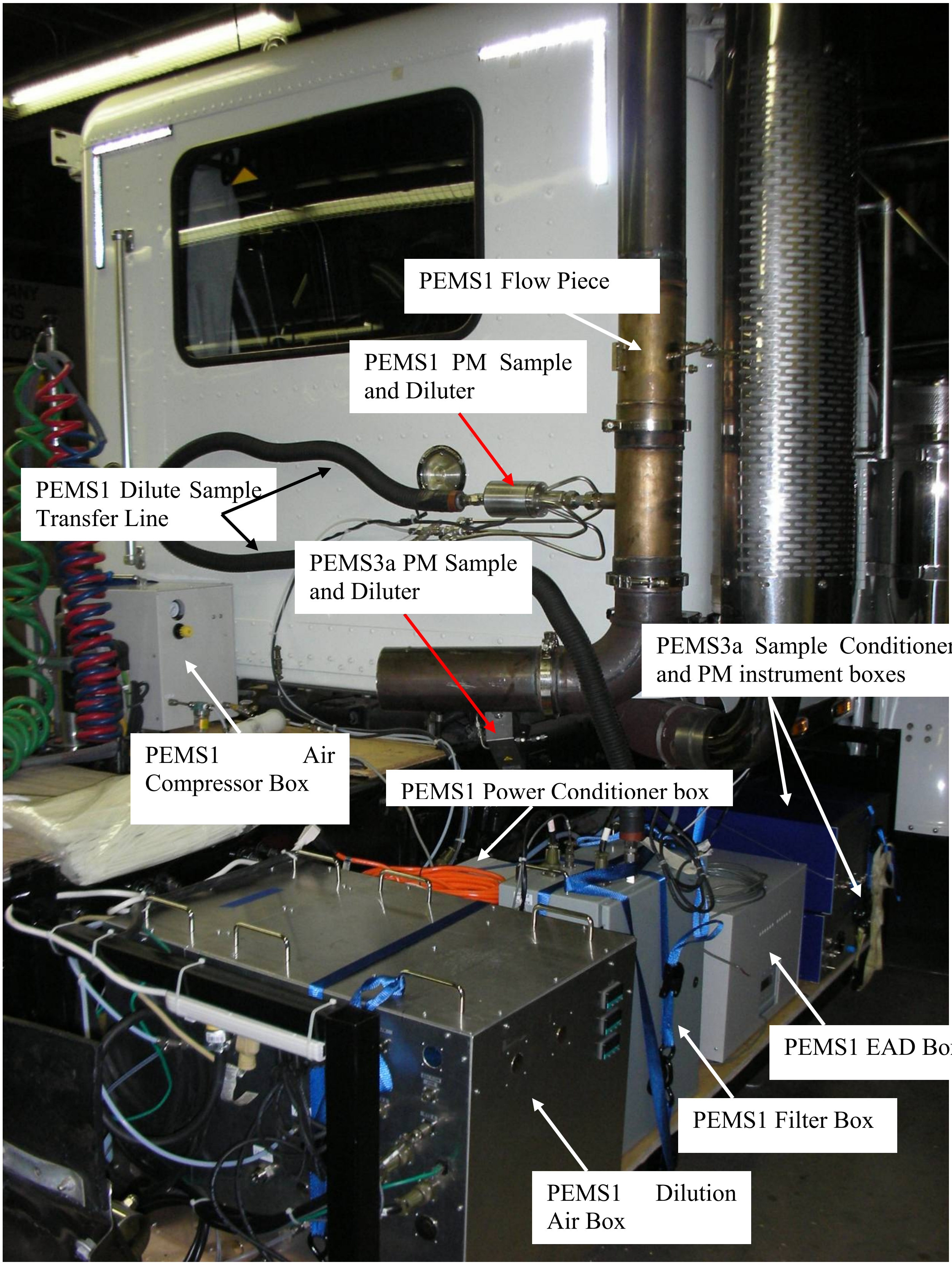


Figure 3-8 Vehicle installation for PEMS1 and PEMS3a

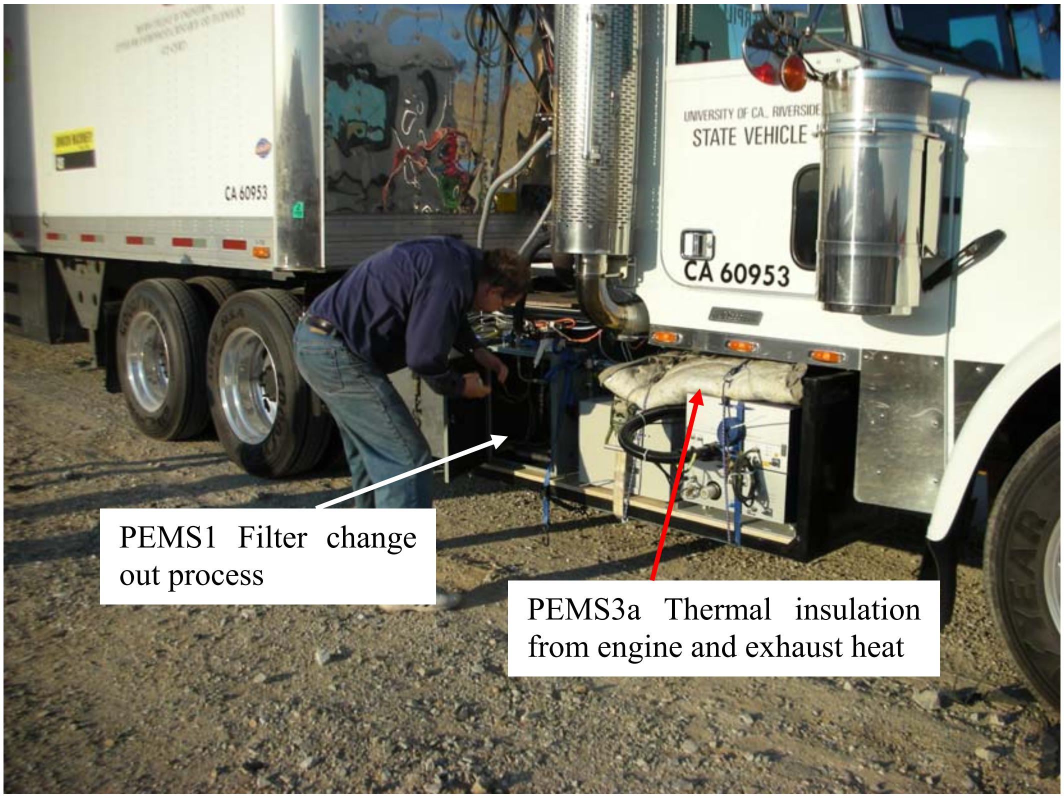


Figure 3-9 PEMS1 changing filters between test runs and PEMS3 thermal blanket

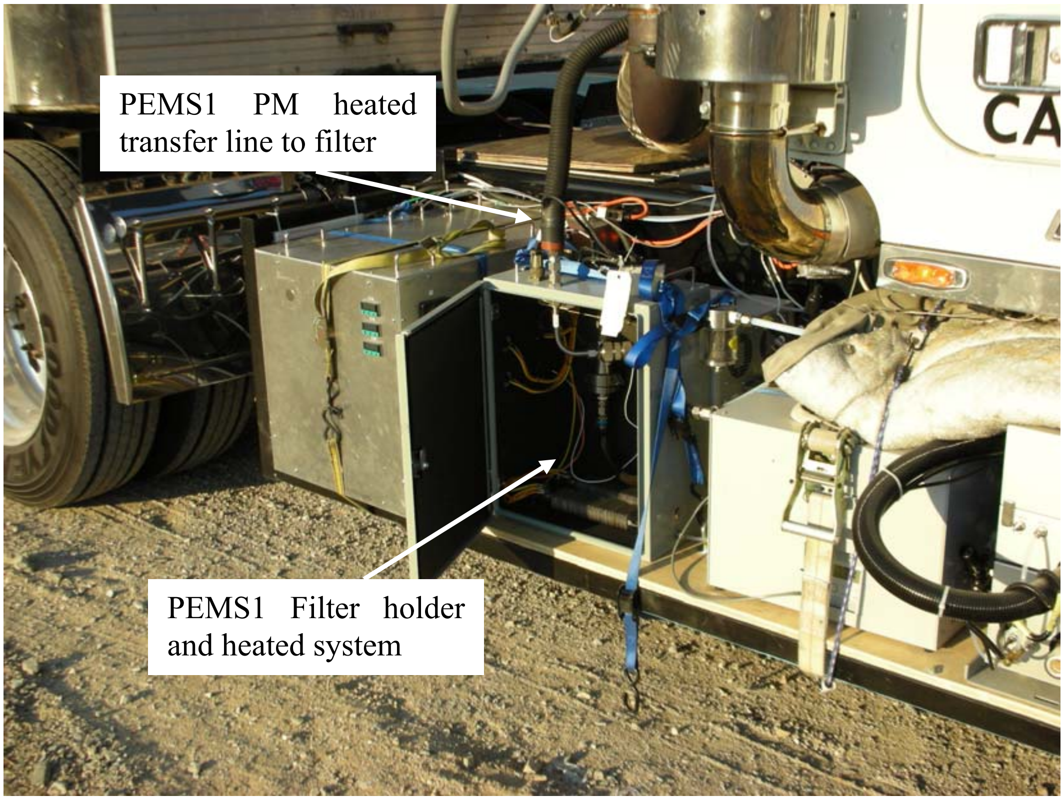


Figure 3-10. PEMS1 filter holder system after changing filters

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, the 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 the 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.

The PEMS3a 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. PEMS3 utilized two resources from the MEL, a compressed air source and a single 120VAC, 20 amp circuit. The PEMS3a 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 PEMS3a constant diluter. The PEMS3a 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 PEMS3a 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.

Installation PEMS2/PEMS3a/2000CAT

PEMS2 and PEMS3 were operated simultaneously for the second part of the testing on the Caterpillar engine. 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.

The gaseous and PM systems of PEMS2 were mounted on a frame where the passenger side fuel tank is typically located (see Figure 3-11). 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 3-12. 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.

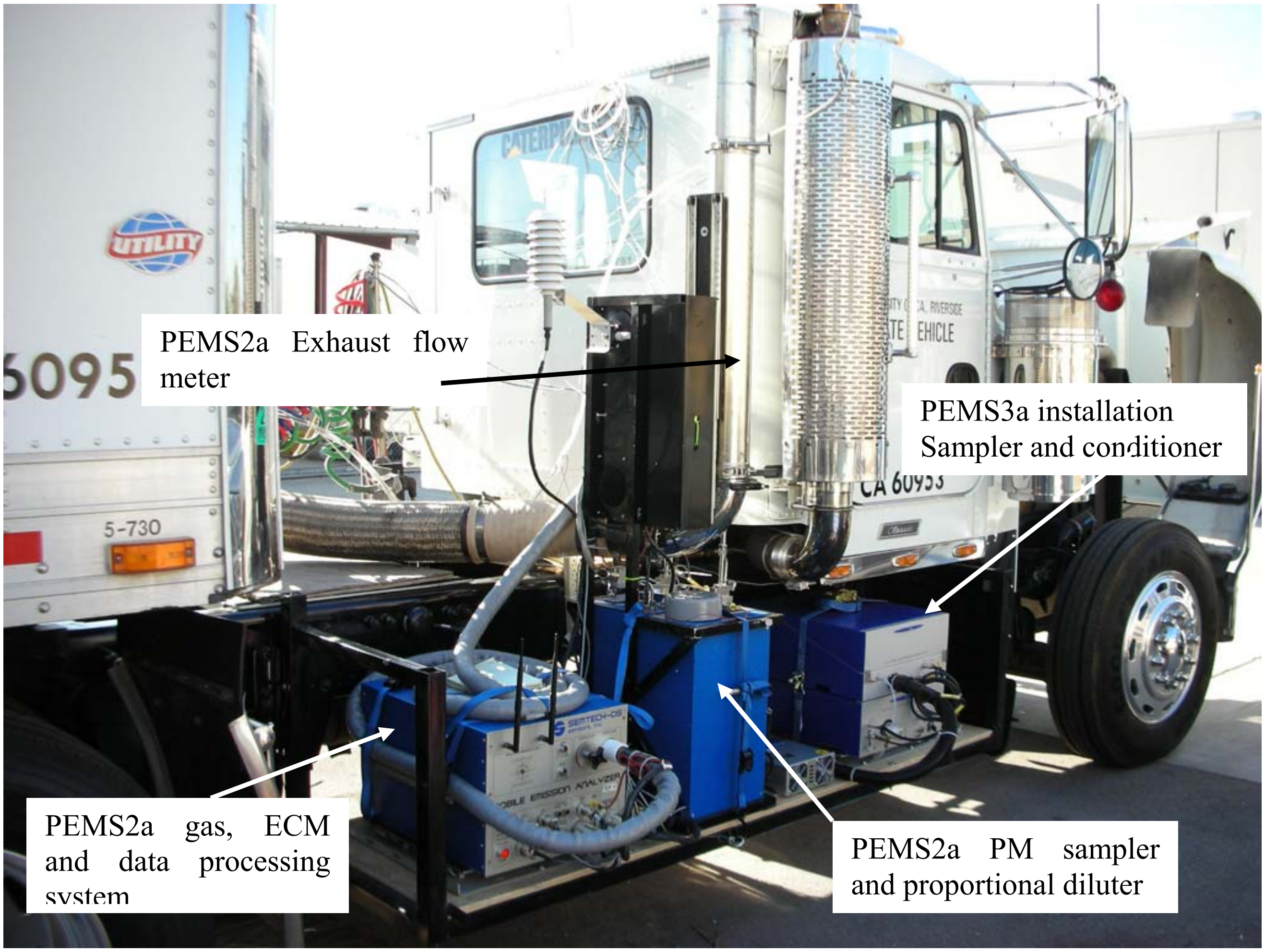


Figure 3-11. PEMS2a and PEMS3a installation outside of cab on test vehicle frame rails

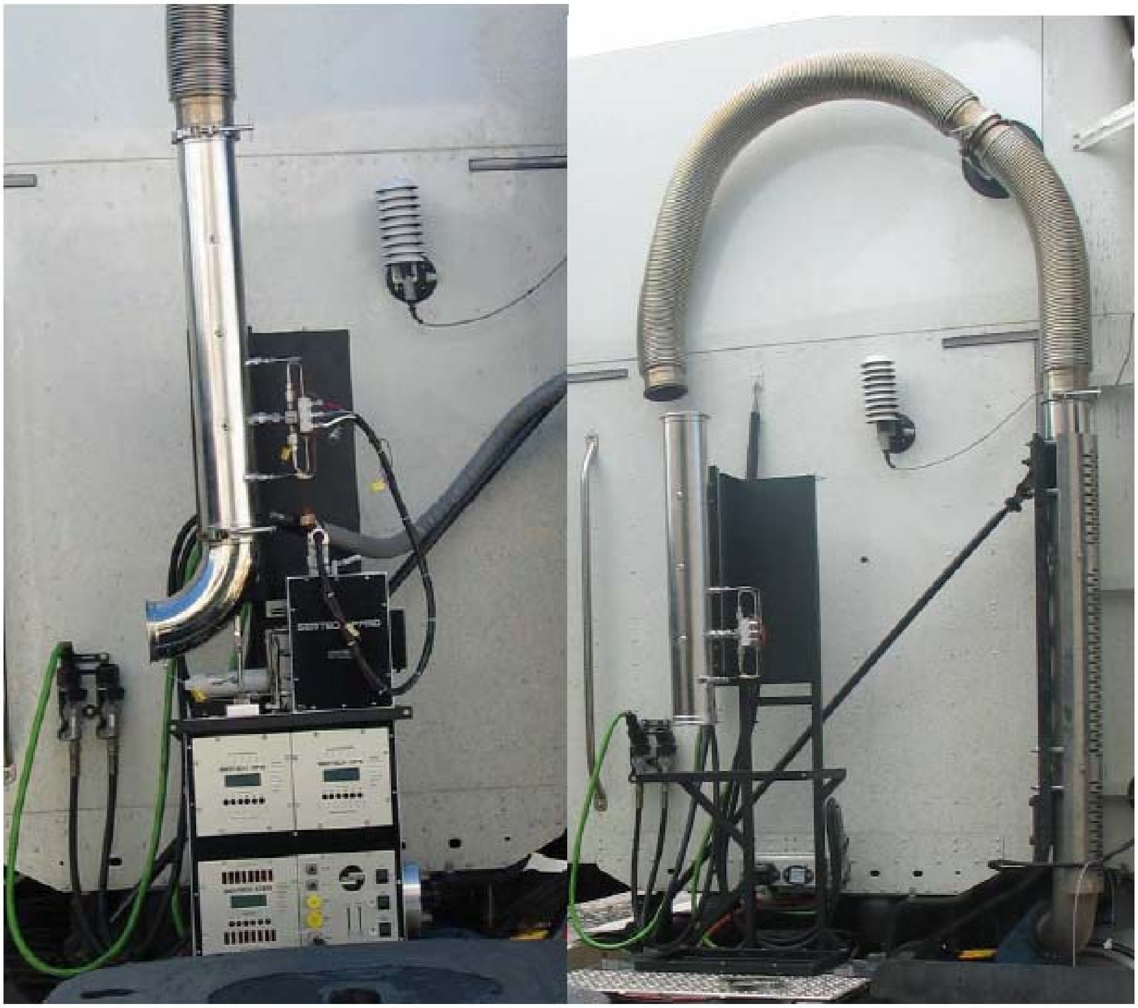


Figure 3-12 PEMS2a manufacturer recommended installation details (ref manual)

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 PEMS2a 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 facilitate 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 3-13. On-road testing route 3 during MEL filter change out and PEMS inspection

3.4.2 PEMS2b/PEMS3b/2007 Cummins

Figure 3-14 below shows the Cummins PEMS2 and 3 installations. The Cummins setup did not require the removal of the fuel tank since there was more space on either side of the frame rails for PEMS2b and 3b. PEMS2b was mounted on the passenger side and PEMS3b was mounted on the driver side. Both PEMS were mounted directly to the frame. PEMS2b did not request any vibration isolation and PEMS3b provided their own vibration mounts similar those use in the Caterpillar instillation. It should be noted that PEMS3 had an issue with noise on the installation on the Cummins. This issue is discussed in detail in section 6.3. Although this noise was significant on a second-by-second basis, the overall average bsPM did not appear to be affected over the longer intervals of the forced events.

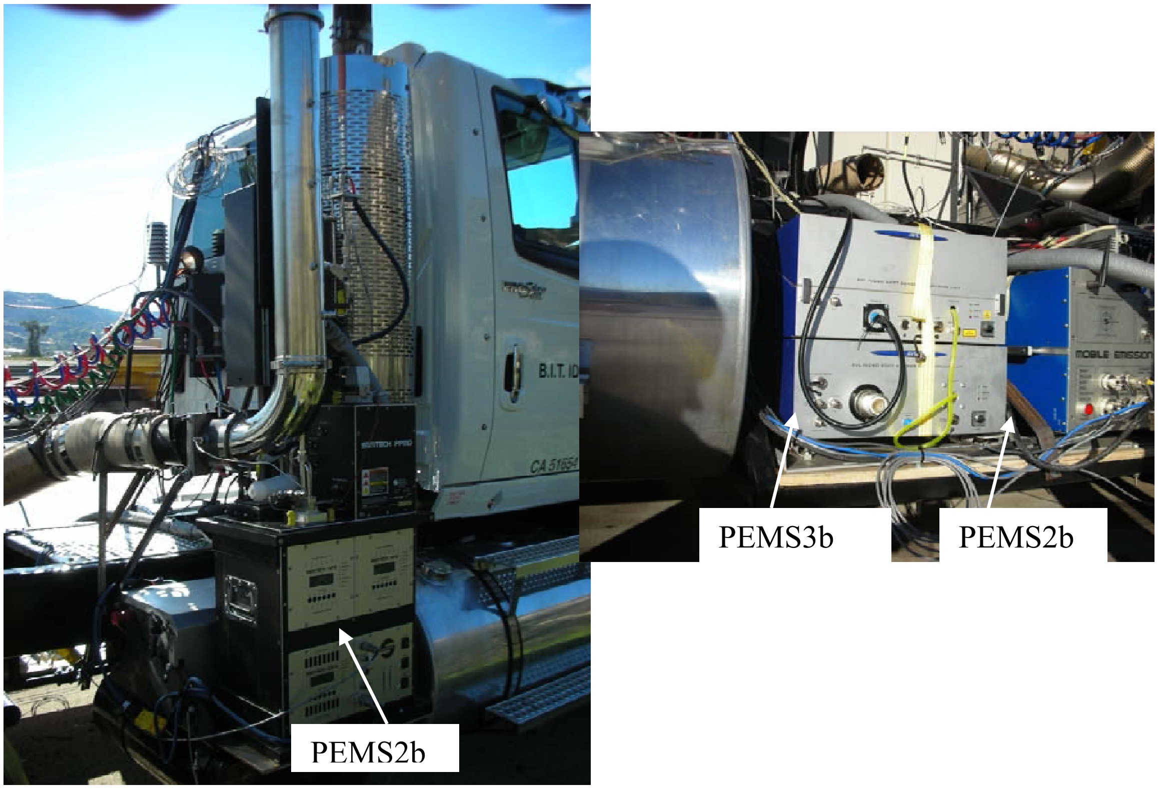


Figure 3-14 Cummins vehicle installation for PEMS2b and 3c. Left figure is PM part of PEMS2b and the right figure is the PM PEMS3b and gaseous part of PEMS2b.

3.4.3 PEMS2c/PEMS3c/2007 Volvo

Figure 3-15 below shows the Volvo PEMS2c and 3c installations. The Volvo setup was similar to the Caterpillar where the passenger side fuel tank was removed to make room for both PEMS2c and 3c. Again, PEMS2c did not request any vibration isolation and PEMS3c provided their own vibration mounts similar to the other vehicle instillations. PEMS3c was mounted further away from the exhaust and engine heat compared to the Caterpillar installation. This was desired due to the excessive heat experienced by PEMS3c during the Caterpillar testing. The issue with the PEMS3c vibration on the Cummins was not present on the Volvo thus only one mount for PEMS3c was considered which was on the frame rails.

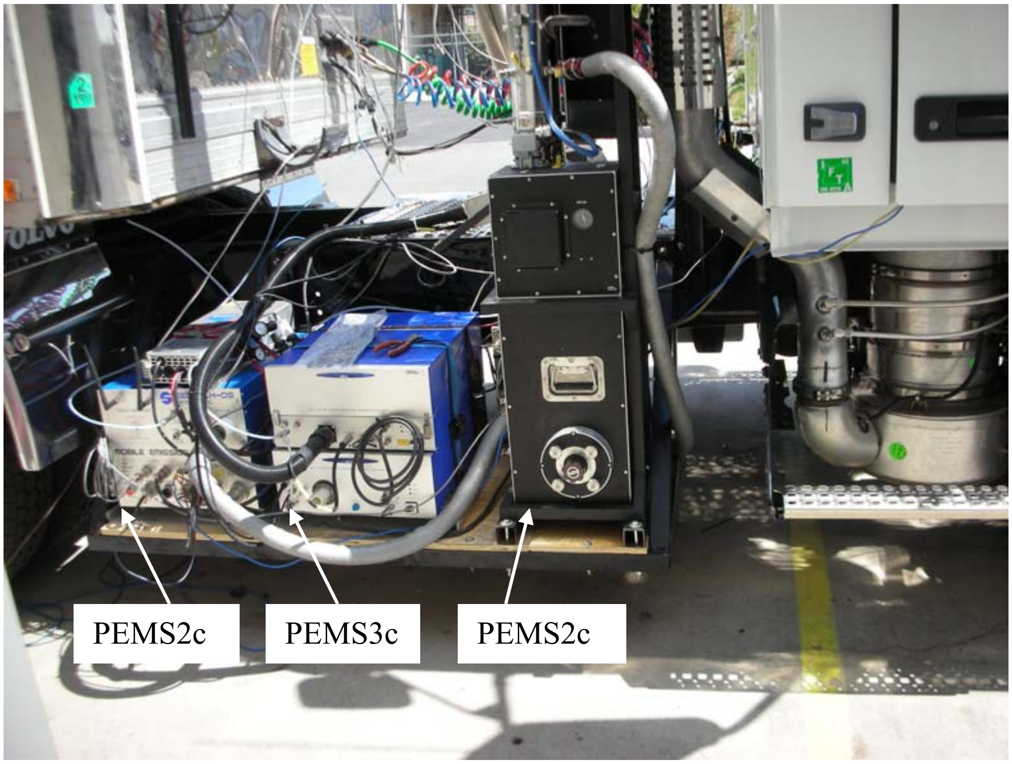


Figure 3-15 Volvo vehicle installation for PEMS 2 and 3

3.4.4 PEMS4 and PEMS5

PEMS4 and 5 were both installed in the MEL for the testing on the Caterpillar, Cummins, and Volvo and sampled from the MEL CVS. The PEMS4 was installed in the MEL laboratory and typically sampled from a separate high dilution, secondary dilution tunnel for the Caterpillar testing, but not for the Cummins and Volvo testing. 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 that with an 80 to 1 dilution the average NTE concentrations were less than 50 $\mu g/m^3$, which is near the low end of the PEMS4 analog output resolution scale. It was decided to try to 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. All of the PEMS4 data for the Cummins and Volvo testing was sampled directly off the MEL CVS. PEMS5 sampled directly from the MEL CVS during testing on all three vehicles.

3.5 PEMS Operation

3.5.1 2000 Caterpillar

For the Caterpillar testing, PEMS1, 2 and 3 were operated by the manufacturer, due to their level of development and/or 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 Caterpillar 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. The PEMS2 manual was thus available at the time for testing with the Cummins and Volvo engines. 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.

For this study, actual real-time NTE operation was not exercised for all PEMS and only forced events were analyzed. As such, errors associated with short NTE events (i.e., rapid filter sampling on and off conditions) were not evaluated. PEMS3, 4, and 5 could be analyzed for their real time NTE bsPM given their signals are continuous, but there would be no reference for comparison, thus this comparison was not made. On the final day of PEM2 testing, the manufacture attempted to run in real NTE operation, but the real time NTE operation did not work and is discussed in Section 6.

Over the course of the Caterpillar testing, the PEMS2 manufacturer tried a number of operational settings of variables such as dilution, crystal operation, and NTE triggering. This caused some large variations in PM emissions that are discussed in greater detail in later sections of this report. A listing of the configurations used for each test day is provided for PEMS2.

- Day 1: Single dilution 6:1 and 0.4 slpm QCM flows (overloaded crystals)
- Day 2: Secondary dilution added and set to 50:1, and 0.4 slpm QCM flows
- Day 3: Secondary dilution set to 50:1, and 0.4 slpm QCM flows
- Day 4: Secondary dilution dropped to 10:1, lower QCM flow of 0.25 LPM, and combined crystals (5 min max each)
- Day 5: Single dilution only with secondary turned off, 0.25 LPM flow rate, and combined crystals
- Day 6: Same as Day 5, but attempted real NTE operation

The PEMS2 firmware at the time of the Caterpillar testing was unknown and the post processor version was 1.02.

Note that the PEMS2 manufacturer indicated that the crystals were considered overloaded on the first day because the ungreased QCM crystal weights exceeded 0.2 µg, which is considered overloaded for dry soot, such as with this engine. As such, the data for day 1 was not provided by the PEMS2 manufacturer.

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.

It is important to point out that due to the different sampling methods for PEMS1 and PEMS2, there are differences in how the samples are batched together for these instruments for comparison with the MEL. For PEMS1, 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. PEMS2, on the other hand, sampled on each quartz crystal over the same duration as the MEL, so that for each forced event there was a corresponding PM mass for the MEL and PEMS2.

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. For PEMS2, the mass loadings on the quartz crystals were typically much lower than those on the gravimetric filters, by approximately a factor of 100. In other words, for samples where the MEL filter measurements were 100 μg, the PEMS would sample 1 μg.

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. PEMS2 and PEMS3a were used and combined over the final 100 forced events on the Caterpillar.

With the PEMS2 and MEL having different PM dilutions for the Caterpillar tests, the difference in the amount of mass sampled is the ratio of the sample flow rates and dilution ratios. Thus, their loading was (25 slpm/0.4 lpm)*(10 to 50 DR/6DR), or ~100 to 500 times less than the MEL's PM mass loading. During some testing, the MEL acquired about 600 μg in 30 minutes during heavy loads and regeneration conditions. This is equivalent to ~0.0026 μg/sec for the PPMD system on the low DR. According to the PEMS2 manufacture this was a large rate of accumulation and thus the PEMS2 manufacture desired higher dilution ratios to 50:1.

PEMS3 was operated following routine standard operating practices for the Caterpillar, as well as the other two 2007 engine vehicles. During the Caterpillar study the PEMS3 was operated by the manufacturer while PEMS3 was operated by UCR for the two late model vehicles. For all three vehicles the operational procedures for PEMS3 were the same. A copy of the procedures employed is in appendix D. PEMS3a sampled with a fixed dilution of four to one for the 2000

Caterpillar engine. The dilution ratios were lowered for the 2007 engine equipped vehicles due to their lower PM levels, as discussed below.

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 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 may be utilized in future publications.

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 the Caterpillar testing. The PEMS5 zero was checked daily and was not adjusted between tests, similar to the operation for PEMS4.

3.5.2 Cummins and Volvo Testing

The PM PEMS used for the second part of the testing effort were all operated by UCR staff with the exception of some help from EMA members represented by Caterpillar and Detroit Diesel. PEMS1 was not used for this testing as such only PEMS 2, 3, 4, and 5 were evaluated for the 2007 MY engines.

For the Cummins and Volvo testing, CE-CERT operated the PEMS2 as follows and PEMS3 similarly as for the Caterpillar testing except a dilution ratio of 2 for Cummins and 3 for the Volvo testing (bypass higher soot levels was expected).

One unexpected result learned from the Caterpillar testing was the large variability in PM emissions when allowing PEMS2 to vary its sampling parameters. As a result all the PEMS in the Cummins and Volvo tests were performed with sampling parameters locked down based on PEMS manufacturers and EMA committee recommendations. The locked down parameters provide a level of confidence in the data given a set of operating conditions. It is also important to point out the level of variability these instruments will yield given changes in operating parameters. Thus, it is cautioned in repeating these experiments to match operating parameters as close as possible to achieve similar results. Not all parameters are available to the user and may also vary with firmware versions of PEMS2, thus it is also important to use note the PEMS2 firmware versions. The PEMS2 firmware was version 2.204 for the Caterpillar testing. It is also important to know the PEMS2 post processor version for comparisons. The post processor version was 2.104 for both the Cummins and Volvo testing. A summary of the user configurable PEMS2 operational parameters are provided below:

1. Crystal greasing was performed (5-20 μg of grease was used as recommended)
2. Flow rates set at 0.4 lpm
3. MPS1 dilution ratio set at 6:1
4. Crystal temperatures targeted 47 C
5. No combined crystals were used
6. The maximum crystal loading before cleaning was 1 μg. Cleaning involved removing grease and then reapplying the grease to 5-20 μg. Cleaning was done daily.
7. Forced event (dry contact) was available and was used for all tests
8. The Semtech PPMD is typically set up to be disabled during regenerations. This feature was disabled so that sampling during regenerations could be performed. This modification was approved by the manufacturer.
9. PEMS2 is equipped with a system that allows for additional dilution if needed. This automatic fixed dilution (MPS2) is designed with a threshold of 0.001μg/sec. If this value is exceeded three times, additional dilution is engaged (fixed at 10 to 1 on top of the MPS1 dilution of ~6). Once engaged the PPMD power needs to be cycled to clear the use of the MPS2. MPS2 was never enabled during testing.

With the PEMS2 and MEL having similar PM dilutions of ~6 for the Cummins and Volvo tests, the only difference in the amount of mass sampled is the differences in sample flow. Thus, PEMS2 loading was 50 slpm/0.4 lpm, or ~125 times less than the MEL's PM mass loading. During some in-use testing on the Caterpillar engine, the accumulation rate was ~0.0026 μg/sec for the PEMS2 systems, which exceeded the 0.001 μg/s threshold. The mass loadings for the Cummins and Volvo tests were much less and thus the 0.001 μg/s threshold was not exceeded for the Cummins or Volvo testing. Since the 0.001 ug/s threshold was never exceeded the MPS2 was not operational for any of the Cummins or Volvo tests.

UCR was able to obtain all calibration and audit data to fully drift correct the gaseous PEMS2 results, due to the efforts by Caterpillar in operating, auditing and calibrating the gaseous part of PEMS2. This added effort allowed an additional evaluation of the gaseous data such as NO_x, CO_2, CO and THC brake specific emissions. Since the MEL and the PEMS2 gaseous systems were operated with all their calibration and audit data, both data sets were available for a gaseous NTE delta analysis. Some gaseous analysis is added to the report in the gaseous analysis section. The gaseous data is fully audited and represents valid results and can be used to draw conclusions about deviations between the PEMS2 and the MEL.

PEMS 3, 4, and 5 used the same operating practices with the 2000 Caterpillar testing since these instruments have only a single parameter to vary which is sample dilution ratio. Other parameters were set based on startup operating procedures for optimal performance. PEMS3 and PEMS4 both used a slightly lower dilution ratio as a result of the lower level PM emissions for the 2007 engines. PEMS3 used a primary dilution ratio of 2 to 1 for the Cummins and 3 to 1 for the Volvo. PEMS4 sampled directly from the MEL CVS without additional dilution from UCR's secondary dilution tunnel. PEMS4 did not require daily cleaning for the Cummins and Volvo engines due to the low PM levels.

3.6 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), face velocities (50 cm/s), and other conditions (2 sec residence time). The filter sample volume flow rate was doubled which increased the face velocities from 50 cm/s to 95 cm/s for the Cummins and Volvo testing. The upgraded face velocities were similar to those to be used by SwRI in the main PM MA program.

A standard zero span calibration was performed every hour and before each test throughout the correlation. Typically, the MEL performs a 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 for the Caterpillar testing. Audits were performed for the Cummins and Volvo testing. 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 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 event and the end of the MEL filter sample.

For the Caterpillar testing, 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 five runs per day were performed.

For the Cummins and Volvo testing, fewer forced events were performed per test run as a result of the longer sample times. Typically only two events were performed per run where the overall test run was around one hour. Thus, the time between zero and span calibrations were also around one hour. Typically five test runs were performed per day.

Figure 3-16. MEL Driver's Aid Interface

3.7 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. Each test vehicle performed the following test routes where the route to Palm Springs was performed the most due to its convenience of large highway shoulders to handle instrument problems.

Route 1 – Riverside Local Freeways

Route 1 was a local loop on the freeways in the Riverside area, as shown in Figure 3-17. 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.

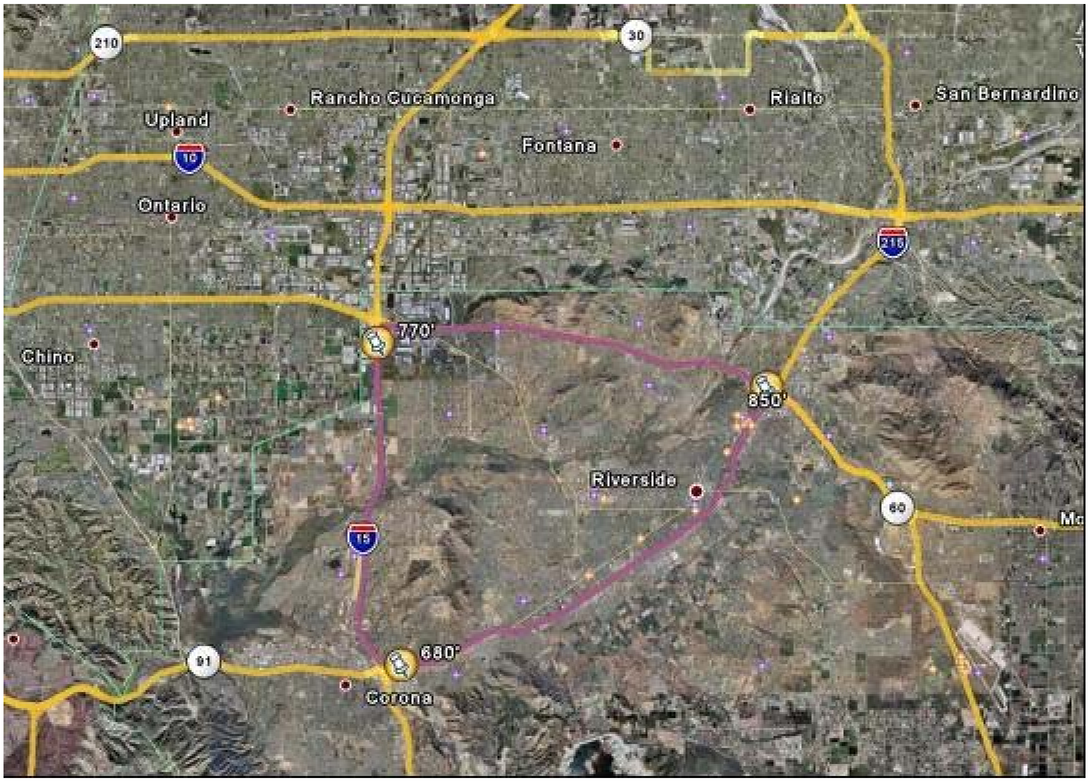


Figure 3-17. Riverside Local Freeway Route.

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 3-18. 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.

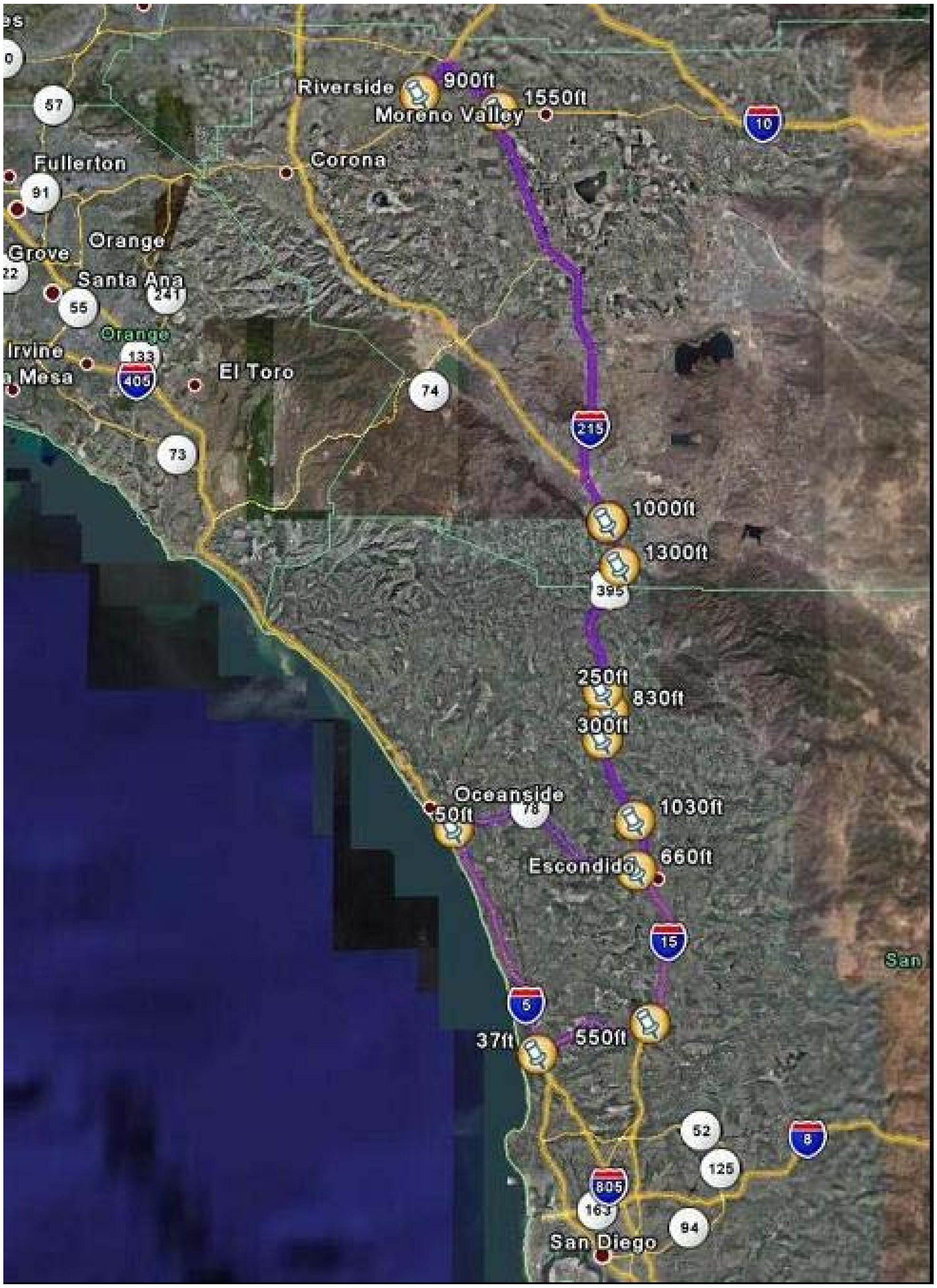


Figure 3-18. Riverside to San Diego Route

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 3-19. 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 3-19. 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 3-20. 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 3-20. Riverside to Baker/State Line Route.

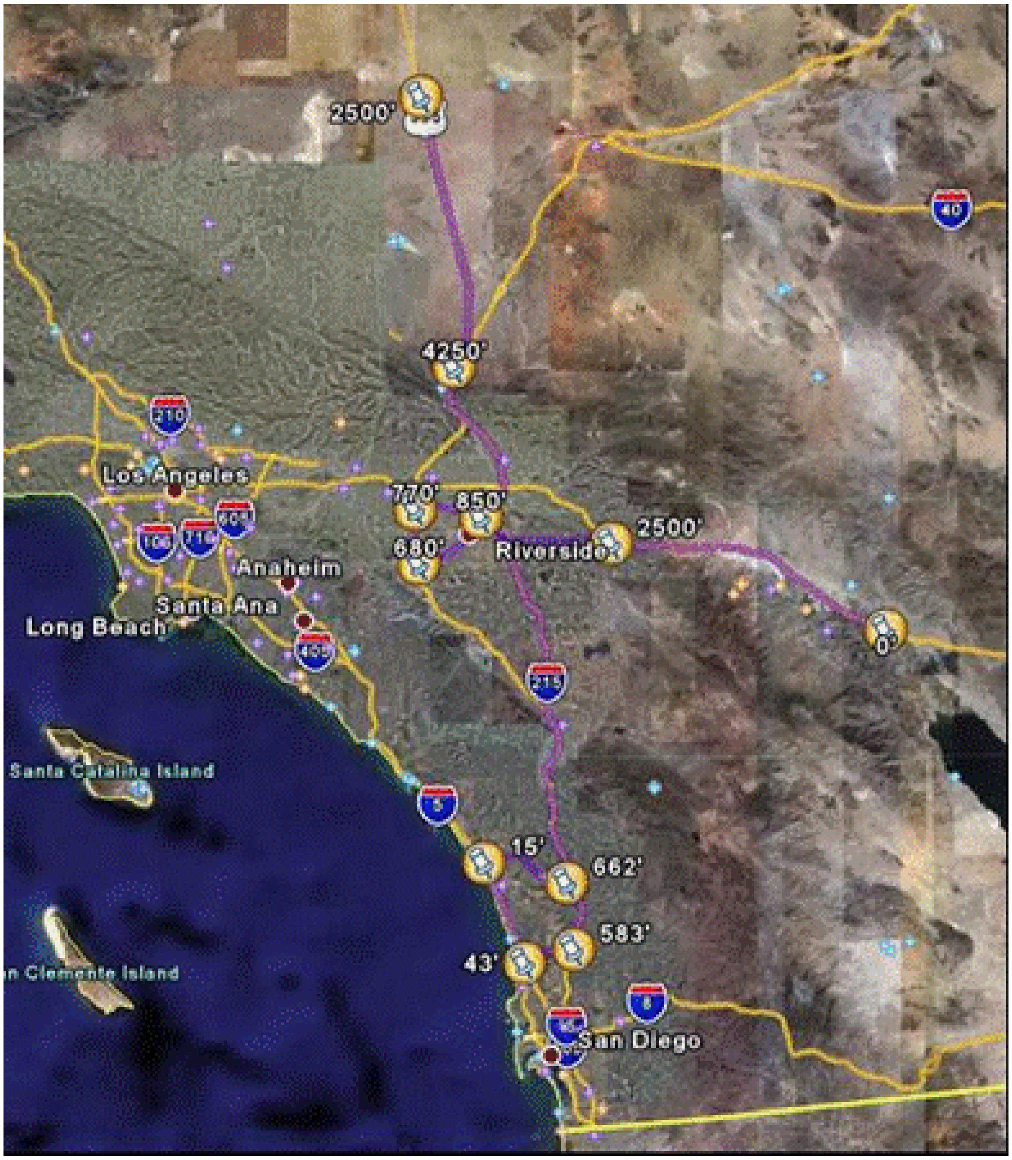


Figure 3-21 Overview of all routes relative to Riverside and LA area.

4 On-Road Testing – PM Experimental Results

The experimental results and cross comparisons between the different PM PEMS and the MEL are presented in this section for the 2000 Caterpillar, 2007 Cummins and 2007 Volvo engines. All the results presented are from in-use testing with UCR's MEL simultaneously with the PEMS. Because the PM source is related to the engine and not the chassis, the remainder of the analysis will refer to the engines (Caterpillar, Cummins and Volvo) and not the chassis. A detailed final report to the MA committee was already prepared for the Caterpillar data, so the Caterpillar data are presented here to provide a comparison to the previous work. For a more detailed discussion on the Caterpillar data, see the final report to the MA committee (Durbin et al 2009). This section covers only forced-event, PM emissions for the tested engines. Some gaseous data is provided in the next section.

There were several unique requirements for performing in-use PM emissions comparisons tests that were not necessary for gaseous in-use testing. These included meeting desired filter loading, maintaining NTE conditions (i.e., engine speed, torque and hp) and achieving bsPM levels near the in-use standard of 0.03 g/hp-h. As such, sub sections were included to the PM results to specifically address the ability of UCR to meet the above requirements while performing the in-use testing.

These sections include the PM analysis section, where the reason and impact of controlling sample time is discussed. Also, a section is added to discuss the distribution of work, average power, filter loading, and bsPM. In these sections, the ability of UCR to meet the program objectives is discussed. The final results are then presented for each PEMS relative to the MEL on a test vehicle basis. A final section shows all the data pulled together and considered as a whole.

In addition to differences between emission level, PEMS and engines tested, an unexpected result was discovered with the analysis of the PM composition and particle size distributions. The composition and size distributions varied significantly for each test engine, with the Caterpillar having mostly elemental carbon, the Cummins having sulfate as the largest fraction, and the Volvo having organic carbon as the highest fraction and very little sulfate mass. The PM composition and size distribution effects on the PM PEMS are explained in more detail in this section.

4.1 PM Analysis

The PM analysis is on a brake specific basis during events that were forced by a manual trigger from the MEL to the PEMS. The manual triggering, called a "forced event", was necessary due to the nature of PM sampling and the difficulty of predicting in-use NTE operation. PM emissions are batch operated for the reference (i.e., the MEL), PEMS1 and 2. The MEL, PEMS1 and PEMS2 operate by depositing mass on a Teflon filter, while PEMS2 deposits PM mass on a quartz crystal surface. The other PEMS (3, 4, and 5) are real-time instruments that could be used to process real bsPM NTEs emissions, but the primary focus is comparisons to the reference with

PEMS1, 2 and 3. Because the reference is batched operated, the main PM comparisons presented here are based on “forced events”.

The forced events were manually controlled by two limitations, overloading the PEMS2 crystals and depositing enough mass on the MEL reference filter. As a result of these two opposing constraints, UCR was asked by the MA and EMA committee members to vary weight gains from 50 to 200 µg. For the 2000 Caterpillar engine these weight gains were easy to achieve in a few minutes, but for the two DPF-equipped engines, the sample times were much longer (on the order of 20 minutes), as will be discussed in Section 4.3.2.

The NTE work zone is an integral part of in-use compliance testing and is the basis for this study. The basic idea of the NTE emissions is to characterize emissions when the engine is under some representative load and environmental conditions for a minimum of 30 seconds (CFR40 Part 1065). According to the NTE regulation, if the engine drops out of the NTE work zone, the integrated emissions are evaluated from the time entering to exiting the work zone. Short transitions (<30 seconds) in and out of the NTE work zone would not count as valid NTE’s and events that are longer than 30 seconds would count as individual events. Thus, long “forced events” as defined in this program would most likely contain some invalid NTE’s and multiple valid NTE’s.

During the UCR in-use study, it was practically impossible to maintain single continuous NTE operation for long periods of time around 20 minutes. Figure 4-1 shows a typical real time plot of the J1939 calculated power and the reference threshold NTE power during the Volvo testing (based on Volvo’s published lug curve). The two grayed areas show forced events #19 and #20. Notice how the J1939 power repeatedly drops below the NTE threshold condition during both forced events. The fact that the sampled event drops below the threshold would indicate both forced events are not valid NTE’s. Event #19 is composed of several invalid NTE’s and about three valid NTE’s. It is important to point out, however, that most of the engine operation was above the NTE power threshold and hence is representative of NTE operation.

Ironically, the forced events presented in this paper are very similar to the European work-based window approach where NTE drop out is allowed. The main difference between the forced events used in this study and the work based window is that the forced events are controlling the sample time from filter loading instead of total work. In summary, events #19 and #20 represent typical forced events which are used as the basis for the main PM analysis presented in this report.

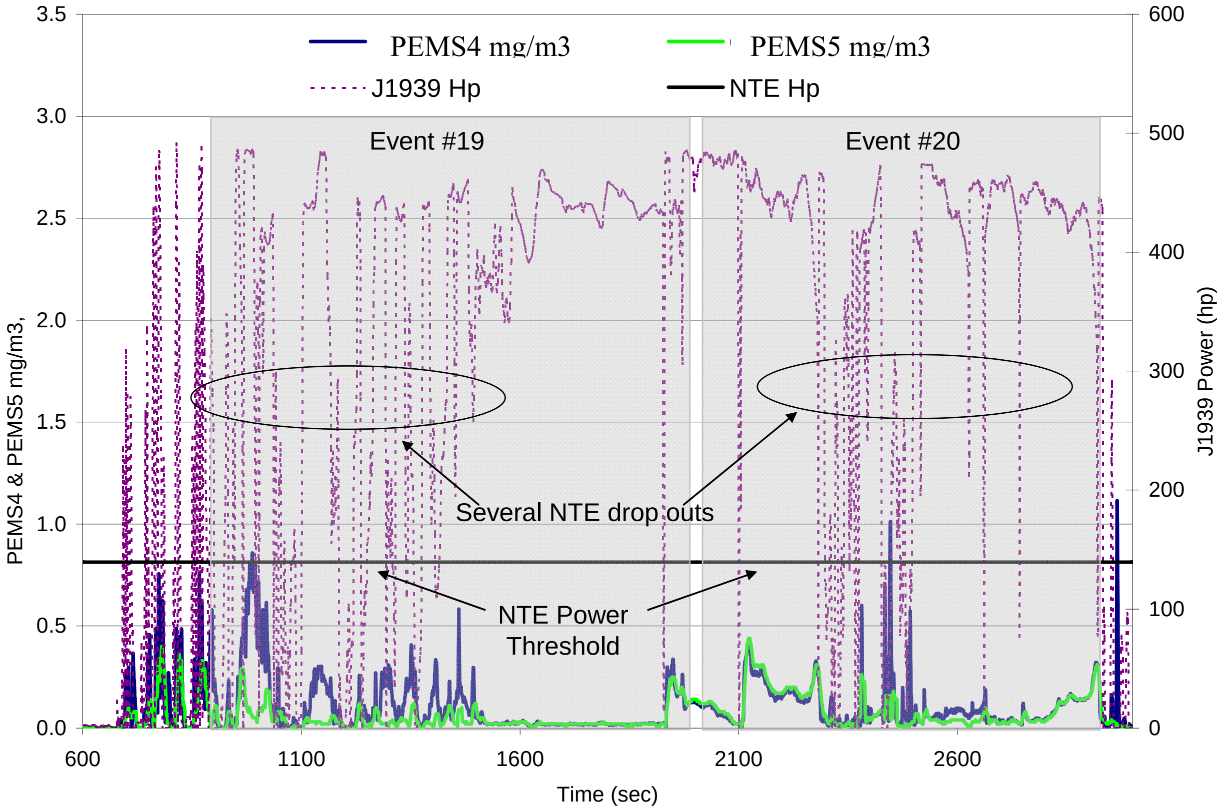


Figure 4-1 Real time evaluation of the 19th and 20th forced events for the Volvo engine

4.2 Data Collection

The results presented in this report are based on a subset of the actual data sampled. The need to use a smaller data set is due to PEMS operational issues, which ranged from environmental conditions to instrument operation and data processing. Table 4-1 shows a breakdown of the forced events attempted and the percentage of events for which bsPM data were processed and reviewed. Processed data is data that was provided by the manufacturer as-is or processed using the PEMS post processors. During the time UCR operated the PEMS2 system, it was discovered that some data that was validated by post processor had to be invalided upon UCR review (thus the name reviewed). A deeper look at the signals used to calculate PEMS2 bsPM uncovered some system issues that were not obvious at the time of testing. The reviewed data is data that UCR examined and found to be reliable using good engineering judgment. A detailed explanation of data loss and operational issues is provided in Section 6.

It is important to note that the measurement data results represent a snap shot of the PEMS development at the time of testing. Development of the PEMS generally is continuing on an ongoing basis. Nevertheless all PEMS were considered to be commercially available at the time of testing. PEMS1 at the time of testing was only available from the manufacturer. PEMS2 had a couple serial numbers that had been purchased. PEMS3 has been available for several years and is owned by many organizations. During the Caterpillar testing, all PEMS were operated and supplied by the PEMS manufacturer. During the Cummins and Volvo testing, all PEMS were acquired from EMA members. The EMA-owned instruments were operated by UCR with fixed parameter settings and conditions, as explained in the experimental Section 3.4.

There is a strong correlation to instrument maturity and the percentage of data yield, where PEMS1 was the least developed at the time of testing and PEMS3 the most. PEMS4 and 5 showed the highest data yield, but these instruments were in the MEL and were not subjected to the same harsh environment as PEMS1, 2 and 3. As such, the PEMS4 and 5 data yield is offered as a point of reference. The PEMS1 system showed the lowest overall data yield mostly because at the time of testing the system was very preliminary. PEMS1 provided results on 62 of 70 forced events, but only 16 of the data points were considered best-cases by the manufacturer. The manufacturer felt that the PEMS performed best on the final day of testing, thus the PEMS1 data yield was 23% for their best-case and 88% for what was submitted. PEMS2, which has had more time being evaluated at different levels of commercial availability, showed a data yield from 40% to 64%. PEMS3 showed the highest data yield of the PEMS sampled in the harsh environment with a yield from 65% to 100%. The lower 65% data yield on the Caterpillar testing was attributed to the instrument being placed too close to the engine exhaust, where temperatures could be 40°C higher than experienced by the other PEMS. The PEMS3 was located away from the exhaust during the Cummins and Volvo test and, as such, their data yield improved to 100% and 93%, respectively.

Test Vehicle	PEMS	Sampled	Processed	Reviewed	% Reviewed
Caterpillar	1	70	62	16	23%
Caterpillar	2a	94	38	38	40%
Caterpillar	3a	152	99	99	65%
Caterpillar	4	170	170	170	100%
Caterpillar	5	170	170	170	100%
Cummins	2b	28	22	18	64%
Cummins	3b	28	28	28	100%
Cummins	4	28	28	28	100%
Cummins	5	28	28	28	100%
Volvo	2c	39	21	19	49%
Volvo	3c	45	42	42	93%
Volvo	4	45	45	45	100%
Volvo	5	45	45	45	100%

Table 4-1. PEMS Data Summary of Forced Events for all test vehicles.

The data presented in main PM analysis considers all the supplied PEMS data and only the reviewed data by UCR. There is additional analysis that considered smaller subsets to show the effect of the different groupings such as all PEMS1 data and only day4 data and All PEMS2 data and only the Cummins and Volvo engine PEMS2 data.

4.3 Statistics and Results

This section on statistics looks at the data as a whole to see where the average, 5th, 50th and 95th percentiles lie. This section gives the reader a feel for the distribution of work, sample times, filter weights and MEL bsPM emission levels under which the PM PEMS were evaluated. This allows an evaluation of the representativeness of the forced events in terms of NTE operation, filter loading, and bsPM emission levels.

4.3.1 Brake Horsepower and Work

Figure 4-2 shows the distribution of average power measured for all engines and for each specific engine manufacturer. These figures show that the Caterpillar testing was centered around 200 hp and had a 50th percentile power of 233 hp with 5th and 95th percentiles of 100 and 400 hp, respectively. The Caterpillar testing looked normally distributed, but for the trap equipped tests there was less of a normal distribution trend and the hp distribution looked almost flat from 100 to 400 hp. The differences could be due to the longer sampling times and more averaging of the data. The 5th, 50th and 95th percentile values were similar for all three test engines. Overall, the combined effort showed that the majority of the average power was well above the individual engines NTE calculated hp thresholds, which varied from 147 hp for the Caterpillar engine to 139 hp for the Volvo and Cummins engines. Although the higher engine speed NTE threshold is governed by the 30% minimum torque, these figures show that most of the following PM emission correlation data is represented by NTE type of engine operation. This suggests that the forced event method employed by UCR provided reasonable comparisons of PM data during NTE-type operation.

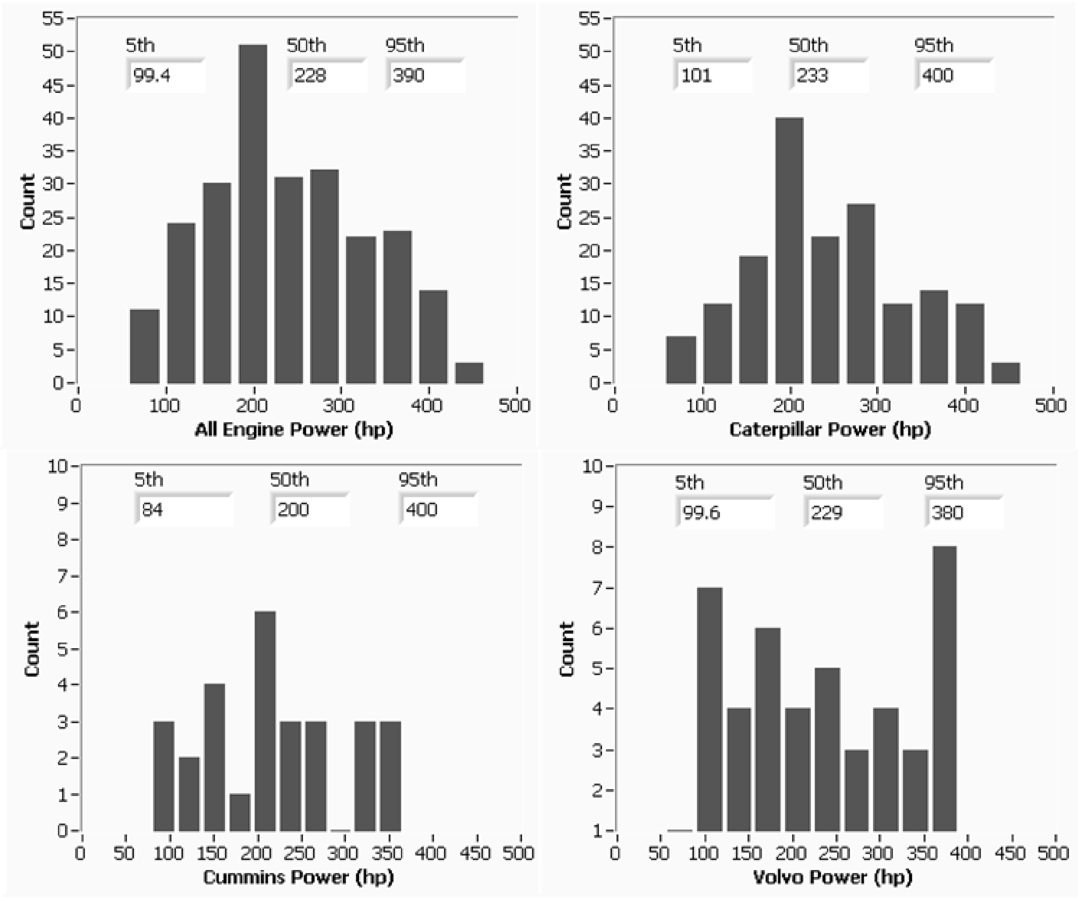


Figure 4-2 Histogram of event average power for all test engines and for each engine individually

4.3.2 Filter Mass and Sample Times

It is important to understand the gravimetric 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 manually forced events. The distribution of filter masses is shown by the histograms in Figure 4-3, where the results for the filters pooled together are in the top left figure then the other histograms show the results for the three vehicles individually. From this Figure, one can see quickly that the Caterpillar engine showed the highest filter weights, which makes sense since there was no DPF. The Cummins and Volvo engines showed much lower filter weights, with the Cummins having the lowest 50th percentile at 42 µg/filter compared to the Volvo at 70 µg/filter and the Caterpillar at around 100 µg/filter.

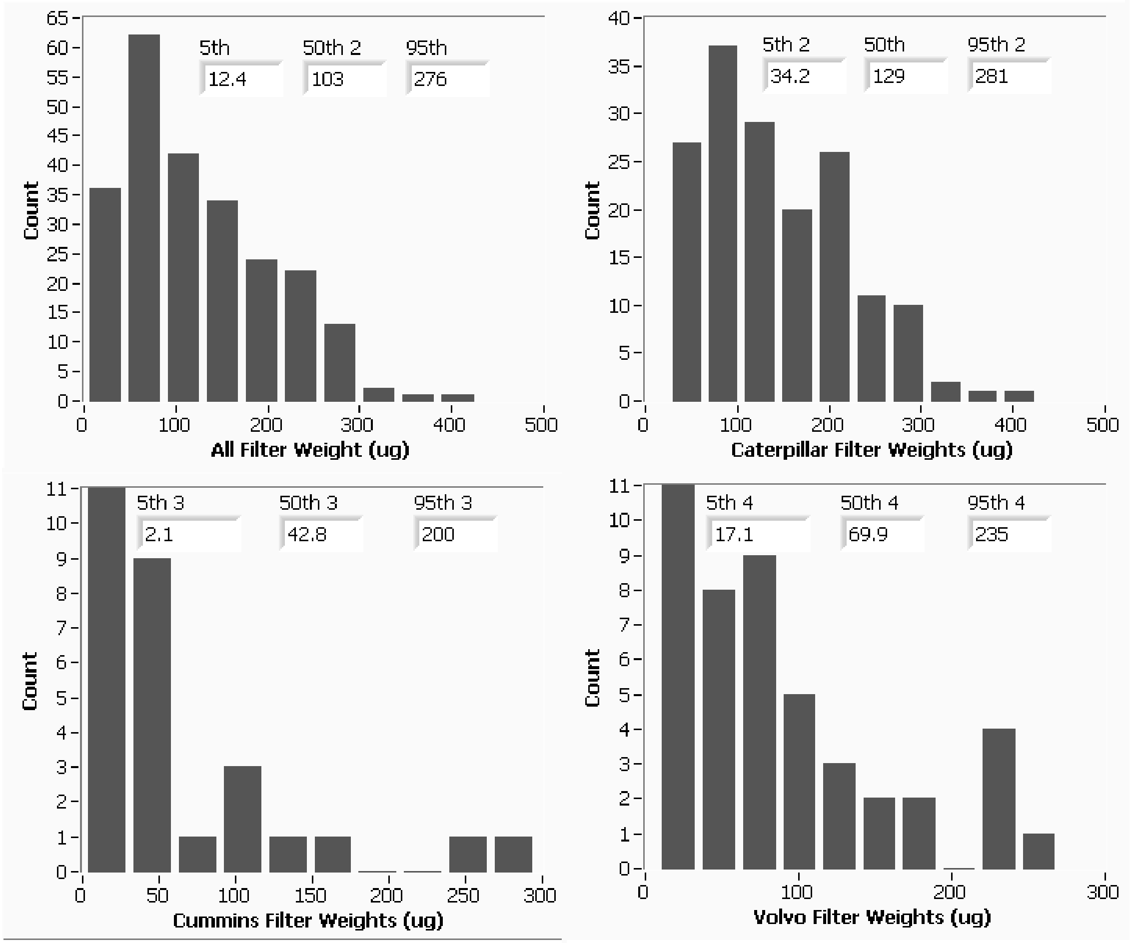


Figure 4-3. Histogram of event filter weights for all test engines and for each engine individually

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. The UCR MEL was upgraded to provide filter sample flow rates with face velocities of ~95 cc/sec for the Cummins and Volvo test engines (at 47°C and 740 mmHg absolute pressure for Riverside). EPA requested using the Whatman filters for the MA testing, but due to the large pressure drop across the Whatman filter, Paul Teflos filters were used, as described in the experimental section. UCR has recently completed the final upgrade to its PM sampling system and can now perform high flows using the Whatman filters (which will be used during the MA PM PEMS validation runs).

Figure 4-4 shows the sample time for all the data pooled together and by each engine manufacturer. Notice the distribution for the overall and for the Caterpillar sampling times are skewed to the left (shorter sample times). The shorter times for the Caterpillar is a result of the higher concentration in the exhaust compared to the two DPF-controlled engines. The sample times are longer for the DPF-equipped engines compared to the non-DPF-equipped engine is due to the much lower PM concentrations sampled. The Volvo engine showed a more normal distribution than the Cummins maybe due the larger sample population of the Volvo compared to the Cummins. The sample durations varied mostly between the non-DPF and DPF-equipped engines. For both DPF engines, the 5th percentiles ranged from 86 seconds to ~ 500 seconds and the 50th percentiles ranged from 300 second to 1000 seconds. The 95th percentile varied from 700 to 2000/1500 seconds for non-DPF to DPF-controlled engines, respectively. Overall, the forced events were on average much longer than the typical in-use NTE, which averages less than 80 seconds (Miller et al. 2007).

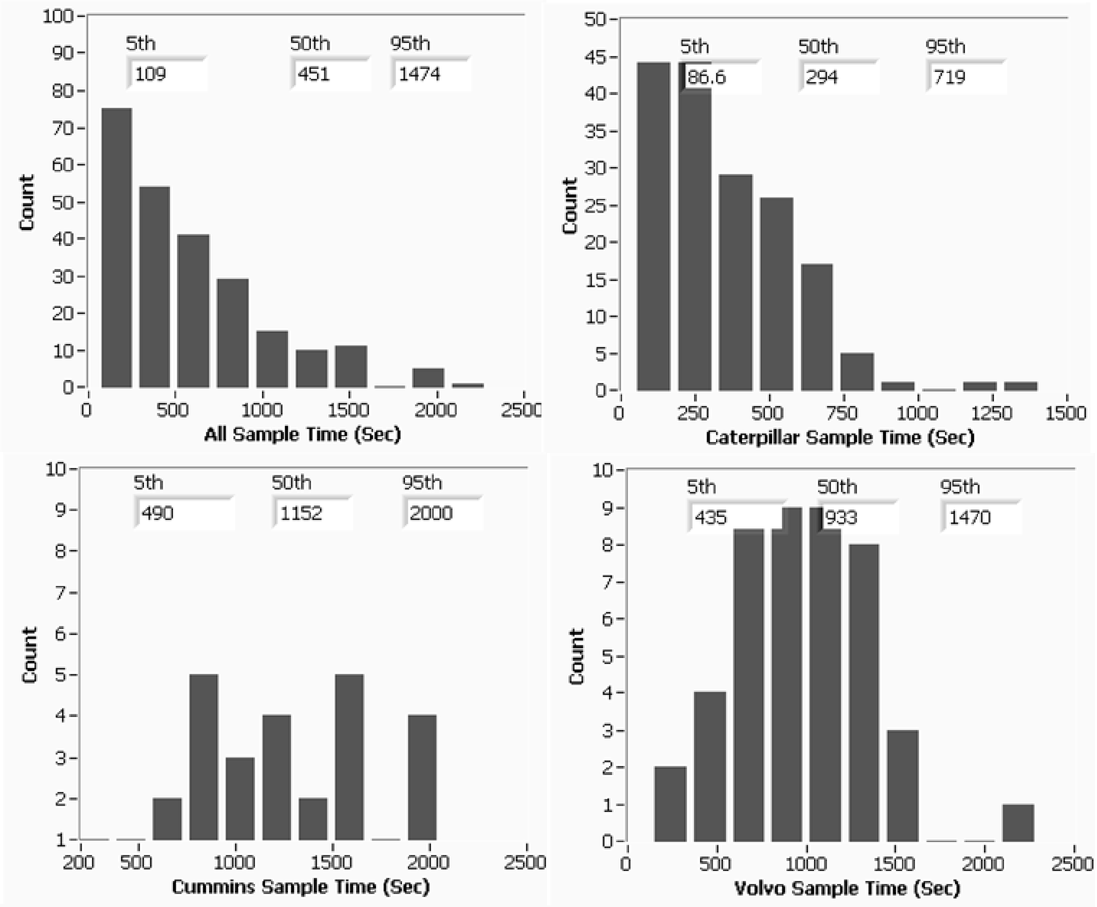


Figure 4-4 Histogram of event sample time for all test engines and for each engine individually

4.3.3 MELS bsPM

One of the other objectives for the in-use testing was to target a bsPM around the in-use NTE standard of 0.03 g/hp-h. Overall, the bsPM level varied for each vehicle and provided comparisons from 0.1 g/hp-h to 0.00003 g/hp-h, as shown in Table 4-2. Figure 4-4 shows histograms of the event sample time for the composite testing and for the individual engines tested. The Caterpillar averaged 0.043, which is just above the in-use NTE standard. The DPF-controlled engines averaged 0.0026 and 0.0057 for the Cummins and Volvo, respectively. Statistically though the distribution of PM was skewed to the lower PM levels for all the test engines with some high bsPM measurements making for large tails to the right (high bsPM). Notice how the Caterpillar and Volvo tests showed the largest bsPM tails at relatively high bsPM levels, while the Cummins was mostly lower bsPM emissions. This suggests that the regeneration only approach for the Cummins did not increase the bsPM as much as the bypass and regeneration approaches on the Volvo testing.

The average bsPM for all the tests pooled together was 0.03 g/hp-h, which is ironically the target bsPM desired for these testing programs. If you consider the 50th percentile of the data, since the distributions are not normal, the 50th percentile is slightly higher at 0.032 g/hp-h for the pooled data. The 50th percentile for the individual test engines was 0.04, 0.002, 0.003 g/hp-h, respectively, for the Caterpillar, Cummins, and Volvo engines. It is interesting to show how low the DPF-controlled engines PM emission levels were on average and how they were even lower for the 50th percentile. The 95th percentile levels were 0.07, 0.009, 0.019 g/hp-h for the Caterpillar, Cummins, and Volvo test engines, respectively. These low PM levels at the high 95th percentiles indicate that the regenerations and bypass systems were not sufficient to increase the bsPM levels to the 0.03 g/hp-h desired.

In general, it appears the forced regenerations may not represent a true regeneration. Emissions levels during true regeneration may be higher and closer to the 0.03 g/hp-h levels based on some previous work. The bypass system was very small and may not represent a typical crack and thus may be showing lower bsPM levels. During the next round of in-use testing for the MA PM PEMS validation testing UCR is designing a bypass system with 3 to 4” tubing and throttle type valves to force bypass and maintain filter pressure as apposed to the small 1” tubes used in this study. Since the flow is restricted according to the square of the internal diameters and restrictions, it is expected the new bypass system will have no trouble achieving bsPM near or above the 0.03 g/hp-h target.

	MEL Level g/hp-h		
Manufacture	ave	max	min
CAT 2000*	0.0431	0.108	0.01143
Cummins 2007	0.0026	0.010	0.00003
Volvo 2007	0.0057	0.040	0.00083

Table 4-2 UC Riversides average, minimum and maximum bsPM emission levels for all three test engines

In general, the objectives were achieved of obtaining various PM levels and sufficiently challenging the PM PEMS in-use while comparing to UCR’s MEL. The Caterpillar testing showed bsPM levels above and below the 0.03 g/hp-h, while all the DPF-controlled engines showed bsPM levels mostly below the 0.03 g/hp-h level (except for two tests above 0.03 g/hp-h during the Volvo testing). Overall, the PM PEMS systems were challenged near the in-use standard of 0.03 g/hp-h, as desired by the MA committee members.

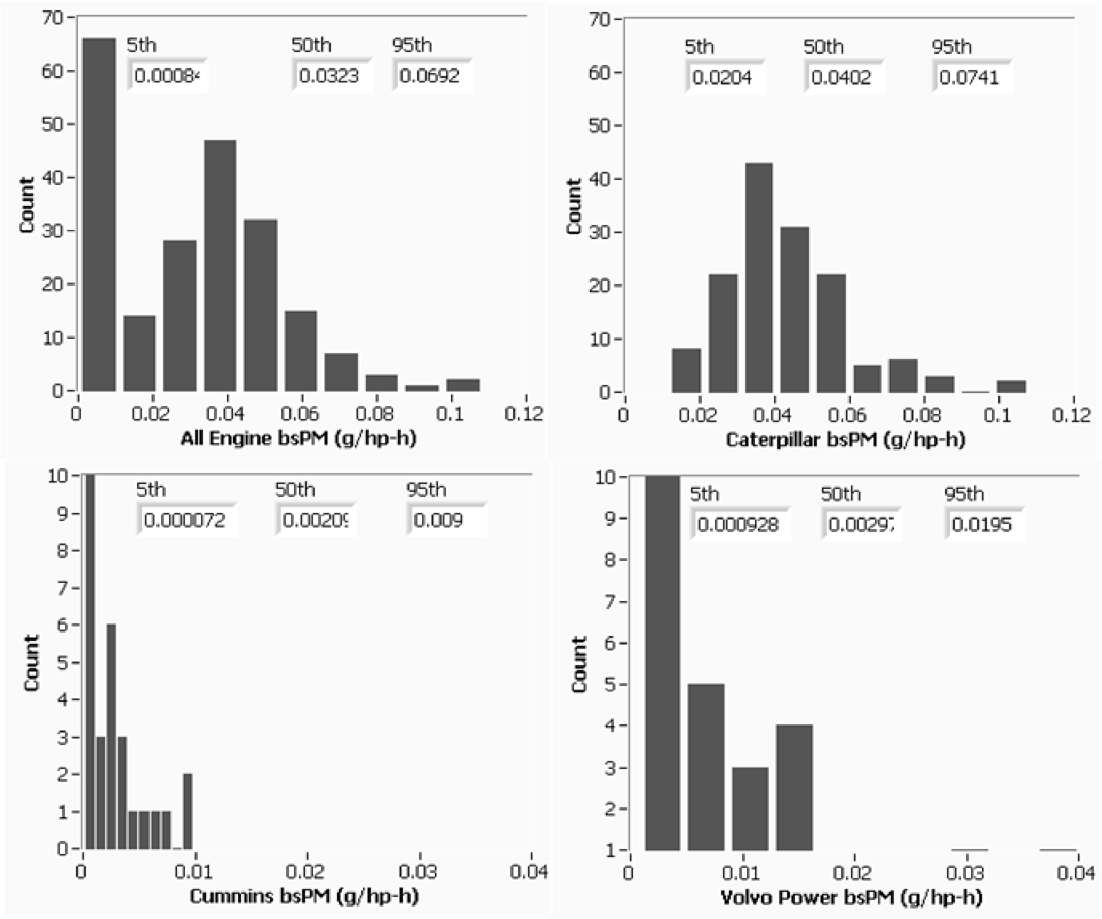


Figure 4-5 Histogram of event sampled bsPM for all test engines and for each engine individually

4.4 Reference PM Measurement Confidence

Due to the light loading on the filters, some analysis of filter weighing is necessary to have confidence in the PEMS comparison. This section discusses the ability of the MEL to make filter weight measurements down at the 50 µg/filter level since several filters weights were at or below this level. It is important to understand the reference uncertainty in order to have confidence in the PM PEMS comparisons and trends.

Typically, the target filter weight for the MEL is greater than 100 µg to provide levels that are sufficiently above the measurement error. Due to the need for in-use testing with short sample times, low PEMS mass loadings, and the low PM concentration levels of properly functioning DPF, the MEL filter weights were as low as a few µg/filter. Typical tunnel blanks for the MEL system are between 5-10 µg for a 1 hr tunnel blank. During these PM PEMS testing programs, reference and tunnel blank filters were lower than usual, with the tunnel blanks just under 5 µg for a 1hr sample duration and reference filters were around 1-3 µg. Typically, filter contamination (background, handling, and artifacts) increases mass loading, while loses from evaporation of volatile compounds can lead to lower filter weights. In this case, with the sub-10 µg filter weights, it is anticipated that the artifacts and other background contamination might play a bigger role, hence the gravimetric filters may be more prone to overestimate PM. The fact that the results are showing very low bsPM levels is interesting, however, and may suggest that the gravimetric filters underestimate as opposed to overestimate the PM levels. More analysis and understanding of filter weight gain is necessary to fully characterize this observation, but the understanding adds to the significance of the results at the low bsPM emission levels.

Another way to consider bsPM for marginal filter weights is to consider trends of emissions to see if any trends are noticeable that would invalidate the reference bsPM. Two figures are presented that provide trends between filter weight and bsPM and bsPM and concentration. Both figures give the reader a feel that the trends are reasonable and thus add more validity to the MEL reference measurements at these low levels.

Figure 4 6 shows the MEL filter weight as a function of the bsPM level for all three test engines, where the x and y-axis are both on a log scale. The regression lines are power functions where the power of zero means the data is basically flat and a power of near one suggest a strong power relationship. The Caterpillar PM results show a power of 0.02 which suggests the bsPM emissions are not varying significantly with filter weight. Thus, the MEL was able to provide relatively consistent bsPM emission values over the range of filter loadings that were used for the testing on the Caterpillar engine.

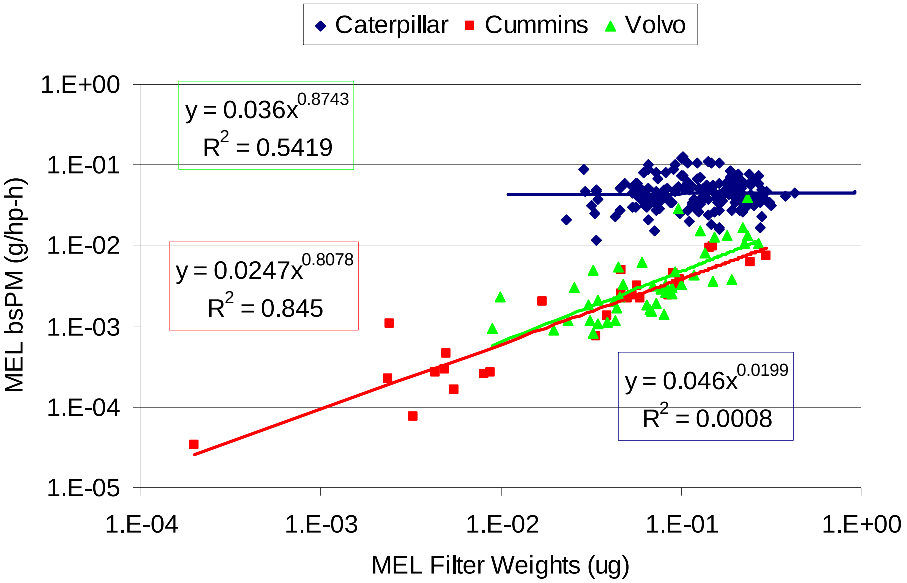


Figure 4-6. PM Emission Level (g/hp-h) as a Function of Filter Weight for the MEL.

The Cummins and Volvo testing showed a trend where filter bsPM dropped with decreasing filter weight by several orders of magnitude. This trend is expected since these vehicles were tested in their baseline configurations with fully functioning DPFs as well as with conditions using a bypass and regeneration to increase the bsPM level. Thus, the distribution of filter weights and corresponding bs PM emission levels is consistent with the experimental design and provides a rough measure that the MEL was capable to making the required measurements over the range of experimental conditions examined. It should be noted that the majority of the low filter weights (10 tests) are from the Cummins testing where there was no bypass and only varying levels of regeneration were performed. These light filter weights represent bsPM levels from 0.00003 g/hp-h to 0.001 g/hp-h, as shown by the small cluster of red squares in Figure 4-6.

4.5 PM PEMS Comparisons

This section covers the PEMS comparisons for all test vehicles and all PEMS, where PEMS1 was only operated during the Caterpillar testing and PEMS2 – 5 were used for all three vehicles. In order to provide a more comprehensive assessment, some of the Caterpillar data from the earlier study is repeated here to aid in the comparison between PM emissions sources. For more details on the Caterpillar results see Durbin et al (2009a). Three serial number PEMS2 and 3 were used during this study, as explained earlier. The PEMS2 and 3 subscript denotations are not maintained in this section, but are documented in the experimental section.

A note of caution in interpreting the PM comparisons between the PEMS and reference system is needed. The debate about measuring PM is ongoing not only at the regulatory level, but also at the scientific level. The PM PEMS are real-time and semi real-time instruments and are not designed to measure PM mass in a same manner as the gravimetric filter reference method. Some PEMS measure mass directly with systems that affect particle collection and other PEMS measure properties of PM that infer the mass, such as particle mobility, surface area, size, composition, and combinations of these. Those that measure mass directly like PEMS2 still require particle charging to collect the PM and have absorbing surfaces that are different then a Teflon filter.

The reference system measures PM mass deposited on the surface of a filter after two stages of dilution with requirements for face velocities, residence times, dilution temperatures, etc., as per CFR40 Part 1065. The deposited PM mass is partially from the mass filtered from the solid and liquid particles in the gas sample. Some of the mass is from gaseous hydrocarbon molecules absorbing onto the Teflon/PM surfaces due to intermolecular forces. Other mass is from water equilibrium in the filter weighing room. These different masses define the reference PM total mass. These differences are all added into the analysis as biases and variability in the PEMS measurement. PM mass composition and particle size is discussed in Section 4.5 to help understand relationship between PM and PEMS measurement methods.

Unlike the previous gaseous comparison one should not expect a perfect correlation, and thus wider allowances are expected for PM mass. Differences in the correlation are not necessarily issues with the PM PEMS measurement capability, but issues with correlating with the reference systems definition of PM mass. These PM PEMS can provide new and sometimes more useful information about PM and its impact for health affects and its influence on atmospheric chemistry. It is understood that the point behind this program is to consider the PM PEMS as in-use surrogates for laboratory testing. It is thus important to consider the differences for the PM PEMS to the mobile reference system.

The following linear correlation analysis are performed as if the PEMS and the reference system are measuring the same species and any difference is an error in the PEMS system. It is recognized that the reference system has a measurement uncertainty. The reference system uncertainty was not evaluated with this program, but will be evaluated with the full MA study. The analysis presented considers the differences between the PEMS and the MEL over three vehicles, where regeneration, bypass, particle composition, particle size distribution and particle number varied and are evaluated.

In evaluating the data, it is important to note that the manufacturer for PEMS2 has increased the sensitivity of the quartz frequency to PM mass relationship. It is important to consider this change in light of the current test program so it is mentioned here, but the data is not corrected unless noted otherwise. This new relationship increases the PEMS2 PM mass output by a factor of 1.25 for all serial numbers of PEMS2 tested. PEMS2 response would be 1.25 times higher if this correction was applied. Some discussion for each vehicle will be considered as a result of this change to the PEMS2 system, but the main analysis is without the 1.25 factor.

PEMS3 manufacturer provided some additional analysis as part of their effort to better incorporate the soluble organic fractions (SOF) and sulfuric acid condensation (sulfate) PM to allow measurement of total PM with their instrument that measures predominantly soot. SOF is typically broken down into fuel derived SOF and lubrication oil SOF. It is expected that DPF-equipped engines will have 40% of the PM mass from lubrication oil SOF at bsPM levels of 0.001 g/hp-h. Their analysis essentially utilizes a correction factor based on measurements of soot, THC concentration, and sampling conditions (exhaust temperature, dilution, etc) 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 thermopheretic losses and sulfate contribution. Sulfate PM is assumed to be from condensing sulfuric acid. The sulfate model uses catalyst temperatures, fuel sulfur levels, fixed lubrication oil contributions, and known reaction kinetics for sulfuric acid conversion on a catalyzed surface. The reaction kinetics are a function of space velocity, catalytic surface temperature, catalyst material and loading. The notation for the total PEMS3 modeled results is tPEMS3 throughout the following analysis. An analysis of the PEMS3 total PM (tPEMS3) data is included for each of the three test engines. It should be noted that all the PEMS3 total PM data are based on the Manufacturers own processed data using a processor version from June 2008. It is expected that the results may change slightly as the manufacturer gains experience with the prediction model.

4.5.1 Caterpillar

The Caterpillar data analysis covers two groups of data where all the data is considered first and then a reduced set of data focused closer to the in-use standard of 0.03 g/hp-h. PEMS1 and 2 data is considered suspect due to operational issues and variability in operating parameters. As such, an additional analysis of PEMS1 data focusing on the last day of testing is provided to show improvements for PEMS1 during the five days of testing. A brief discussion of the PEMS2 data in light of the changes of operating parameters is also added to this section to understand the impact this had on their results and future results from PEMS2. Additional analysis is also provided for PEMS3 that evaluates the PEMS3 augmented data to include the modeled SOF and sulfate PM masses.

All Data (0 – 0.11 g/hp-h)

Figure 4-7 shows the PEMS bsPM emissions correlation to the MEL bsPM for all valid data provided. PEMS3, 4, and 5 showed a relative good correlation with the reference, where the R^2 was greater than 0.75 for each of these PEMS. PEMS3 had the highest correlation with an R^2 of 0.95. PEMS4 and 5 correlated well but had slightly lower R^2 of 0.77 and 0.88, respectively. PEMS1 and 2 showed a poor correlation, with PEMS1 having the lowest R^2 at 0.01 and PEMS2 having an R^2 of 0.57. The low correlation coefficients suggest PEMS1 and 2 did not compare well to the reference.

The slopes for the PEMS in Figure 4-7 range from 1.5 to 0.9 (excluding PEMS1) suggesting some PEMS overestimate PM (PEMS2) and most underestimate the PM (PEMS3, 4, and 5) relative to the reference method. PEMS3-5 had similar slopes. PEMS5 had the slope closest to unity (0.97). The slopes for PEMS3 and PEMS4 were comparable at 0.91 and 0.090, respectively. As a reminder PEMS5 has been calibrated with the MEL and its near unity slope is a result of this calibration, as explained in the experimental section. It should be noted that the span value for PEMS5 is a factor of approximately 10. Thus, PEMS5 out of the box would show a much larger negative bias if the calibration factor was not applied. It is also important to point out that unit to unit differences for PEMS5 have been show to be off by factors of 20 suggesting the optical properties are not accurate in an absolute sense for back calculation to PM mass. They can be calibrated, however, to PM mass and provide a reliable or precise measure of PM mass as demonstrated.

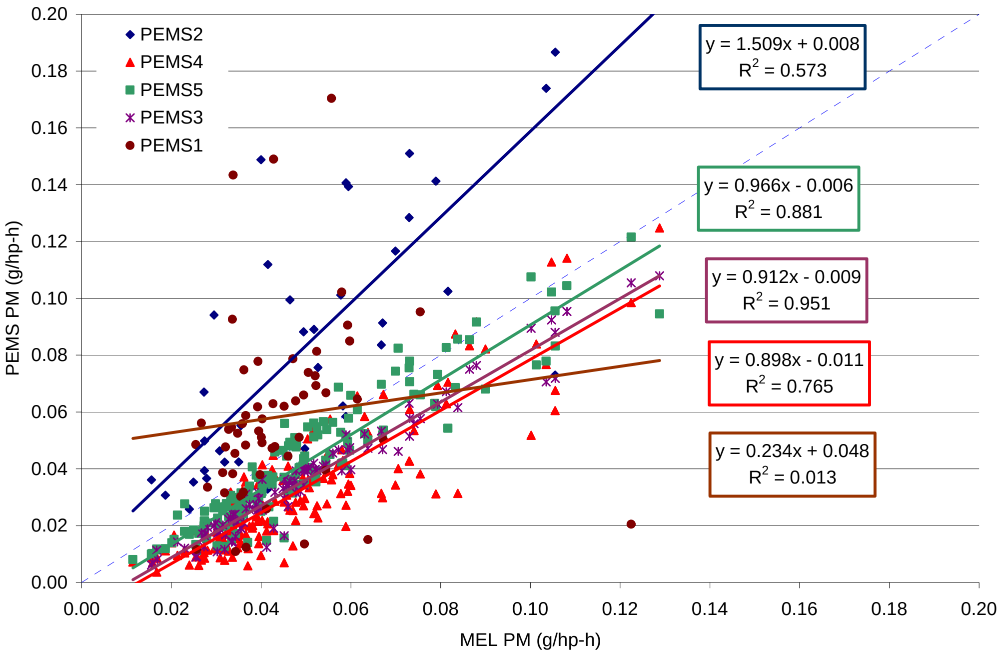


Figure 4-7. bsPM Correlation between the MEL and PEMS emissions level (Caterpillar)

Figure 4-8 shows the PEMS-MEL deltas which show absolute error differences as a function of bsPM level from the MEL. The slope shows the absolute error difference as a function of level and the intercept is a measure of the absolute bias. The net bias at 0.03 g/hp-h MEL level is calculated using the regression equation in Figure 4-8. PEMS2 showed an increase in error as bsPM level increased with a slope of 0.5 and a slight positive bias of 0.025 at the 0.03 g/hp-h level. PEMS3, 4, and 5 showed no trend of increasing bias as indicated by slopes near zero, but did show a small constant negative bias of around 0.01 g/hp-h, where PEMS5 had the smallest and PEMS4 had the largest negative bias.

In addition to the slope, bias and R^2, the SEE is useful for characterizing measurement variability. The SEE is a measure of the bsPM variability about the least squared regression lines shown in Figure 4-7 and Figure 4-8. A low SEE means there is low variability. PEMS3, 4, and 5 had the lowest SEEs, as shown in Table 4-3 and PEMS1 and 2 had the highest SEEs. The SEE for PEMS1 and 2 was around 0.03 g/hp-h where the SEE for PEMS3, 4, and 5 was around 0.01 g/hp-h. The low SEE for PEMS3, 4, and 5 suggest these PEMS have less variability where PEMS1 and 2 have more variability.

A two-tailed, paired t-test on the PEMS deltas (PEMS – MEL) provides information on the significance of the mean differences. The t-test data is listed in Table 4-4. The results suggest that all PEMS mean differences are statistically significant at greater than 99% confidence.

bsPM Range g/hp-h	Test Engine	PEMS1* g/hp-h	PEMS2_rev g/hp-h	PEMS3 g/hp-h	tPEMS3 g/hp-h	PEMS4 g/hp-h	PEMS5 g/hp-h
0.100	Caterpillar	0.0313	0.0278	0.0046	0.0069	0.0101	0.0071
0.050	Caterpillar	0.0291	0.0316	0.0047	0.0032	0.0079	0.0064

*PEMS1 last day SEE was 0.015 g/hp-h

Table 4-3 bsPM SEE results for all PEMS grouped by 0.1 and 0.05 g/hp-h levels (Caterpillar)

bsPM Range g/hp-h	Test Engine	PEMS1*	PEMS2_rev	PEMS3	tPEMS3	PEMS4	PEMS5
0.100	Caterpillar	2.0E-07	6.6E-07	2.1E-43	8.7E-20	5.0E-70	6.2E-69
0.050	Caterpillar	1.4E-05	4.4E-04	4.2E-42	8.4E-14	8.4E-62	2.2E-61

* PEMS1 last day t-test was 5.4E-04

Table 4-4 T-test statistics between MEL bsPM level and (PEMS – MEL) bsPM deltas (Caterpillar)

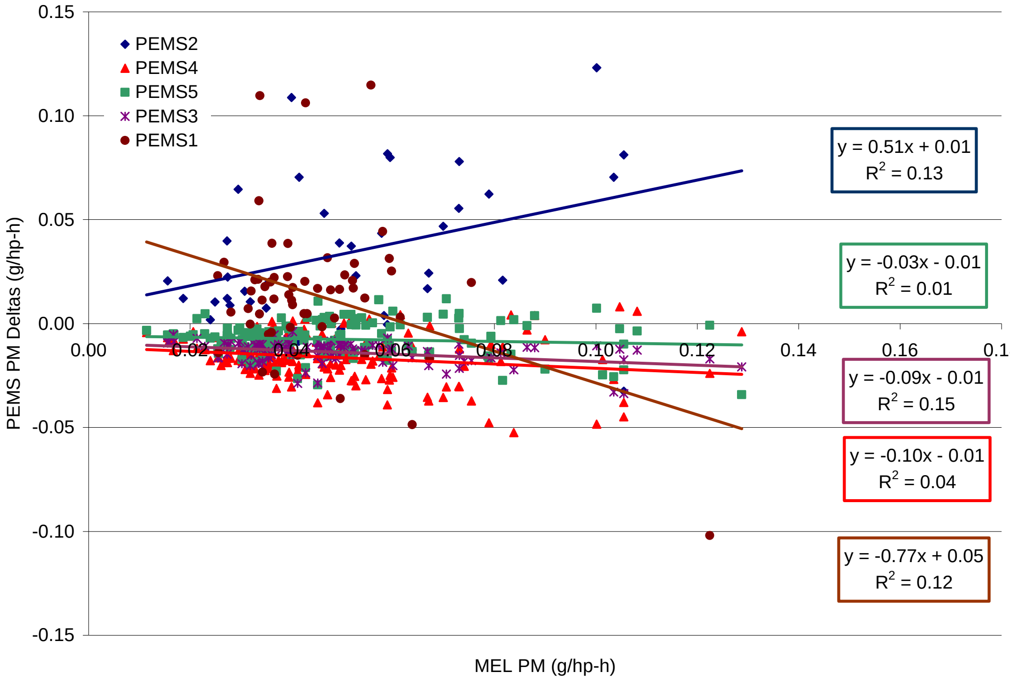


Figure 4-8. bsPM Deltas as a function of the MEL bsPM emission level (Caterpillar)

Reduced Data (0 – 0.05 g/hp-h)

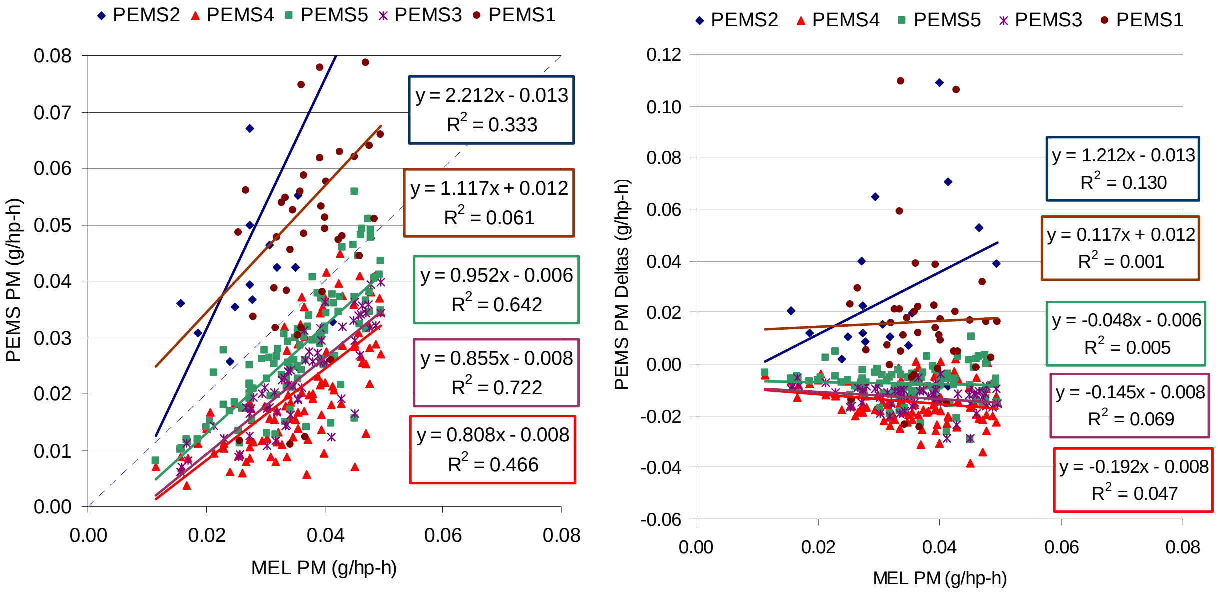
Figure 4-9 (a) and (b) show the same correlation and delta information as in Figure 4-7 and Figure 4-8, but for a reduced set of data with the bsPM less than 0.05 g/hp-h. The reduced data set has a bsPM average of 0.035 g/hp-h and 5th 50th and 95th percentiles of 0.019, 0.035, 0.048 g/hp-h, respectively. The distribution of data is slightly skewed to the right (i.e., higher bsPM levels). The 5th, 50th, and 95th percentiles show that the reduced data represents bsPM levels just above and just below the in-use PM standard and is centered slightly higher than the in-use standard, which should represent the fairest evaluation of the PEMS ability to measure at the in-use NTE standard.

PEMS1 showed a similar poor correlation with an R^2 of less than 0.1 and the PEMS2 correlation was worse (R^2 dropped from 0.54 to 0.3) compared to the full data set. The PEMS2 slope slightly increased and the PEMS1 slope changed from negative to positive. The PEMS2, 3, 4, and 5 correlations were lower for the reduced data set compared to the full data set, as indicated by the lower R^2, with PEMS3 showing the best correlation ($R^2 = 0.72$). PEMS3, 4, and 5 had a slope similar to the full data set to within about 10% and there was no significant change in their zero intercepts. The SEEs listed in Table 4-4 were slightly lower for all PEMS suggesting the variability about the regression line was slightly less at the lower bsPM range considered.

Figure 4-9 (b) shows the error deltas between the PEMS and the MEL at the lower PM emission levels. PEMS1 this time shows a positive bias with level, where the trend for the full data set was decreasing with increasing bsPM level. PEMS2 still shows a large positive bias that increases with increasing bsPM level. At 0.03 g/hp-h MEL level the bsPM bias for PEMS1 and 2 are 0.015

and 0.023 g/hp-h using the linear regression equation in Figure 4-9 (b).The PEMS3, 4, and 5 bias's are similar to those presented for the full data set at around -0.01 g/hp-h where PEMS5 was the smallest negative bias and PEMS4 the largest negative bias.

The two-tailed, paired t-tests suggest that the mean differences between the PEMS and the MEL are statistically significant for the reduced data at greater than 99% confidence, see Table 4-4.



(a) (b)

Figure 4-9 bsPM correlation (a) and bsPM deltas (b) for bsPM less than 0.05 g/hp-h (Caterpillar)

PEMS1 All vs Last Day

The PEMS1 manufacturer had difficulty performing the in-use testing and offered their data as preliminary and not representing their final product. The manufacturer provided all available data even though they were experiencing difficulty with their system, as will be described in Section 6.1. Figure 4-7 through Figure 4-9 represented all provided data, with each data point representing a single NTE event. In looking at these figures, the correlation between PEMS1 and the MEL was poor. 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 indicating that the discrepancies were not related to the work term. Discussions with the PEMS1 instrument manufacturer indicated that the instrument was not operating optimally during the initial days of testing, but was improving day-by-day. To evaluate the instrument performance for the best day of performance for PEMS1, an additional correlation was made utilizing only the results from the final day of testing. These results are shown in Figure 4-10. The results show an improved correlation ($R^2 = 0.56$ from $R^2 = 0.1$), with a lower positive bias that is not varying with bsPM level. A paired t-test suggests the mean differences are statistically significant at greater than 99% confidence, as shown in Table 4-4 for the last day analysis.

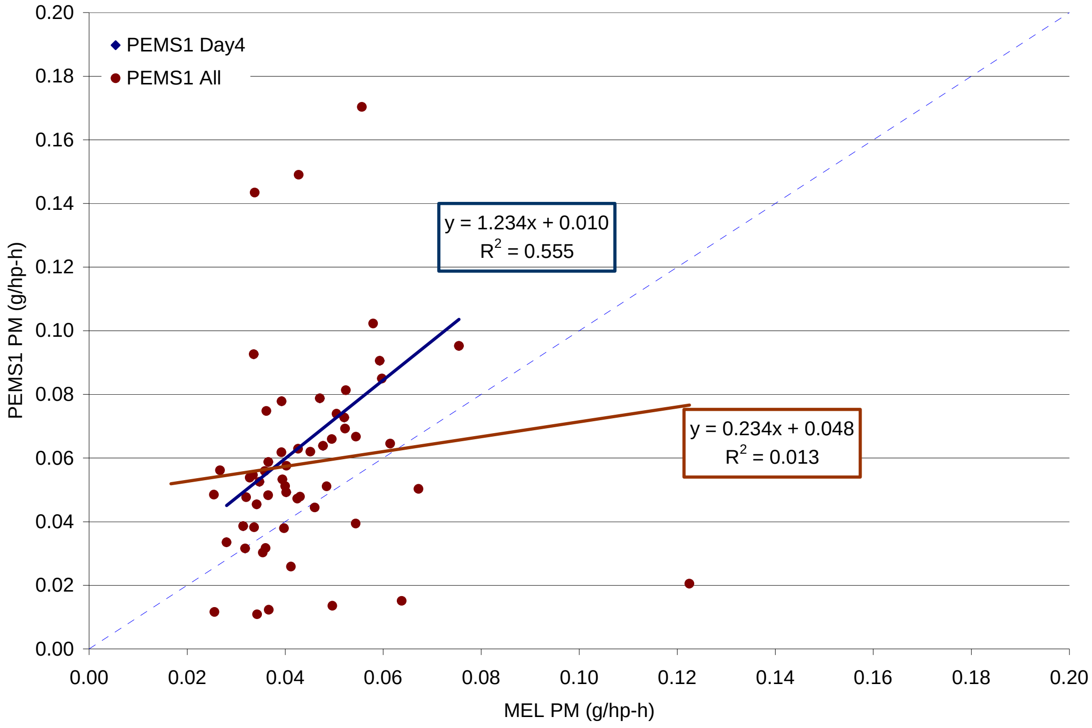


Figure 4-10. bsPM Correlation between the MEL and PEMS1 for all days and day 4 only (Caterpillar)

PEMS2: Discussion on Operation

PEMS2 correlation was low for the full data set (R^2 = 0.57) and was even lower for the reduced data set (R^2 = 0.3). The main cause for the consistently poor correlation, based on the manufacturers explanation, was a result of several operating parameter changes, such as sample flow rates, crystal loadings, crystal greasing methods, dilution ratios, and other changes being performed during testing. These issues are described in more detail in the Section 6.2. UCR staff was not able to evaluate the causes for poor correlation due to limited access to the raw data. Even though the data analysis shows a poor correlation as a result of all the parameter changes, it is important to point out that varying parameters for PEMS2 may cause significant changes in the bsPM emissions. The poor correlation resulting from parameter changes may also indicate how difficult some PEMS can be to operate or how easily their measurements can vary given changes in operating practices.

PEMS3: Total Modeled PM

The results utilizing the total PM data correction model are presented in Figure 4-11 in units of PM g/ kWhr (i.e., not in g/hp-h). The data correction was only calculated for the tests conducted with the PEMS2 system because PEMS1 did not measure some needed parameters. These results show a similar good correlation with the MEL gravimetric PM values (R^2 = 0.94), and essentially eliminated the slight negative bias seen in Figure 4-7 and Figure 4-8. It should be pointed out that the model worked well for this engine, which had a dominate fraction of the PM from EC and minor contributions from Sulfate and OC. Additional PM composition analysis, as discussed in Section 4.7, will show the effectiveness of this model for other PM compositions and size distributions.

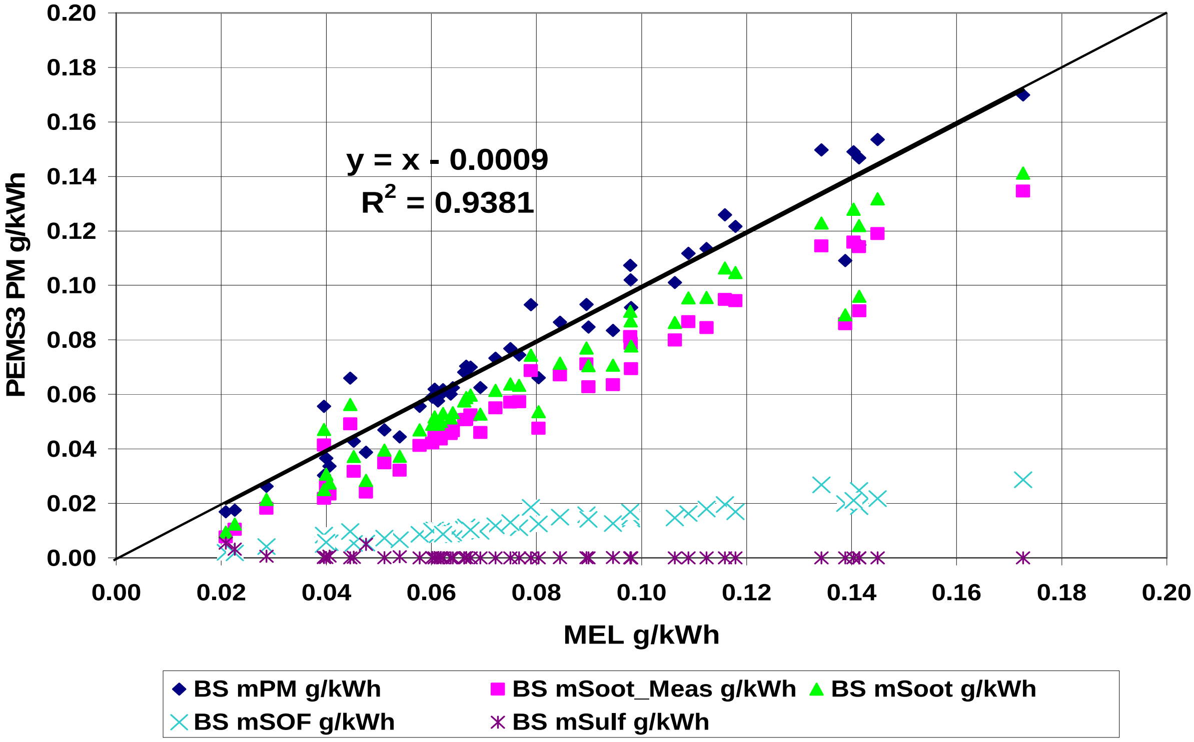


Figure 4-11. bsPM Correlation between the MEL and PEMS3 emissions level with total PM model (Caterpillar)

Caterpillar Summary

In general, PEMS1 and 2 did not correlate well with the MEL, while the PEMS3, 4, and 5 correlated well with the MEL and showed a negative bias. PEMS3 measures soot and it is expected to have a low mass reading as demonstrated. The PEMS3 augmented total PM data appears to improve the correlation and practically eliminates the negative bias. The PEMS correlation improved when only a subset of data for the best day of testing was considered, but it was still relatively poor. PEMS4 had a lower correlation and higher SEE than PEMS3 and 5. This suggests PEMS4 measurement principle is more variable than PEMS3 and 5. One reason for the larger variability could be due to the sensitivity in particle size measurement and density calculations by PEMS4. Once calibrated, however, it appears engine out size distributions are consistent enough that the optical light scattering properties are not significantly impacted. PEMS5 showed a similar R^2 as PEMS3 and a smaller negative bias. The good correlation for PEMS5 can largely be attributed to the fact that PEMS5 is calibrated based on 2005 gravimetric filter mass from diesel exhaust. For engines equipped with properly functioning DPF's however, PEMS5 provides essentially no measured signal, as will be shown in the next two sections.

4.5.2 Cummins

This subsection covers the data collected during the Cummins testing. The Cummins engine bsPM range was lowest for all engines tested and showed a skewed to low bsPM distribution, as described in Section 4.3.3. Since the bsPM never exceeded 0.01 g/hp-h, there was no need to categorize the data based on emissions level.

All PEMS were operated without manufacturer involvement. As a result, PEMS2 data required different levels of post processing. The PEMS2 post processor was not complete at the time of testing and the post processed data required additional review, thus analyses are presented for both the data obtained from the post processor and the data that had undergone this additional review. PEMS1 was not tested for this engine. The other PEMS were all sampled using good engineering practices and following manufacturer recommended procedures and calculation methods, as described in Section 3.4. The PEMS3 total PM analysis is added to this section to evaluate the PEMS3 augmented data for SOF and sulfate.

Because filter weights were significantly lower for both the Cummins and Volvo testing compared to the Caterpillar testing, a filter weight uncertainty was added to the figures for the next two sections (denoted by the faint red dotted line). The filter weight uncertainty, on the right y-axis, is defined as (3*2.5µg/net filter weight), where 2.5 µg is the typical uncertainty for replicate weights of a filter. Thus, for a filter weight of 7.5 µg, the relative 100% filter weight uncertainty will be 100%. As discussed above, the uncertainty can be attributed to a number of possible factors that can either increase or decrease the filter mass. Thus, the ± uncertainty may not actually be distributed evenly to the plus or minus side. A complete discussion of the reference uncertainty is provided in Section 4.4.

All Data (0 – 0.01 g/hp-h)

Figure 4-12 shows the bsPM correlation between the PEMS and the MEL for the Cummins engine. PEMS2, 3, and 5 showed a poor correlation with an R^2 of 0.1, 0.5, and 0.4, respectively. PEMS4 showed a high correlation with an R^2 of 0.8. Even though some PEMS showed a good correlation, all of the PEMS had slopes around 0.1 or less suggesting the PEMS tested were not able to measure the PM mass measured by the reference system. An analysis of PM composition and size distributions, as discussed in Section 4.7, suggests that most of the PM mass was sulfate and centered around 30 nm. Additional real-time comparisons provide a better understanding for the differences between PEMS3, 4, and 5 in Section 4.9.

During the Caterpillar testing, PEMS2 had operational issues that the manufacturer suggested could be the result of varying the system parameters. During the Cummins testing, PEMS2 operating conditions and setup parameters were set based on the best engineering judgment provided by the manufacturer, and thus the PEMS2 data in Figure 4-12 represents best available technology and operational practices at the time of testing. The poor correlation (R^2 = 0.1), low slope (0.1), and highest positive zero intercept (0.001 g/hp-h) suggest the PEMS2 correlation with the reference system was poor even with the system parameters held constant for this PM composition and size distribution.

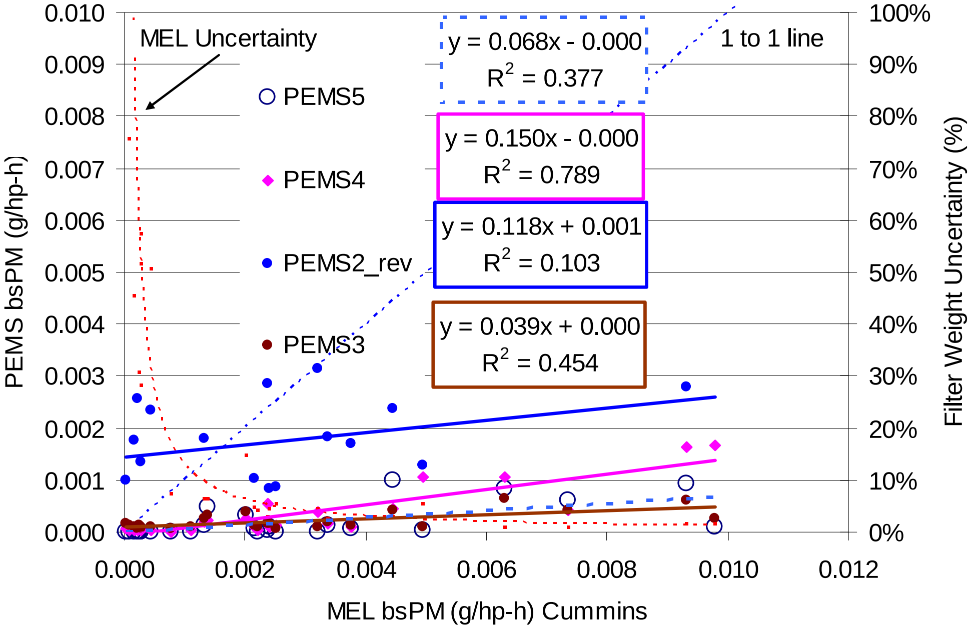


Figure 4-12. bsPM Correlation between the MEL and PEMS (Cummins)

Figure 4-13 shows the comparison between the MEL and PEMS absolute error deltas as a function of MEL level with the filter weight uncertainty on the right y-axis. Since Figure 4-13 shows the differences in absolute terms, one can show absolute uncertainty boundaries to illustrate the biases. Figure 4-13 shows dashed lines which represent positive and negative bsPM emission biases of +100% and -100%. For example, if the PEMS-MEL delta is - 0.001 g/hp-h at a bsPM of 0.001g/hp-h then the error is on the - 100% bias line (i.e., there is a negative 100% bias). All of the PEMS bsPM results follow the negative (-100%) bias line. PEMS3, 4, and 5 are closest to the -100% line. PEMS2 was furthest away from the line with a constant offset. The constant PEMS2 offset appears to be present even at the 0 g/hp-h emission level measured by the reference, see the circled data on the y-axis. The bias at the zero reference level suggests PEMS2 has a zero noise level that may be inherent in their measurement system. If the PEMS2 offset were removed all the PEMS2 data would be close to the -100% error line for this engine.

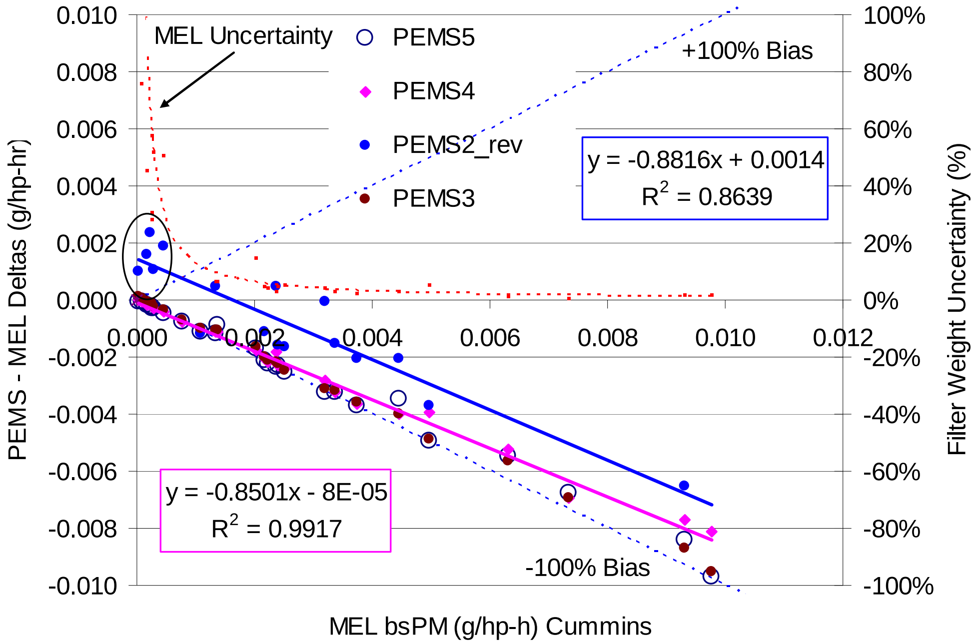


Figure 4-13. bsPM Deltas as a function of the MEL bsPM emission level (Cummins)

All the PEMS showed less variability on an absolute level compared to the Caterpillar data, as seen by the low SEEs listed in Table 4-5. The lower SEE was probably due to the lower mean bsPM and low PM responses for all the PEMS. PEMS2 showed the highest variability with an SEE of 0.0008 g/hp-h, while PEMS3, 4, and 5 had an SEE of ~ 0.0002 g/hp-h.

Although the SEE's were low on an absolute scale, they were large relative to the mean bsPM levels measured from the Cummins engine. A two tailed, paired t-test suggests the mean measurement differences between the PEMS and the MEL are statistically significant at greater than a 99% confidence level for PEMS3, 4, and 5, but not for PEMS2. The PEMS2 p-value was 0.57 which suggests mean difference between PEMS2 and the MEL was not statistically significant. The lack of statistical significance for PEMS2 is largely due to the variability in PEMS2 measurements as indicated by the relatively large SEE. The PEMS2 variability thus precludes the identification of positive and/or negative mean biases for the Cummins tests, although the data has the appearance of a negative bias that increases with bsPM level, as seen in Figure 4-13.

bsPM Range g/hp-h	Test Engine	PEMS1 g/hp-h	PEMS2_rev g/hp-h	PEMS3 g/hp-h	tPEMS3 g/hp-h	PEMS4 g/hp-h	PEMS5 g/hp-h
0.010	Cummins	n/a	0.0008	0.0001	0.0012	0.0002	0.0002

Table 4-5 bsPM SEE results for all PEMS g/hp-h levels (Cummins)

bsPM Range g/hp-h	Test Engine	PEMS1	PEMS2_rev	PEMS3	tPEMS3	PEMS4	PEMS5
0.010	Cummins	n/a	5.7E-01	4.0E-05	1.2E-03	2.5E-05	3.1E-05

Table 4-6 T-test statistics between MEL bsPM level and (PEMS – MEL) bsPM deltas (Cummins)

Even thought the PEMS2 mean measurement differences between the MEL and the PEMS is not statistically different, the results show that PEMS2 measurement is significantly underestimating the PM from the Cummins engine similarly to the other PEMS tested. It looks like from Figure 4-12 that PEMS2 measurement at 0 g/hp-h is similar to 0.01 g/hp-h which is probably why the t-test showed a high p-value. The fact that tthere appears to be an difficulty for PEMS2 ability to measure the PM can be see from Figure 4-12 and Figure 4-13. The PEMS2 measurement was consistently lower than the MEL by a factor of about 3 with the offset in the data and ~8 if the offset is removed.

PEMS2 Reviewed Data Evaluation

The PEMS2 post processor was still being developed at the time of this testing and was not locked down until requested by the MA HDIUT committee in April of 2009. All of the data presented in this report is based on the version of the post processor available on April 2008 (ver 2.104). Because PEMS2 is batch operated and the PM mass depends on pre- and post-crystal conditions, the PEMS2 mass can vary greatly depending on the post processor design. Figure 4-14 shows a comparison between PEMS2 and the MEL for different levels of processed data. PEMS2_valid is data processed by the PEMS post processor without UCR engineering review. PESM2_rev is the data reviewed by UCR based on verifying each real-time integration signal for consistency and reasonableness. Some data was discarded if the integration was carried out when there was not data in the filtered file and instead data was arbitrarily grabbed from a different time in the sample period. This phenomena is hard to understand, but will be discussed further in Section 6.2. The PEMS2_all is the data processed with the filters turned off and PEMS2_rev2 is data corrected for the manufacturer's announcement on December 2008 that the crystal sensitivity was off by a multiplier of 1.25. UCR did not get an explanation of this factor and thus can not explain it for this report. The PEMS2_all data is the worst case scenario where no filtering by the manufacturer is performed.

It is interesting that the PEMS2_valid data had the lowest R^2, which was lower than the unfiltered PEMS2_all data. PEMS2_valid also has a negative slope where PEMS2_rev has a positive slope. Another interesting point is the data indicated by the circled area in Figure 4-14 shows an example where a filtered result (0.006 g/hp-h) was twice as high as the unfiltered result (0.003 g/hp-h). The real-time data on this bsPM event showed the PEMS2_rev data was discarded because the post processor used data from some other time segment that did not relate to this event. These data suggest that the post processing and data filtering by PEMS2 can have a significant affect on the final bsPM emission results and that these elements should be thoroughly characterized to prevent significant outliers that can cause large measurement uncertainties.

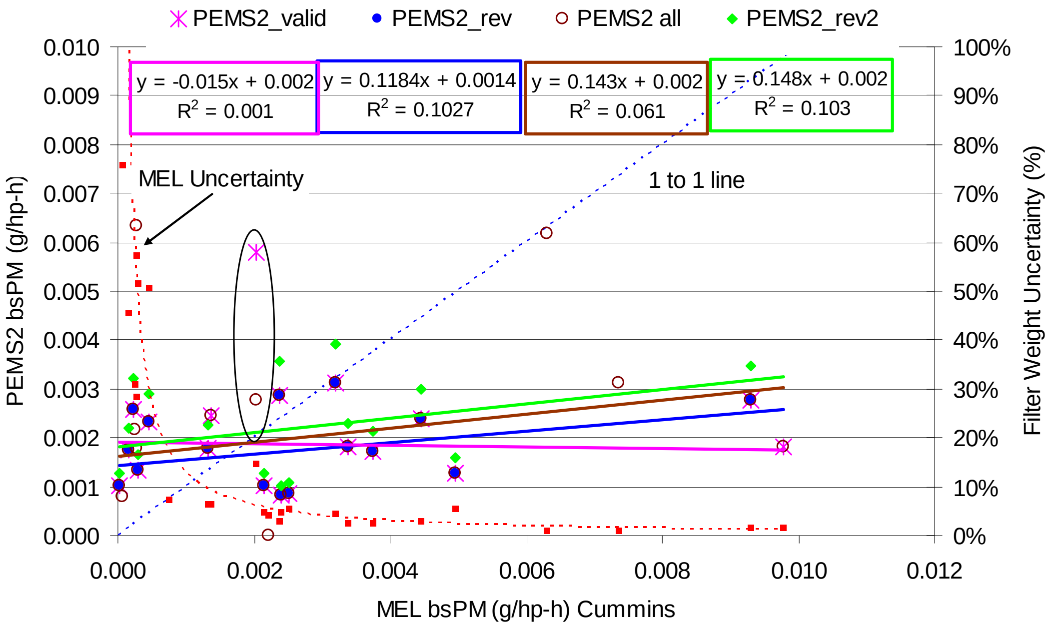


Figure 4-14. bs PM Correlation between the MEL and PEMS2 post processed options (Cummins)

PEMS3: Total Modeled PM

The PEMS3 bsPM emissions for the total PM results (tPEMS3) and the measured bsPM results (PEMS3) are shown in Figure 4-15. The tPEMS3 show an improvement from the direct measurement results. The slope is considerably improved compared to the direct measurements, although there is still a negative bias. The correlation R^2 is still relatively poor for the tPEMS3 and is similar to that for the measured values. Analysis of the PM composition and size distribution, covered in Section 4.7, suggests most of the PM mass is from sulfate, some from OC, and trace amounts from EC. The dominate sulfate PM mass suggests the model is not predicting the sulfate properly as seen by the large over predicting OC at the low PM level. Others suggest that sulfuric acid formation from gas phase to particle phase is not know and highly unpredictable and requires good knowledge of exhaust dilution on a real-time basis.

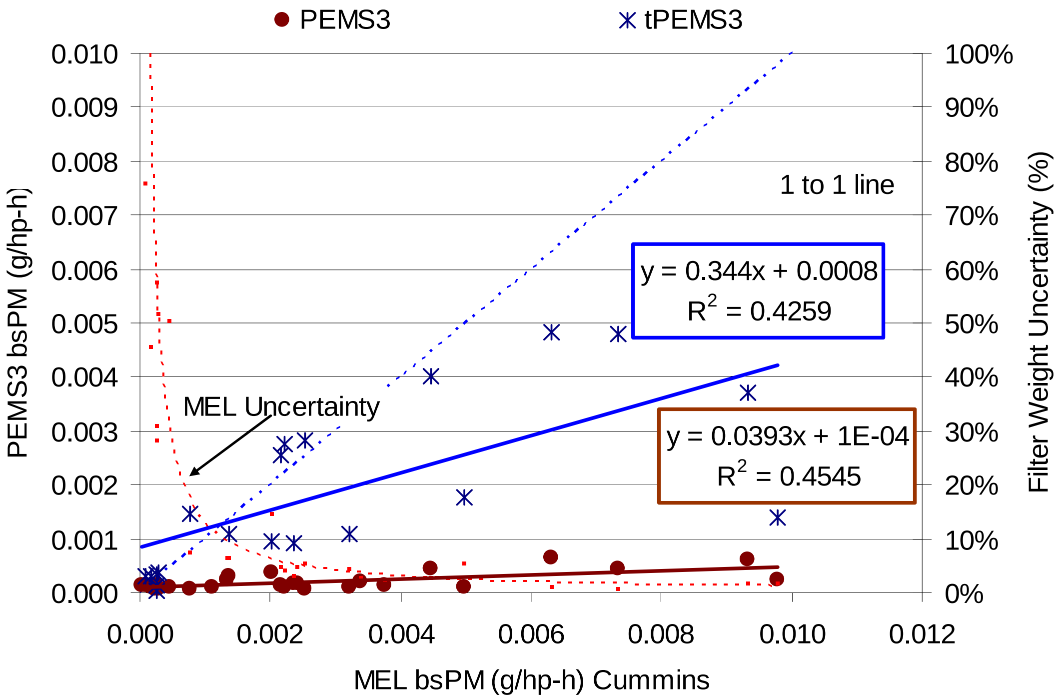


Figure 4-15. bsPM Correlation between the MEL and PEMS3 emissions level with total PM model (Cummins)

In general, all PEMS for the Cummins testing showed a significant negative bias in bsPM emissions. The negative bias increased with increasing bsPM level. The negative bias suggests all the PM PEMS measurements underestimate PM mass at magnitudes close to the levels being measured. The composition of the Cummins samples were mostly sulfate with some OC and trace amounts of EC. Given the high sulfate mass fractions and consistently low PEMS response, additional studies of the response of these PEMS to particles that are predominantly sulfate could be of interest. PEMS4 showed the best overall correlation to the reference system for the Cummins test comparison. The PEMS2 PM measurements were generally lower than those of the MEL, although these differences were not statistically significant due to the low measurement levels and the large associated variability.

4.5.3 Volvo

This sub section covers the data collected during the Volvo testing. The analysis covers two groups of data, where all the data is considered first, then a reduced set of data focused closer to the Cummins maximum level of 0.01 g/hp-h is analyzed. The PEMS2 post processor was not complete at the time of testing and yielded data that required additional review, thus an additional analysis of the PEMS2 post processor is added to this section. Again the PEMS2 post processor was based on Ver 2.104. PEMS1 was not tested for this engine. The PEMS3 total PM analysis is included in this section to evaluate the PEMS3 augmented data for SOF and sulfate.

In general, the bsPM level was higher for the Volvo testing compared to the Cummins, but less than the Caterpillar tests. The higher bsPM level appears to be a result of the combination of using both regeneration and bypass strategies. The distribution of bsPM is skewed to lower bsPM emissions similar to the Cummins results, as shown in Section 4.3.3. The Volvo 50th percentile was around 0.003g/hp-h with some outliers at 0.04 g/hp-h bsPM, while the 95th percentile was at 0.02 g/hp-h. The skewed distribution of results has the effect of weighting the higher bsPM points more. In order to further evaluate the Volvo data and draw comparisons to the Cummins data, it was important to consider a reduced grouping of data that more closely matched the emission levels for the Cummins engine. The reduced data was filtered to less than 0.011 g/hp-h and represents a distribution similar to the bsPM Cummins values. The reduced data group represents 38 data points out of the total of 45 sampled.

All Data (0 – 0.04 g/hp-h)

The Volvo bsPM linear correlation between the PEMS and the MEL is presented in Figure 4-16. The R^2 ranges from a good correlation (0.9, 0.8 for PEMS2 and 4, respectively) to a fairly poor correlation (0.4 and 0.5 for PEMS5 and 3, respectively). The slopes also vary significantly between the PEMS, with PEMS2 showing the largest slope and PEMS5 was the lowest. The slopes for PEMS2 and 4, which had the better correlation, were 0.84 and 0.47, respectively. The slopes for PEMS3 and 5 were 0.3 and 0.1, respectively. The high R^2 for PEMS2 and relatively high slope for PEMS2 suggests this PEMS showed the best correlation, but still underestimated the bsPM by about 15%. The high R^2 for PEMS4 and lower slope suggest this PEMS consistently underestimated the bsPM emissions by 50%. The other PEMS showed poor correlations and lower slopes that suggest PEMS3 and 5 underestimate bsPM more than PEMS2 and 4 for the Volvo tests.

The data variability was lowest for PEMS3 and highest for PEMS2, 4, and 5, as listed by the SEE in Table 4-7. The SEE for PEMS3 was 0.0007 g/hp-h and PEMS2, 4, and 5 were between 0.0028 to 0.002 g/hp-h at the 0.04 g/hp-h range. The reason the variability for PEMS3 was lowest was the lower absolute response/emission levels for PEMS3 compared to the other PEMS, as indicated by the low slope of 0.1. PEMS2 slope was 8 times higher than PEMS3, but only 4 times the variability.

PEMS3 and 5 had the lowest R^2 at 0.5 and 0.4, respectively, and low slopes of 0.1 and 0.4, respectively. The low R^2 and slope of 0.1 for PEMS3 suggests PEMS3 measured less than 10% of the PM mass. The SEE for PEMS3 at 0.0007 g/hp-h was the lowest of all the PEMS. PEMS3 measures only the soot portion of the PM and during the Volvo testing a high fraction or the PM was organic carbon, as will be discussed later. Thus, the lower PM measurements for PEMS are consistent with measurements of PM with a fairly low contribution from EC. PEMS5 showed a better slope, but worse R^2 than PEMS3, with an SEE similar to PEMS2 and 4. This suggests PEMS5 does not has strong a responses to the PM from this source and is more variable, which could be a result of size and/or composition.

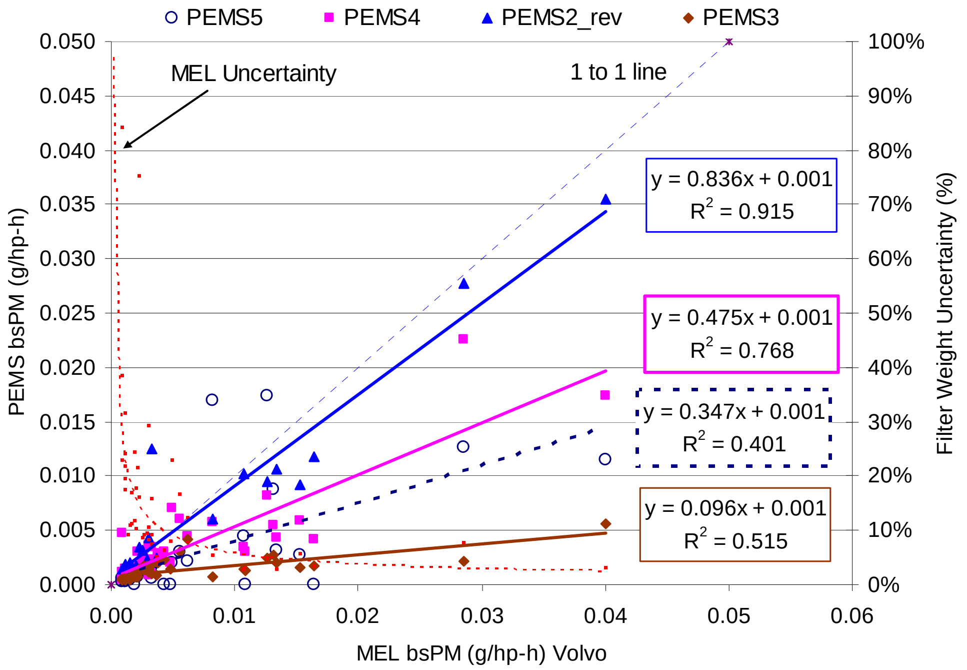


Figure 4-16. bs PM Correlation between the MEL and PEMS (Volvo)

Figure 4-17 shows the comparison between the MEL and PEMS error deltas as a function of MEL level with the negative and positive lines representing +100% and -100%, respectively, as explained earlier. Fewer points are following the negative one-to-one line compared to the Cummins tests. The higher PEMS response could be due to the addition of a bypass compared to only using regenerations during the Cummins testing. Another difference discovered between the Volvo and Cummins testing was the PM composition for the Volvo testing was dominated by organic carbon where the Cummins was dominated by sulfate mass.

There were also some PEMS2, 4, and 5 points that exceed the positive one-to-one line as shown by the circled data in the figure. This is significant because it shows that PM instruments can report some erroneous values that could be two times to an order of magnitude greater that that being measured by the reference method. It is unknown what caused these high values for PEMS2 and PEMS5. Real-time analysis showed some trends during such events for PEMS3, 4, and 5 that could help explain this behavior, as provided in Section 4.9.

For the most part all the PEMS show a similar negative bias that increases (i.e., becomes more negative) with increasing MEL bsPM level. This same trend was found for the Cummins testing, suggesting the trend of the PEMS underestimating the reference method bsPM is consistent regardless of regenerations, bypass, and trap equipped PM composition and/or size. A two tailed, paired t-tests for all the PEMS suggest the differences in the paired data are statistically significant at a greater than 99% confidence level, as shown in Table 4-8. Only PEMS2_rev had a poor p-value of 0.5 where the t-test suggests the paired data for this data set was not different at a statistically significant level. This lack of statistical significance can primarily be attributed to a large amount of variability rather than a similarity between the PEMS2_rev and the MEL data.

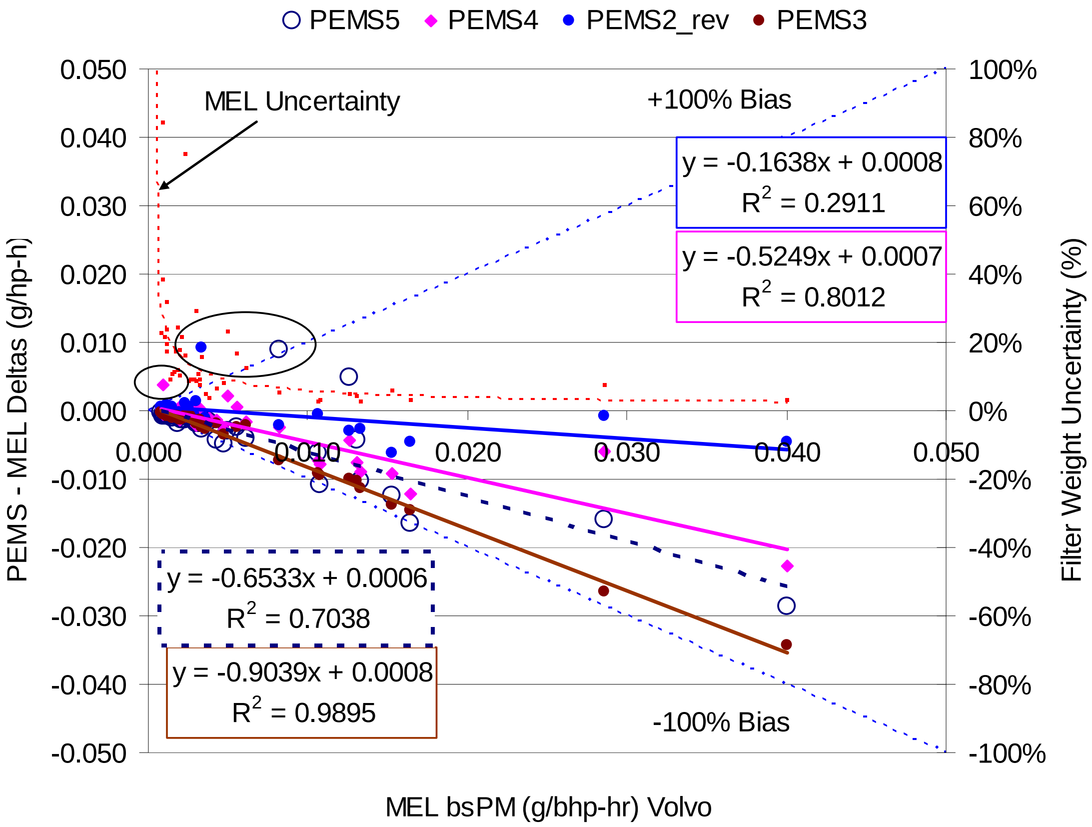


Figure 4-17 bsPM Deltas as a function of the MEL bsPM emission level (Volvo)

bsPM Range g/hp-h	Test Engine	PEMS1 g/hp-h	PEMS2_rev g/hp-h	PEMS3 g/hp-h	tPEMS3 g/hp-h	PEMS4 g/hp-h	PEMS5 g/hp-h
0.040	Volvo	n/a	0.0028	0.0007	0.0022	0.0020	0.0033
0.011	Volvo	n/a	0.0028	0.0007	0.0009	0.0013	0.0024

Table 4-7 bsPM SEE results for all PEMS g/hp-h levels (Volvo)

bsPM Range g/hp-h	Test Engine	PEMS1	PEMS2_rev	PEMS3	tPEMS3	PEMS4	PEMS5
0.040	Volvo	n/a	5.1E-01	5.8E-05	7.6E-05	3.5E-05	3.4E-05
0.011	Volvo	n/a	8.2E-02	3.9E-07	3.2E-08	6.4E-07	4.7E-08

Table 4-8 T-test statistics between MEL bsPM level and (PEMS – MEL) bsPM deltas (Volvo)

Reduced Data (0 – 0.011 g/hp-h)

Figure 4-18 and Figure 4-19 show the correlation data for PEMS relative to the MEL and the PEMS-MEL deltas relative to the MEL level, respectively, for the reduced set. The range of bsPM is from 0 to 0.11 g/hp-h, which matches that for the Cummins engine. It is interesting to point out that all the PEMS show a significant improved response, with PEMS2, 3, 4, and 5 having slopes of 0.8, 0.2, 0.5, 0.8, respectively. The correlation R^2 dropped for all PEMS and was low at around 0.4. The SEE dropped slightly between the high and low groupings and was 0.003, 0.0007, 0.0009, 0.001 and 0.002 g/hp-h for PEMS 2, 3, 4, and 5, respectively. The lower SEE values are consistent with the lower absolute levels of the PM values. Overall, the PEMS response was much better for the reduced data set for Volvo, where the typical slopes were around 0.8 to 0.4, than for the Cummins tests, where the typical slopes for all PEMS was around 0.1.

The deltas in Figure 4-19 show a similar trend as with the full data set. As the reference bsPM level increases, the negative bias increases for all the PEMS. The same two outliers for PEMS2, 4, and 5 are more clearly shown giving the reader a feel for the magnitude of outliers possible for PEMS2, 4, and 5. The PEMS2_rev zero offset is also shown more clearly with the reduced data set, where below 0.002 g/hp-h most of PEMS2_rev response is greater than the reference, but at higher PM levels it is less than the reference. A two tailed, paired t-test suggests all the data is statistically different at greater than a 99% confidence level, except for PEMS2. PEMS2 p-value decreased from 0.5 for the full data set to 0.08 for the reduced data set, indicating the differences for the reduced data set for PEMS2 are statistically significant at greater than a 90% confidence level.

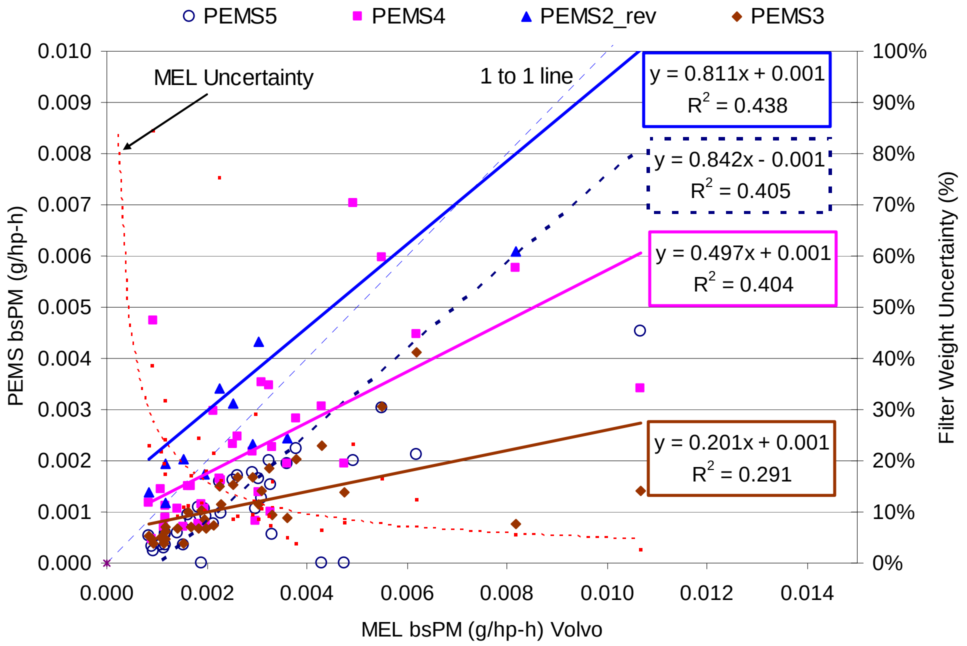


Figure 4-18. bsPM Correlation between the MEL and PEMS limited to 0.01 g/hp-h (Volvo)

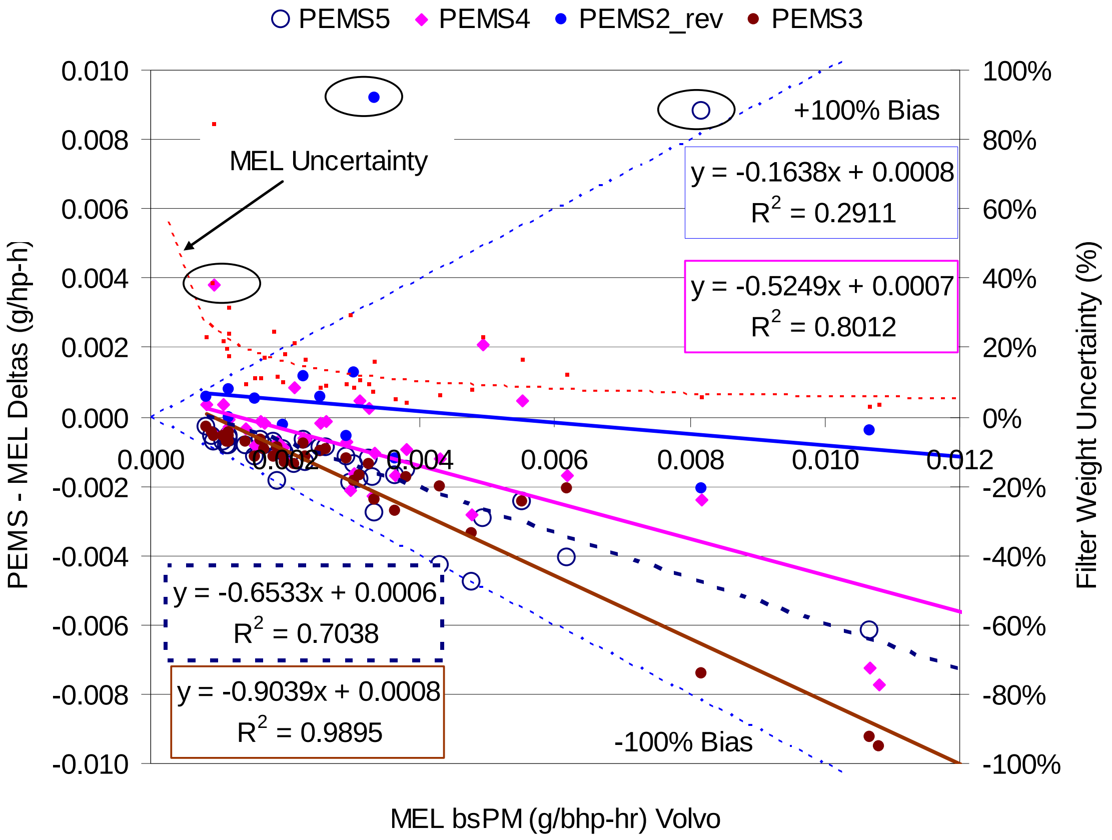


Figure 4-19 bsPM Deltas as a function of the MEL bsPM emission level limited to 0.01 g/hp-h (Volvo)

PEMS2 Reviewed Data Evaluation

Figure 4-20 shows the PEMS2 correlation data for different levels of processed data, as explained in the previous section. The unfiltered data was not processed for the Volvo testing and is not presented in the figure. The R^2 was 0.8 and 0.9 for PEMS2_valid and PEMS2_rev, respectively, which suggests the review process improved the correlation. This time the PEMS2_rev2 improved the slope from 0.84 to 1.04, changing the bias from negative to slightly positive. This is a important point, because PEMS2 now is the only PM PEMS that responds to a trap equipped PM mass at a level near or greater than the reference method. It is unclear though on a different vehicle engine combination if this trend would hold given the very low slope on the Cummins engine tests.

Another point regarding the reviewed data is the circle area shows the PEMS2_rev2 increased the outliers by the amount of the sensitivity change (1.25 times higher). The circled data on the x- axis was reported by the PEMS processor, but after investigation was eliminated from the PEMS_rev data set. The zero response point shows that some times the filtered data is positive and sometimes it is negative. Again reasons for the differences with the post processing are difficult to understand, but the point is post processing and filtering of this batched data can have a significant affect on the final results and needs to be thoroughly characterized to prevent significant outliers that could cause large measurement uncertainties.

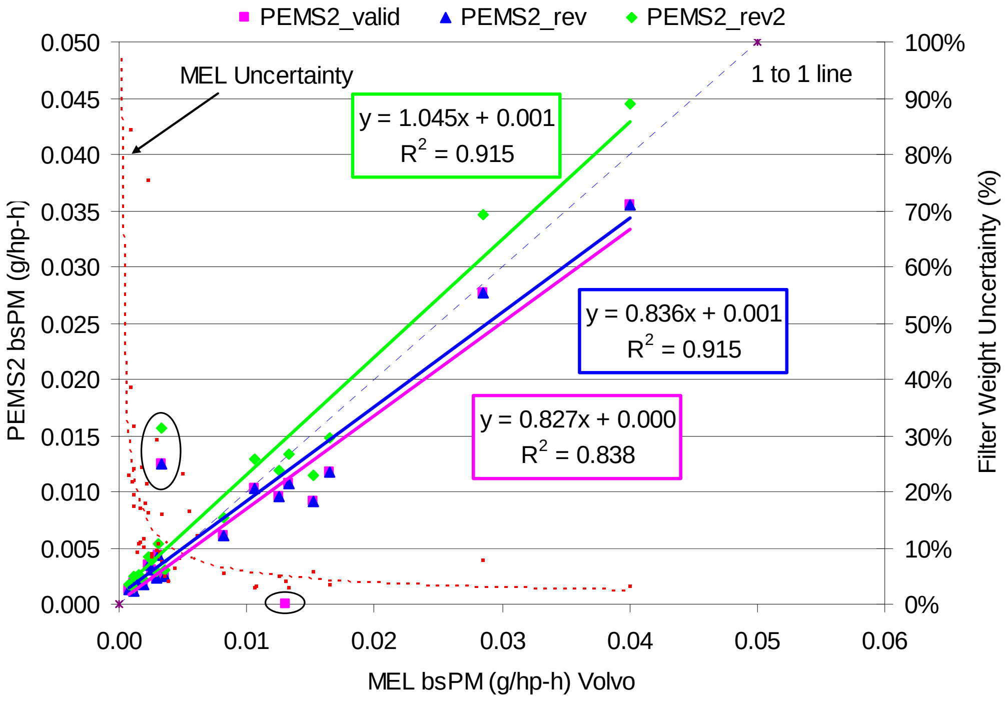


Figure 4-20 bs PM Correlation between the MEL and PEMS2 post processed options (Volvo)

PEMS3: Total Modeled PM

PEMS3 bsPM emissions for both the total PM modeled results (tPEMS3) and the measured bsPM emissions (PEMS3) are shown in Figure 4-21. Figure 4-21 shows the R^2 and slope improved from 0.52 to 0.82 and from 0.1 to 0.6, respectively, for the tPEMS3 response compared to the PEMS3 direct measurements. This suggests the model improves the results for this PM composition and size distribution. The total bsPM model over predicted some points near the lower levels, but for the most part was under predicting PM mass. Analysis of the PM composition and size distribution, as covered in Section 4.7, suggests the PM mass for the Volvo was mostly organic with very little sulfate.

The modeled total PM for PEMS3 provided better results for the Caterpillar and Volvo testing in comparison with the Cummins testing where the results were relatively poor. The fact that the model correlation was good for the Caterpillar and the Volvo, but not for the Cummins where the PM composition was mostly sulfate suggests the model works well for elemental and organic type PM, but not for sulfate dominated PM. This agrees with other results showing that sulfuric acid formation is very nonlinear and unpredictable and possibly dependent on more parameters not considered in these studies.

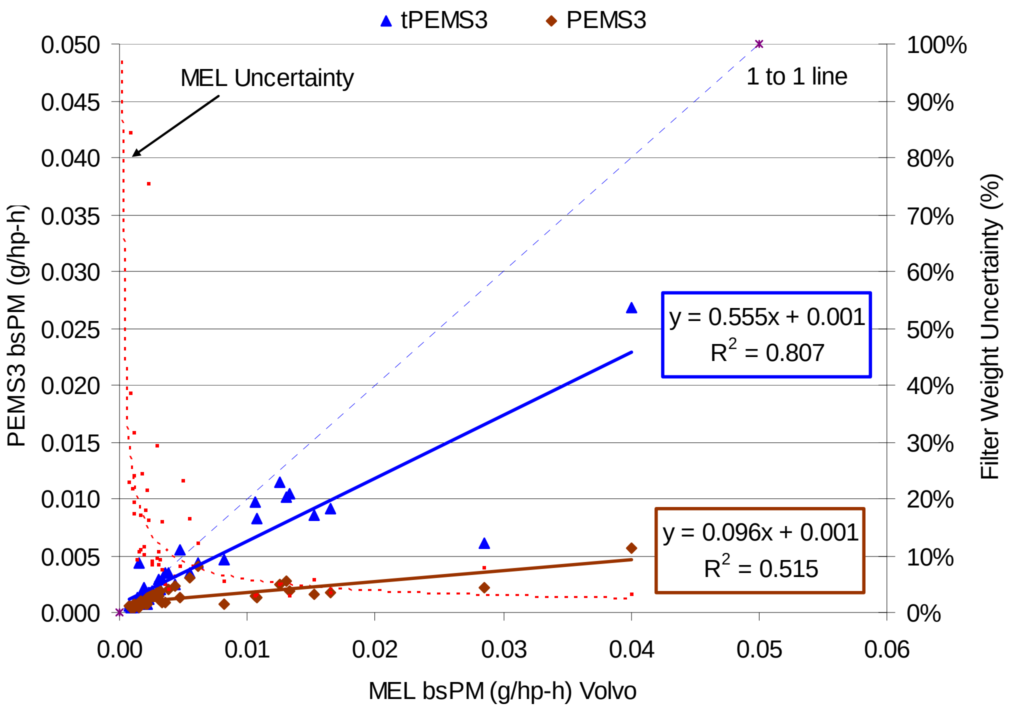


Figure 4-21 bsPM Correlation between the MEL and PEMS3 emissions level with total PM model (Volvo)

4.6 PM PEMS Combined Analysis

This section puts all the valid PM data on the same figures to look at trends across vehicles, PM level, and from all available instruments manufacturers. The data in the combined figures represents all the data supplied by each manufacture and/or the data reviewed by CE-CERT. Thus the data represents valid data, but not necessarily best-case data as discussed in Section 4.2. For PEMS1 and 2 a subset of data is provided to consider base-case data. Also the PEMS2 data is based on the original calibration and does not include the scaling factor of 1.25. Thus, PEMS2 results will be 1.25 times higher than presented in this analysis.

Figure 4-22 shows all the PEMS bsPM deltas on the y-axis and the MEL bsPM level on a log x-axis. The MEL uncertainty line is added to the right y-axis to show the same relative uncertainty in measurements as a function of the measured MEL level. The red lines represent, respectively, a positive 100% bias and a negative 100% bias. As you can see there is a lot of data spread from all instruments, with PEMS1 and 2 showing mostly a positive bias and PEMS3, 4, and 5 showing mostly a negative bias.

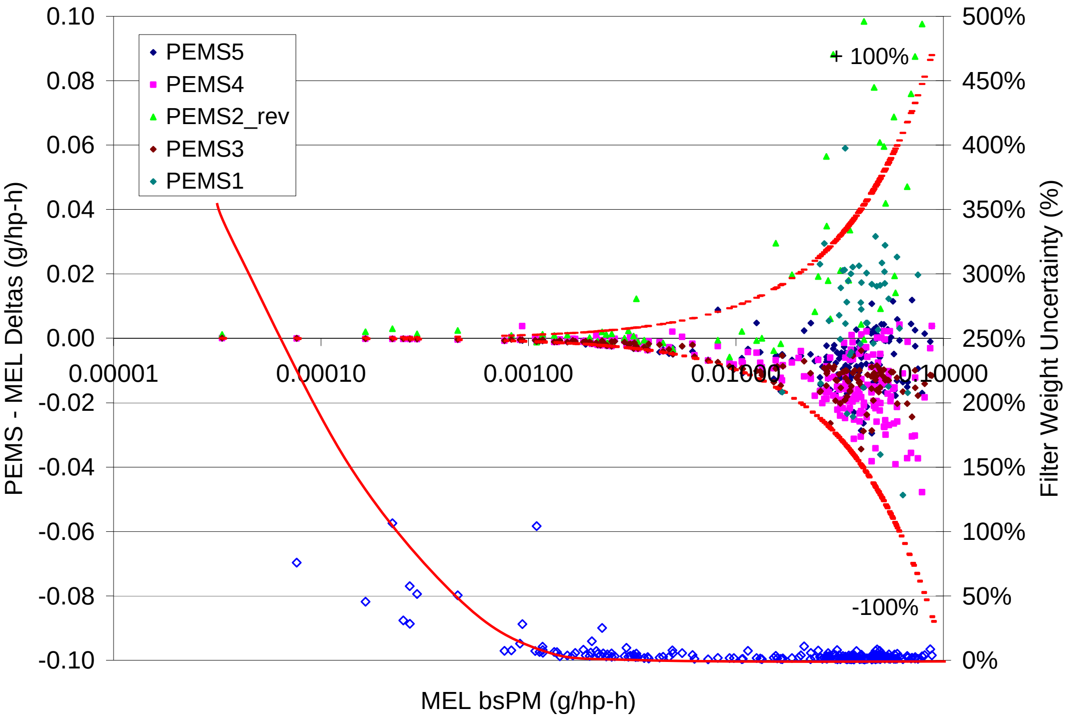


Figure 4-22 bsPM Deltas as a function of the MEL bsPM emission level (All Test Engines)

Table 4-9 shows the same SEE presented earlier, but combined for all PEMS, all engines tested and for the various emission groupings. The Caterpillar tests had the largest SEE and the Cummins and Volvo tests had the lowest SEE. This suggests the data spread is relative to the level being measured and the response to the different composition and size distribution of PM being measured.

bsPM Range g/hp-h	Test Engine	PEMS1 g/hp-h	PEMS2_rev g/hp-h	PEMS3 g/hp-h	tPEMS3 g/hp-h	PEMS4 g/hp-h	PEMS5 g/hp-h
0.100	Caterpillar	0.0313	0.0278	0.0046	0.0069	0.0101	0.0071
0.050	Caterpillar	0.0291	0.0316	0.0047	0.0032	0.0079	0.0064
0.010	Cummins	n/a	0.0008	0.0001	0.0012	0.0002	0.0002
0.040	Volvo	n/a	0.0028	0.0007	0.0022	0.0020	0.0033
0.011	Volvo	n/a	0.0028	0.0007	0.0009	0.0013	0.0024

Table 4-9 SEE for all PEMS categorized by bsPM level and test engine

Figure 4-23 (a) through (f) shows the prediction interval for a future observed response at the 90% confidence level based on each PEMS complete validated data. This data is based on an analysis of a population of data to predict a single future observation. Each figure is formatted to common scales to visually show the differences between PEMS responses. In addition to the PEMS valid data, two additional data subsets were added; PEMS1 on day 4 and PEMS2 for the DPF only vehicles. An additional figure was added to show PEMS3 modeled total PM value in Figure 4-23 (d). The green dot in each figure represents the average delta at the average MEL bsPM level for the range of data considered as a reference point.

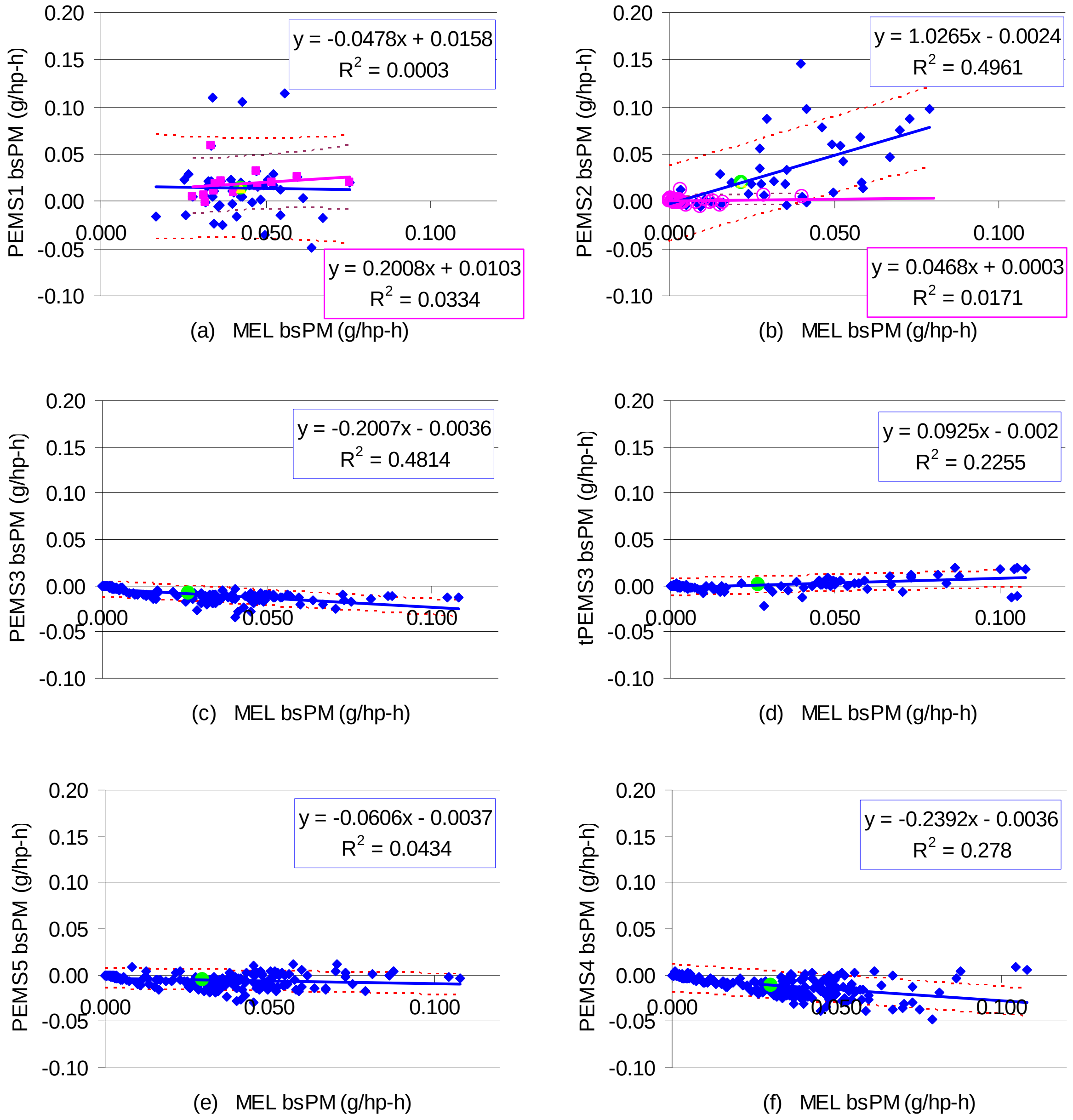


Figure 4-23 bsPM Deltas as a function of the MEL bsPM emission level less than 0.01 g/hp-h (All Test Engines)

Table 4-10 lists the 90% confidence interval values and bias at the 0.03 g/hp-h level. The 90% confidence interval is taken from the predictive model and the bias is calculated at the 0.03 g/hp-h MEL level using the equations from Figure 4-23 (a) through (f). Based on these values, the 95th and 5th percentile confidence limits are then calculated. The 5th and 95th percentile confidence limits thus represent the range of PEMS uncertainty at the MEL bsPM level of 0.03 g/hp-h.

	Values at the 0.03 g/hp-hr Level			
PEMS ID	90% Interval	Bias	95th	5th
n/a	g/hp-h	g/hp-h	g/hp-h	g/hp-h
PEMS1	0.053	0.014	0.068	-0.039
PEMS1 day4	0.029	0.016	0.045	-0.013
PEMS2	0.040	0.028	0.068	-0.011
PEMS2_DPF	0.006	0.002	0.007	-0.004
PEMS3	0.008	-0.010	-0.001	-0.018
tPEMS3	0.009	0.001	0.010	-0.008
PEMS4	0.015	-0.011	0.004	-0.026
PEMS5	0.011	-0.006	0.005	-0.016

Table 4-10 Predicted future value based on 90% confidence intervals and mean reference bsPM for all valid PEMS data

The figures and table show that PEMS1 and 2 have the widest confidence interval of 0.05 and 0.04 g/hp-h, respectively. PEMS3, 4, and 5 have the lowest intervals at around 0.01 g/hp-h. PEMS1 and 2 overestimate bsPM as seen by the positive bias. The PEMS2 bias increases with increasing level. PEMS3, 4, and 5 underestimate the bsPM, as seen by the negative bias. The bias for PEMS3 and 4 increases slightly with the reference level while for PEMS5 the slope was closest to zero. The total PM approach for tPEMS3 showed that the model improved the PM response to a very slight positive bias with a slight positive slope suggesting the total PM model is increasing with level. The reader should be warned that PEMS3 data looks good, but could easily underestimate when the composition of the PM changes from EC dominated to sulfate or OC dominated. The PEMS3 model was only able to achieve 50% of the reference mass for both the Cummins (sulfate dominated) and the Volvo (OC dominated) test vehicles.

PEMS1 and 2 subset data showed improvements compared to the full data set. PEMS1 confidence interval dropped from 0.05 to 0.03 g/hp-h, but the bias slightly increased. It is believed that PEMS1 performance will continue to improve given its early level of development. It is unknown how low of a confidence interval this system will be able to achieve given the possibility for a large dynamic range of particle size and filter mass that is possible with-in a day of testing where the spanning filter mass could bias the real time EAD signal. A discussion of particle size variability is provided in Section 4.8.

PEMS2 confidence interval, for the DPF-only tests, improved the most and actually showed to be the lowest confidence interval of all the PEMS. The confidence interval dropped from 0.04 to 0.006 g/hp-h, which is a factor of six times lower. The bias also improved and dropped from 0.028 to 0.002 g/hp-h, a factor of more than 10. The difference between the two scenarios was the removal of all the data where the PEMS parameters were allowed to be adjusted (i.e., not held fixed), as discussed in Section 4.2. The subset removed all the Caterpillar data but kept the Volvo and Cummins data. It seems unrealistic that operating parameters can have an order of magnitude correction to the PEMS2 confidence interval and bias. The dry soot of the Caterpillar engine, as presented in Section 4.7, may be harder for PEMS2 to measure and the bsPM level may also cause some difficulty for PEMS2 measuring systems. The Caterpillar tests would need to be repeated to fully understand the cause for the poor performance of PEMS2 with the Caterpillar PM.

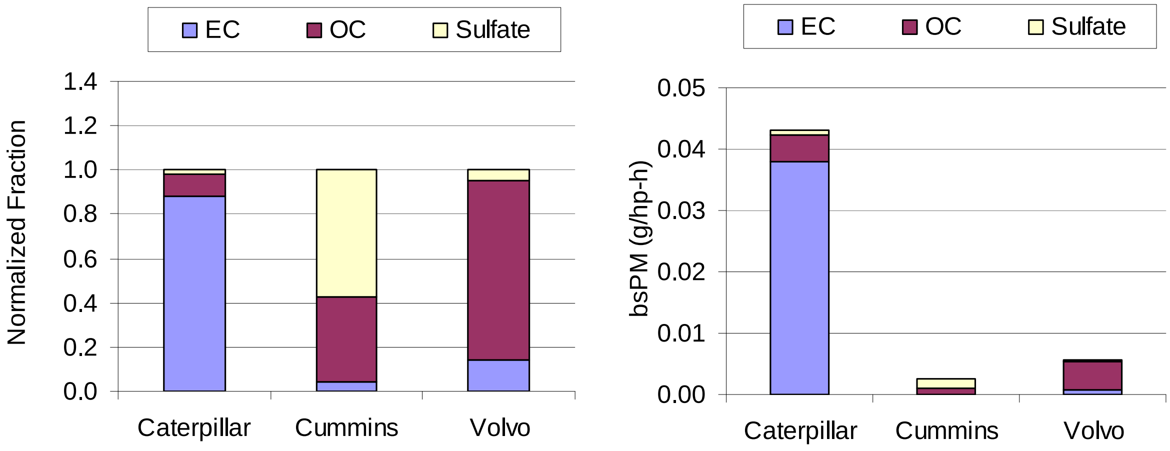
Part of the motivation for this work was to be able to detect in-use failed emission control systems at the 0.03 g/hp-h level. PM control failures are expected to come from cracks in the DPF, for example. The expected PM from this scenario, with the DOC intact, should be sulfate and elemental carbon in nature. It was surprising that there was no sulfate on the Volvo engine, but this could be a result of the Volvo's low accumulated miles (~500 mi) where sulfur build up on the aftertreatment was minor, see discussion Section 4.7. It is uncertain if the high organic carbon PM fractions were only a result of the bypass design (around the DOC). Thus, the ability for each PEMS to detect a failure suggests the PEMS need to identify a positive failure (emissions above 0.03 g/hp-h) while the PM emissions are varying in composition and size distributions.

In general PEMS3 had the lowest overall confidence interval with a slightly negative bias. If the modeled PEMS3 data is considered their confidence interval changes from negative to slightly positive. PEMS1 and 2, which are the two main candidates for the MA program, had the largest confidence intervals where PEMS2 was slightly better. If the subset of the data is considered, then PEMS2 had the lowest confidence interval and a slightly positive bias.

4.7 PM Composition

This section describes the PM composition during all the forced events for all three vehicles tested. The purpose of this section is to understand how differences in PM composition may impact the correlation between different PEMS and the reference method. EC and OC were measured using the NIOSH method and sulfate was determined by measuring SO_4^- ions using Ion Chromatography along with assumptions about the mass of water that binds to the sulfate molecule. For this analysis half the sulfate PM mass is from water hydration. The Cummins OC samples have more uncertainty than the Volvo samples due to the low bsPM levels during the Cummins testing. Although some of the compositional measurements may have uncertainty, the data provides useful information between correlation vehicles. For additional information relating to the PM composition measurements, assumptions, methods, quantification limits, and accuracy, see Appendix E.

Figure 4-24 shows the normalized PM composition (a) and averaged bsPM emissions by composition (b) for all three test engines summarized into bar charts. The Caterpillar engine is UCR's in-house vehicle, which is well characterized from the several studies performed on this vehicle in the past. The Caterpillar EC and OC data presented is based on previous studies (Cocker et al 2004b), but selected forced events were analyzed for sulfate mass. The Cummins and Volvo data represents averages of all the forced events sampled by the MEL. The data shows that the three test engines and test configurations varied not only in emissions level, but also by PM composition.



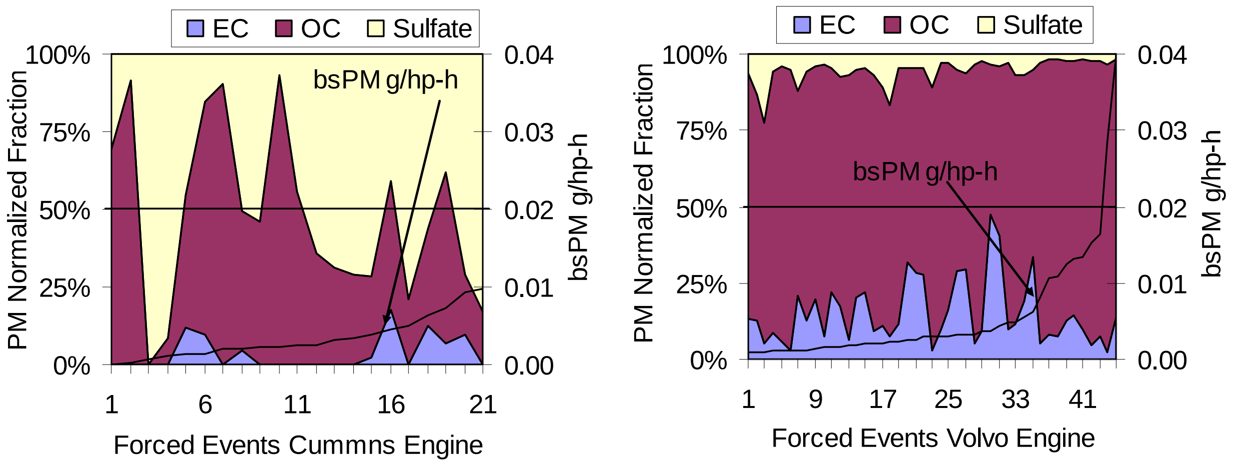
(a) (b)

Figure 4-24 Normalized PM fractions (a) and bsPM fractions (b) for all test engines

Overall, the Caterpillar PM was mostly EC with small amounts of OC and trace amounts of sulfate mass, see Figure 4-24 (a). All the Caterpillar sulfate measurements were at the detection limits of the instrument. The Cummins vehicle showed a majority fraction of the PM from sulfate and less amounts of OC. The Volvo samples were mostly OC with small amounts of EC and very little sulfate. The Volvo sulfate was more than the Caterpillar levels, but was still close to, if not at, the detection levels of the instrument. The low sulfate PM for the Volvo compared to the Cummins could be due to differences in DPF sulfur exposures as seen by the differences in the accumulated vehicles miles of 500 and 17,500 mi, respectively. The Volvo PM also had more OC and EC which could be directly related to the bypass installed on the Volvo test engine, see Section 3.2.2 for bypass details.

The composition also varied from event to event with-in each test engine population. The variation could be due to changes in regen duration, ECM modifications and/or bypass settings. Figure 4-25 shows the same PM composition information as in Figure 4-24, but considers them on an event by event basis for (a) Cummins and (b) Volvo samples. The left y-axis is the normalized fraction and the right y-axis is the gravimetric bsPM emission level. The bsPM trend line is shown in both figures, but is not in the legend. The right y-axis scales were set to the same range to allow visual comparisons between the two data sets. The data is sorted by bsPM from low to high where the high bsPM is on the right side of the figures. Since the data is sorted, the x-axis point #21 does not correspond to event #21 in both figures.

Figure 4-25 (a) shows that the Cummins PM composition was highly variable between sulfate mass and OC mass. The variation occurred over a range bsPM level from 0 to 0.01 g/hp-h. The top six bsPM emissions (#16 to #21) varied from 20% to 60% OC mass with the remaining PM being mostly sulfate. There were trace amounts of EC also present that varied from 0 to 10%. Most of the Cummins OC composition data was just above the quantification limits except for point where the data showed spikes above point #6. Thus, some of the OC trends during non spikes may actually be lower OC and thus higher sulfate fractions as shown in Figure 4-25.



(a) (b)

Figure 4-25 PM composition normalized fraction by forced event for the Cummins engine (a) and the Volvo engine (b)

Figure 4-25 (b) shows the Volvo PM composition was not as variable as the Cummins composition and was mostly OC with variable amounts of EC as the bsPM level increased. The OC varied from 80% to 50% at varying bsPM levels with very little sulfate mass for all the samples. The variability of the EC fraction with bsPM level could be a result of the different bypass settings and engine operation. The sulfate mass was typically less than 10% at the low bsPM level and less than 5% at the higher bsPM levels. Overall, the Volvo composition was dominated by OC mass with varying levels of EC which remained below 50% and very little sulfate for all samples from 0 to 0.04 g/hp-h. The high OC fraction appears to be a result of the bypass during regenerations where relatively large amounts of HC were measured by the MEL and PEMS, as discussed in Appendix E.

The variation in OC and Sulfate composition could contribute to the overall variation in the PEMS correlation with the reference method. When looking at the data in Figure 4-12, the highest bsPM points seem to fall on the same line as if there is no difference in PEMS response between OC and sulfate mass. PEMS2_rev did not generate valid reviewed data for two of the top three points, but still shows no trend between sulfate and OC composition. Overall, the average bsPM was mostly sulfate as shown in Figure 4-24 (a) and Figure 4-25 (a) and it appears the sulfate particles are not easily measured by all PEMS tested (PEMS2 through 5) as indicated by the less than 0.1 slopes in Figure 4-12 (note PEMS 1 was not tested).

The PEMS comparison to the reference method showed an improved slope for the Volvo data over the Cummins data from around 0.1 for all PEMS for the Cummins to 0.8, 0.4, 0.1 for PEMS2, PEMS4 and 5, respectively. The PM composition between the Cummins tests to the Volvo was different, but it seems unlikely that composition alone can explain this difference. The Cummins top six bsPM emission points had an OC composition of 25% to 50% which is similar to the 50% to 80% OC mass dominance of the Volvo samples. PEMS3 is not expected to measure either OC or sulfate given it is a soot (EC) sensor and PEMS3 response is similar at a slope of 0.1 for both engines. PEMS2, 4, and 5 though do not depend on composition necessarily and thus one would expect the Volvo tests to show only a slightly greater slope given the water assumptions for the sulfate mass, as discussed in Appendix E. The fact that the slope improved by a factor of 8 for PEMS2 and a factor of 4 for PEMS4 and 5 suggests particle size may be contributing to the difference in response.

The overall comparisons for all the tested PEMS was better for the Volvo events compared to the Cummins. Since the Cummins PM was dominated by sulfate it appears there may be some inherent issue with each PEMS measurement principal and/or sampling system that is preventing the detection of sulfate based particles weather it is due to particle size or composition is not known since both particle size and composition were different between the Volvo and Cummins tests as will be presented in Section 4.8. Given the high degree of variability for some PEMS it is hard to conclude the amount of deviation for the Cummins tests.

4.8 Particle Number Count and Size Distribution

Particle size is a critical characteristic of PM that can vary by diameter and number by several orders of magnitude. A small change in particle diameter has a mass change on the order of diameter cubed (d^3). Particle diameter typically ranges from around 5 nm to as many as a 1000 nm for diesel exhaust (with and with out DPF controls). Non-DPF compression ignition diesel combustion typically has a mass mean diameter of around 100 nm and varies due to physical processes surrounding the particles. DPF-controlled diesels have been shown by others to produce mass mean diameters around 100 nm.

One way to get a quick overview of the particle size behavior is to consider particle number in combination with PM mass. Particle number or counting particles depends on dilution methods, but when sampling from similar setups one can quickly uncover differences between tests that can provide a qualitative understanding of the nature of the PM between tests. Particle number is measured by counting particles and is related to diameter to a zero power (d^0). Particle size distribution is measured using scanning devices and electrical mobility selectivity. The real-time particle measurement devices used in this study were a TSI 3760 CPC and a fast Scanning Mobility Particle Sizer (fSMPS) and are described in more detail in Appendix F and in Shaw et al (2005).

Figure 4-26 (a) and (b) shows the measurement of particle number as a function of MEL calculated raw PM concentration and regeneration percent for both the Cummins and Volvo tests. The correlation between particle number and MEL concentration was high, with an R^2 of 0.7 for the Cummins and Volvo tests. The high R^2 suggests one can reasonably draw comparisons between the Cummins and Volvo particle number and mass relationships. The slope was larger by a factor of five for the Cummins over the Volvo test. This suggests the Cummins mass was composed of five times more particles than the Volvo PM. Knowing that particle mass is proportional to d^3, then one can infer that the particles measured for the Cummins engine in general were smaller than those for the Volvo engine. The correlation between particle number and regenerations was lower at 0.5 and 0.3. Thus, particle number emissions do not correlate well with regeneration percent since the regeneration percent is a regeneration request not an active regeneration signal.

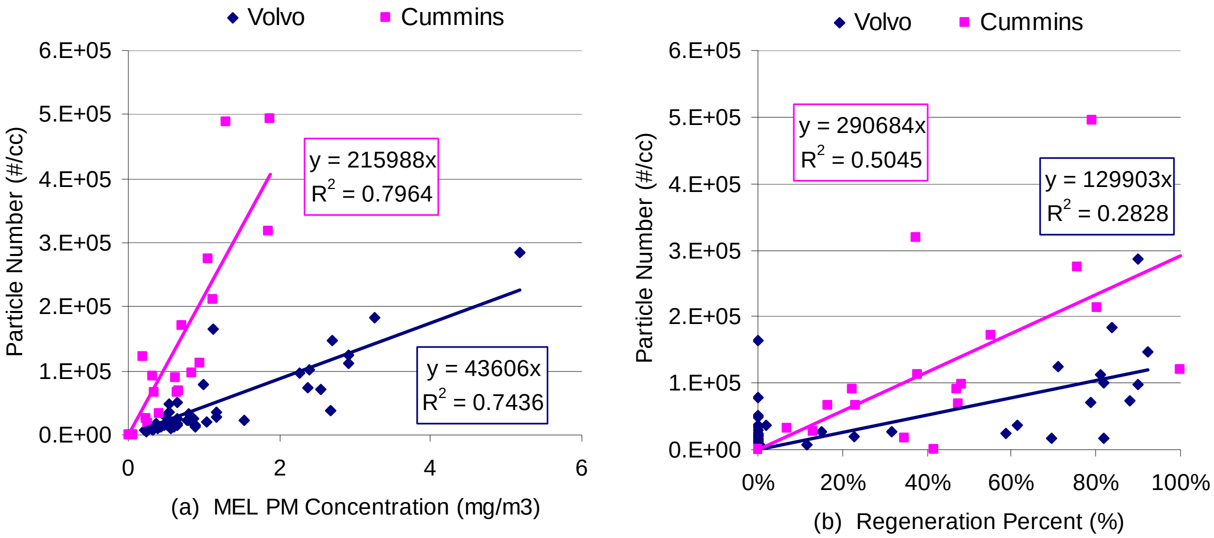


Figure 4-26 Particle number as a function of MEL calculated concentration (a) and broadcast regeneration percent (b) for the Cummins and Volvo tests

Figure 4-27 and Figure 4-28 show the fSMPS number based size distribution for selected forced events for the Cummins and Volvo engines. The selected events represent typical size distributions for both vehicles where the Cummins tests showed spikes that coincided with regenerations but the Volvo spikes did not necessarily coincide with regenerations. The size distribution in Figure 4-27 shows a small number average particle size (d^0) for the Cummins events #1 and #2. The number average particle size was 30 nm for event #1 and around 10 nm for event #2 with relatively very few particles above 40 nm for event #2. The mass average particle diameter for the Cummins tests was around 60 to 20 nm for the two forced events respectively.

The Volvo engine size distribution in Figure 4-28 shows a much larger particle size distribution with an averaged number diameter around 60 nm, but a high concentration also up to 100 nm. The average mass diameter for the Volvo was much larger than the Cummins and was around 120 nm. The Volvo average mass diameter was similar to the Caterpillar's mass average diameter measured during cruise operation on a previous study by Shah et al (2005).

Based on the Cummins particle composition being dominated by sulfate and number averaged diameters of 10 - 30 nm suggest the particles contributing to the PM mass are formed from the conversion of SO_2 to SO_3 over the catalytic surfaces. These nano particles represent a homogeneous nucleation that forms during the dilution process and grow in size. Thus it is possible that the location of the PEMS and the reference may see different particle diameters, but typically particle formation with similar dilution ratios and temperatures should form similar mass levels. Thus the fact that there could be a difference between the reference and the PEMS may not come from the particle formation process, but could come from diffusion losses where the particle size may be significant for the PEMS compared to the MEL. It is hard to say with out further work.

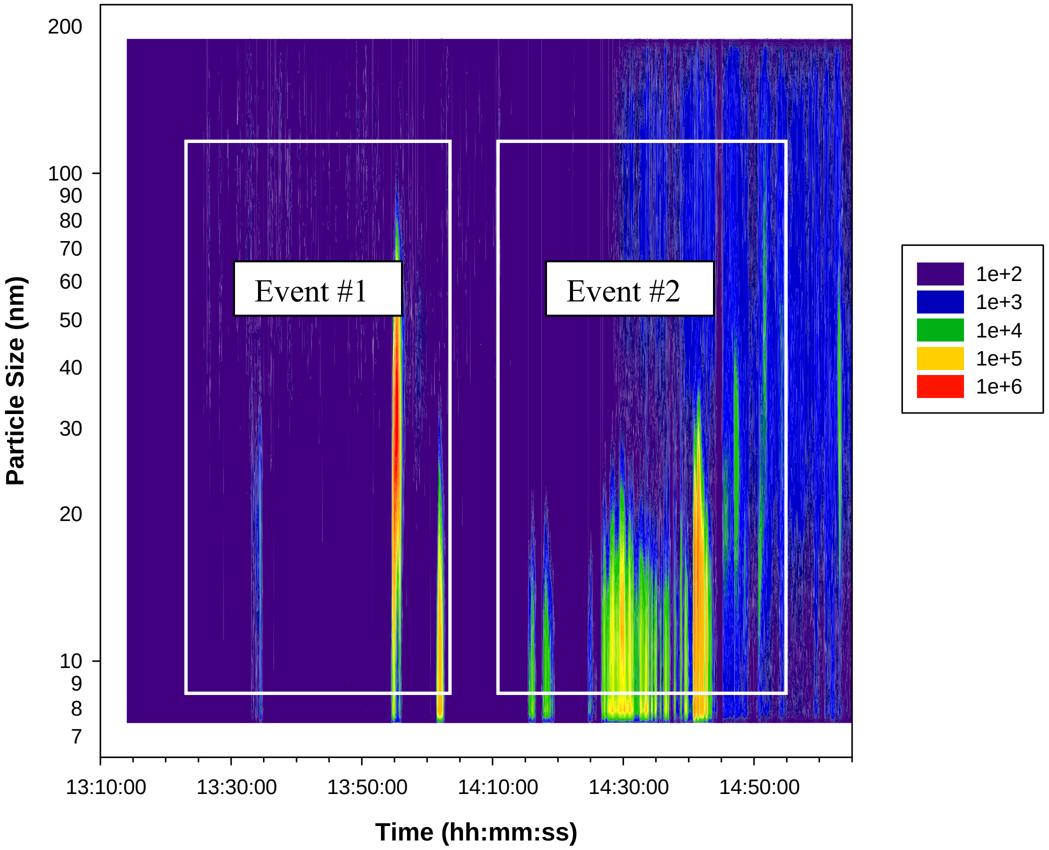


Figure 4-27. PM size distribution dN/dlogDp (#/cm3) for forced event number 1 and 2 (Cummins)

The correlation between the reference and the PEMS was poorest for the Cummins test compared to the Volvo tests. Based on the size distribution data presented, the particle size was much smaller for the Cummins compared to the Volvo and Caterpillar at 10-30 nm and 60 – 100 number averaged diameters, respectively. Thus, it is unclear if the reason for the poor Cummins correlation is due to the composition, particle size, or both. In either case it is obvious that all tested PEMS performed poorly on the Cummins PM composition and/or particle size distributions (i.e. PEMS1 was not tested on the Cummins vehicle).

Small particle size can contribute to a low signal response for several PM PEMS instruments. Small particles do not scatter light well thus affecting PEMS5. Small particles affect the ability for PEMS4 to use its assumption for a log normal distribution being centered at 100 nm the center of their impactor electrometers. Shifting this size below PEMS4 detection of 30 nm could have a significant effect on the particle density and thus overall particle concentration. Small particle size should have less impact on PEMS2, with only a minor effect on charging efficiency and impaction on the crystal surface, as discussed in Section 6. It is interesting though that PEMS2 had such a poor correlation for the Cummins test at relatively large filter mass loading levels of a 0.01 g/hp-h level. PEMS3 should not necessarily have an issue measuring small particles, but because they were not composted of soot, PEMS3 can not be evaluated for its ability to measure nano particles on the Cummins tests. PEMS1 should not have any difficulty measuring small particles given the EAD detection is down to 10 nm and PEMS1 uses a gravimetric filter for EAD calibration. Unfortunately PEMS1 was not tested on the Cummins vehicle.

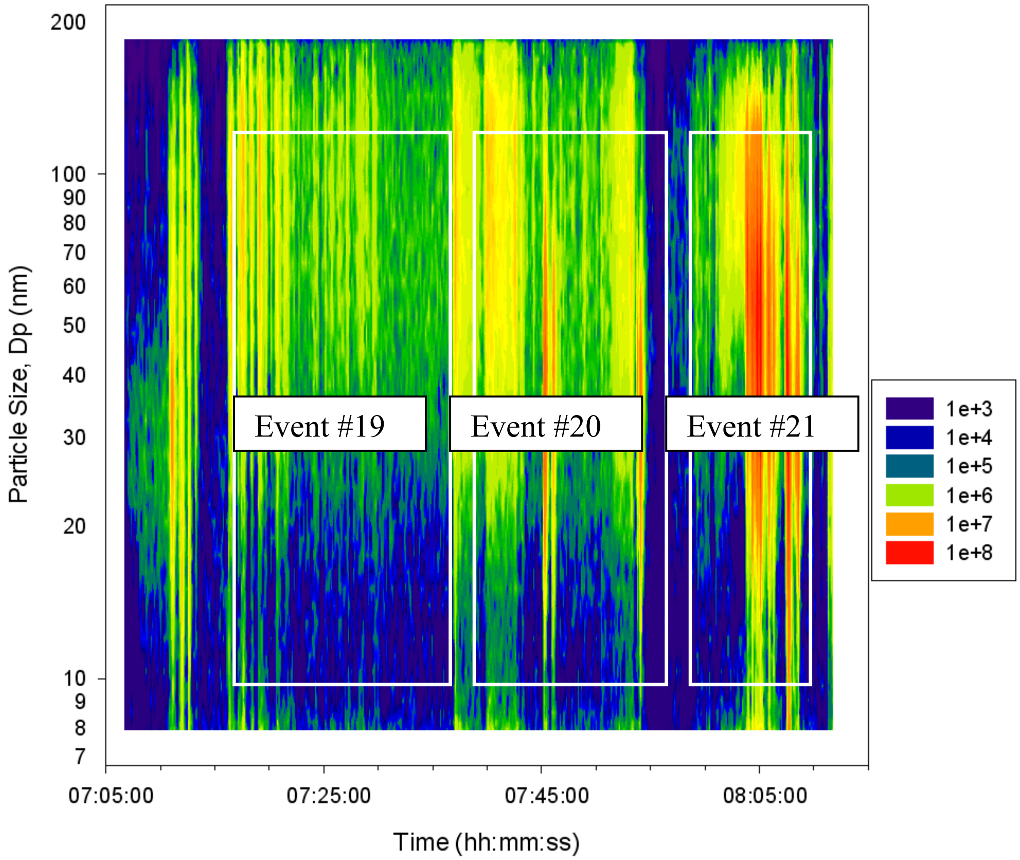


Figure 4-28 . PM size distribution dN/dlogDp (#/cm3) for forced events 19, 20, and 21 (Volvo)

4.9 Deeper Look at Selected Forced Events

Particulate matter and its formation is a dynamic and nonlinear process requiring an understanding of real-time analysis of the PEMS responses that are masked in the integrated analysis presented earlier. This real-time analysis is limited to PEMS3, 4, and 5 where only the Cummins and Volvo test are considered. Knowledge of the PM composition, number and size distribution can be used with the real-time data to understand each PEMS operating principles and limitations. PEMS2 is not considered here since its data reporting is not done on a second-by-second basis.

Dilution between the PEMS is important to understand before presenting the real-time data. PEMS3 dilution was based on a constant ratio, where PEMS4 and 5 sampled CVS where the dilution ratio varies. PEMS3 dilution was 2 to 1 for the Cummins tests and 3 to 1 for the Volvo tests. PEMS4 and 5 dilution ratios varied from a low (2.5) at high exhaust flow (high power) to a high (~10) at low exhaust flow (low power). The MEL CVS flow was 2700 scfm for the

Cummins tests and 2300 scfm for the Volvo tests. The concentration data is presented in raw concentrations for all three PEMS.

Cummins Data

Figure 4-29 shows the same Cummins delta information as presented earlier with the addition of MEL estimated concentration and regeneration event fraction. Notice how concentration and regeneration fraction increases with bsPM level. It appears regenerations were successful in increasing bsPM and is a reasonable approach to increase bsPM up to around 0.01 g/hp-h for the Cummins engine where no bypass was used. The circled event #6 is considered in more detail on a second by second basis. This event was selected since it represents the largest bsPM level measured and show real-time behavior of the PEMS where a significant of mass was detected by the MEL. Other points could have been shown, but given the lower reference response not much information could be extracted. Appendix G shows more additional real-time analysis of other events, but to keep this section brief these figures were not included here.

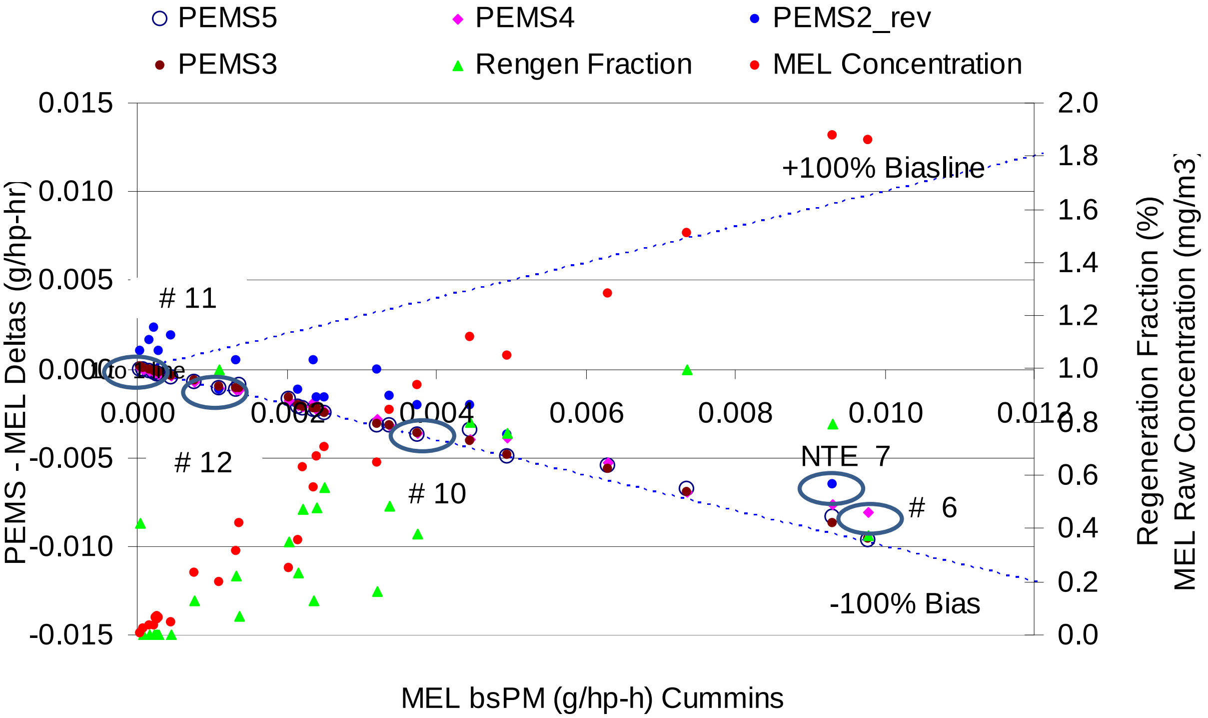


Figure 4-29 Forced event deltas with MEL concentration and regeneration fraction as a function of MEL bsPM level (Cummins)

Figure 4-30 shows the real-time tailpipe concentration of PEMS3, 4, and 5 on the right axis and particle number concentration on the left log scale axis during event #6 for the Cummins engine. The event #6 MEL bsPM emissions were 0.0098 g/hp-h and had the following integrated conditions of 37% regeneration fraction, 50% sulfate and 50% OC, and a nominal particle size of 20 nm. PEMS4 showed the highest response compared to PEMS3 and 5 which agree with PEMS4 bsPM integrated event results. The PEMS4 response coincides with a large particle count suggesting a nucleation event is occurring as a result of the start of the catalyst regeneration, see Appendix G for additional figures of particle number, regeneration flag and regeneration temperature. PEMS3 and 5 did not see the nucleation event, which could be due to their different detection principles. PEMS5 could have missed the event due to an inability to scatter small particles and PEMS3 could have missed it because these particles were most likely dominated by sulfate which PEMS3 measurement principle does not respond to.

The two circled sections “a” show PEMS3, 4, and 5 all measured a similar concentration amount, thus suggesting the particles were large enough to scatter some light and were more carbonaceous for PEMS3 to detect some mass. It is interesting that after the nucleation event, all three PEMS lined up so nicely. It is interesting that this occurred twice with similar behaviors of following a nucleation event. This observation is interesting given their wildly different measurement principles.

The circled section “b” in Figure 4-30 shows a sudden drop in response where the particle count is flat at $1x10^6$ #/cc. It turns out that looking at PEMS4 raw electrometer currents shows that the mobility electrometer currents overranged and dropped to zero during this spike, but not during the second circled event in the same figure, (see Appendix D for additional details on PEMS4 electrometer currents). A closer look at the electrometer currents shows that all the currents also dropped. For some reason though the particle counter did not see the event. This suggests there could be some computational problem with PEMS4 system given the particle counter did not also experience a drop in #/cc. The PEMS4 mobility drop out due to overranging was seen on other events within this program and also on other programs. It is suggested that this may be a design flaw in the calculation methods for PEMS4 detection principles. The PEMS4 electrometer currents were also highest at the lowest particle diameter. This creates a problem for the calculation of concentration since PEMS4 needs to identify the peak diameter in order to estimate density properly. The low PEMS4 response could be a result of the mean particle diameter being below the final impaction stage, see Appendix D for figures on raw electrometer currents.

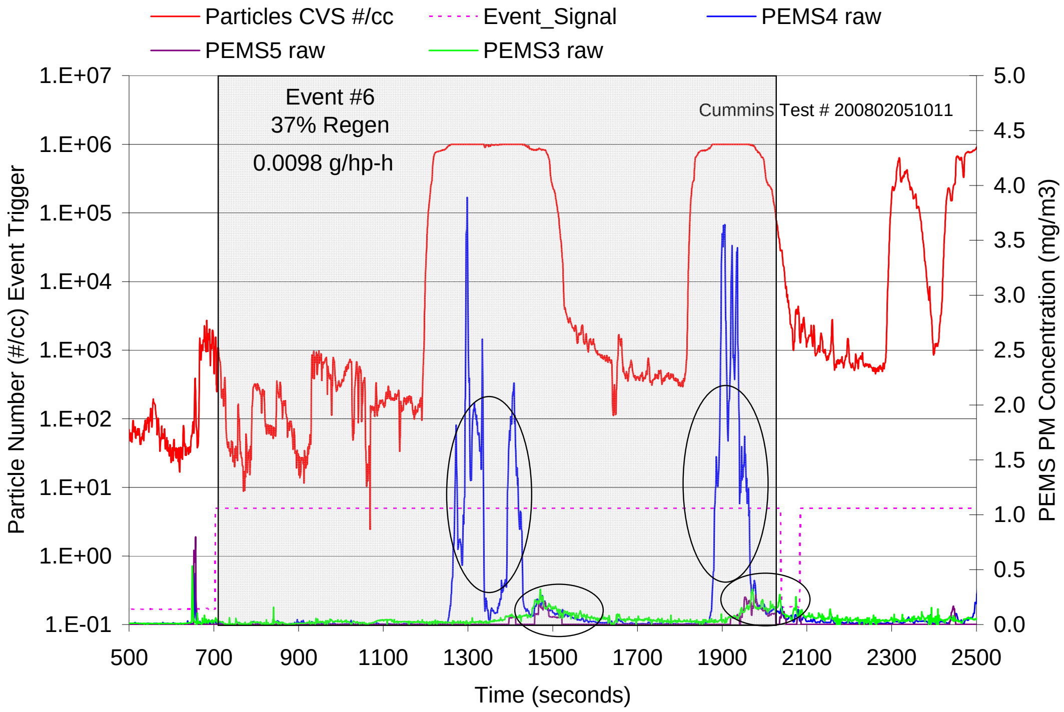


Figure 4-30 Real-time evaluation of PEMS3, 4, and 5 for Cummins forced event #6

Volvo Data

Figure 4-31 shows the same Volvo delta information as presented earlier with the addition of MEL estimated concentration and regeneration event fraction. Notice again how concentration and regeneration fraction increases with bsPM level. Also note that the concentration right y-axis is three times higher than the Cummins tests. It appears regenerations in combination with a small amount of bypass setting were successful in increasing bsPM and is a reasonable approach to increase bsPM up to around 0.04 g/hp-h for the Volvo engine. The circled event #21 and #23 are considered in more detail on a second-by-second basis. These events were selected since they represents the largest bsPM levels measured and show real-time behavior of the PEMS where a significant of mass was detected by the MEL. These points were also selected since PEMS3, 4 and 5 showed different lower responses between these events. Appendix G shows additional real-time analysis of other events.

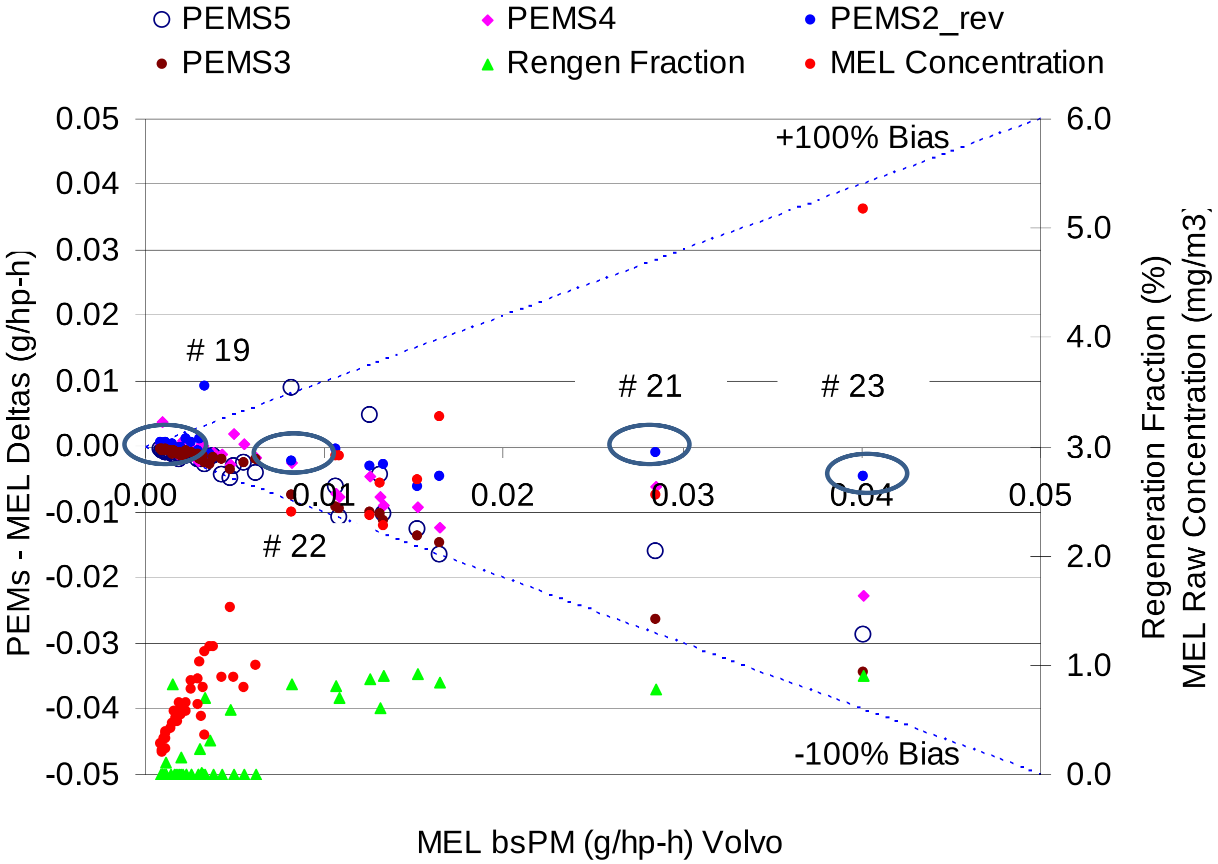


Figure 4-31 Forced event deltas with MEL concentration and regeneration fraction as a function of MEL bsPM level (Volvo)

Figure 4-32 and Figure 4-33 show the real-time tailpipe concentration of PEMS3, 4, and 5 on the right axis and particle number concentration on the left log scale axis during Volvo events #21 and #23. The event #21 MEL bsPM emissions were 0.028 g/hp-h and it had the following integrated conditions of 79% regeneration enable fraction, and 80% OC and 15% EC. Event #23 was similar to #21, but the PEMS responses were different where the integrated conditions of 0.04 g/hp-h bsPM, 90% regeneration enable fraction, and 80% OC, 15% EC. PEMS4 showed a decrease from event #21 to #23 and PEMS3 showed an increase and PEMS5 showed very little change.

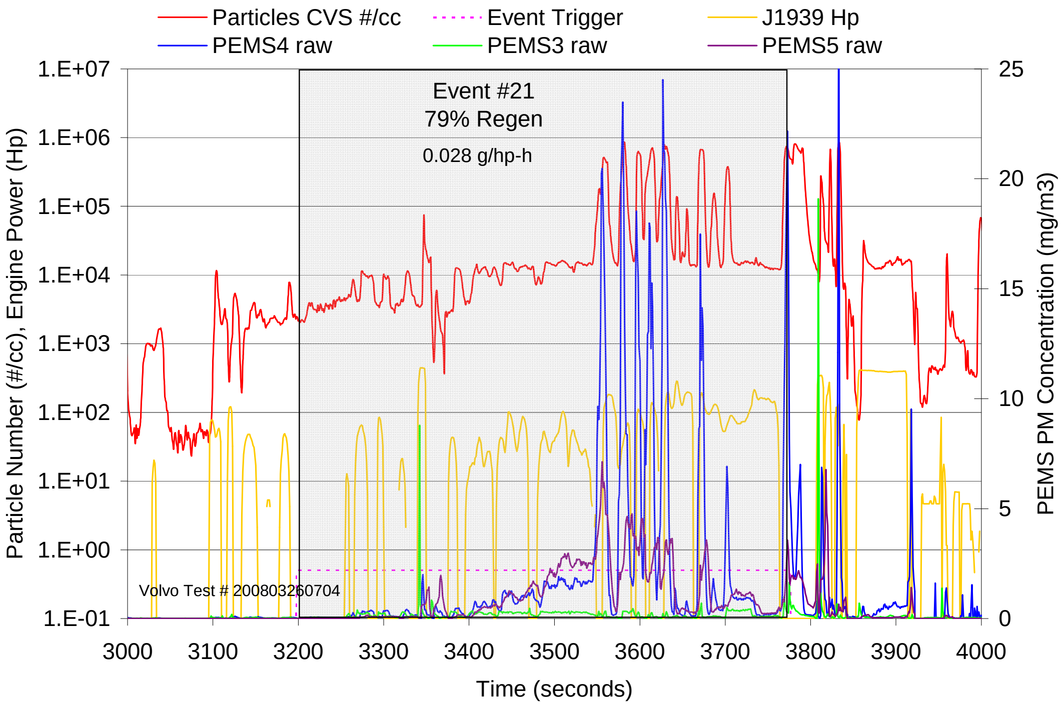


Figure 4-32 Real-time evaluation of PEMS3, 4, and 5 for Volvo forced event #21

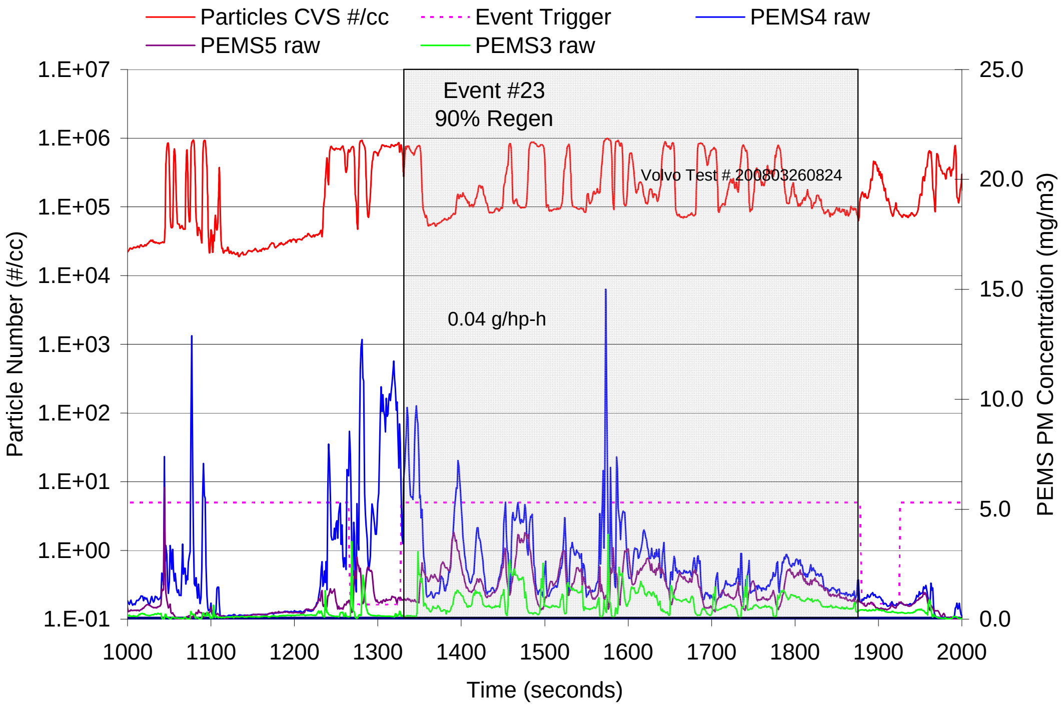


Figure 4-33 Real-time evaluation of PEMS3, 4, and 5 for Volvo forced event #23

Overall, the real-time data suggests the particle formation process has less of an impact on the measurements than the actual measurement principle of the different instruments.

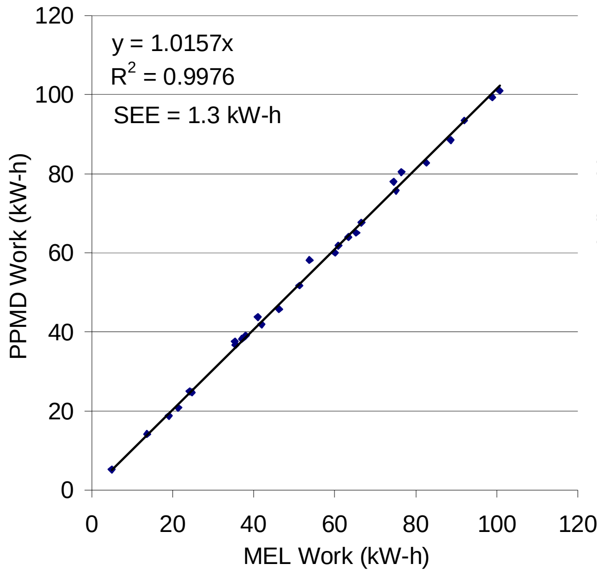
5 On-Road Testing –Gaseous Experimental Results

5.1 Work, Fuel Consumption and Gaseous Emissions

Gaseous emissions data for the PEMS was available for the testing on the two 2007 vehicles that were operated by UC Riverside. These data are useful for understanding the overall quality of the data sampled and to help understand the overall emissions for all species for the two DPF-equipped engine manufacturers. No gaseous data was available for the 2000 Caterpillar data because the PEMS manufacturers were not auditing their gaseous systems. The data were collected over the same forced events examined for the PM results. The gaseous comparisons are based on the in-use NTE calculation method one, as described in CFR40 Part 1065.

5.2 Work Comparison Results

Figure 5-1 and Figure 5-2 show the correlation between the work calculated by the MEL and the gaseous and PM systems of the same PEMS2. The figure on the left is calculated by the PM part of the PEMS and the figure on the right is calculated by the gaseous part of the PEMS. PEMS2 has two independent systems that process and manipulate data. The ECM signals are sampled by the gaseous part, but the calculation and integration of work is done by the gaseous and PM parts of the PEMS. As a result there are two outputs of the same results, one from the PM part and one from the gaseous part of PEMS2. It is interesting to note that the SEE which describes the spread about a best fit line is over an order of magnitude higher for the PM part of the PEMS2 compared to the gaseous part of PEMS2. This became a contentious issue during development of the MA test plan when it was discovered that post processing for the PM PEMS can have a significant effect on the PM emissions reported. These post processors at the time of testing were still under development, so this issue may be resolved by the time of the measurement allowance program and ultimately when the measurement allowance value is finalized.



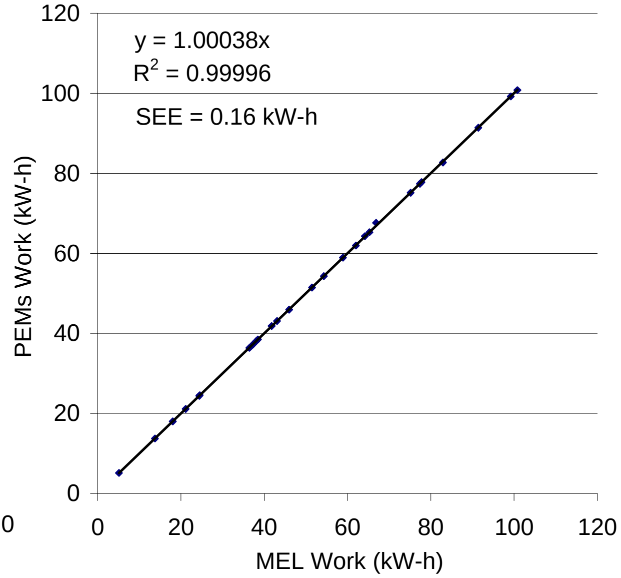


Figure 5-1 Correlation work plot between the MEL and the PEMS for the Cummins engine for both the PPMD derived work and the PEMS derived work

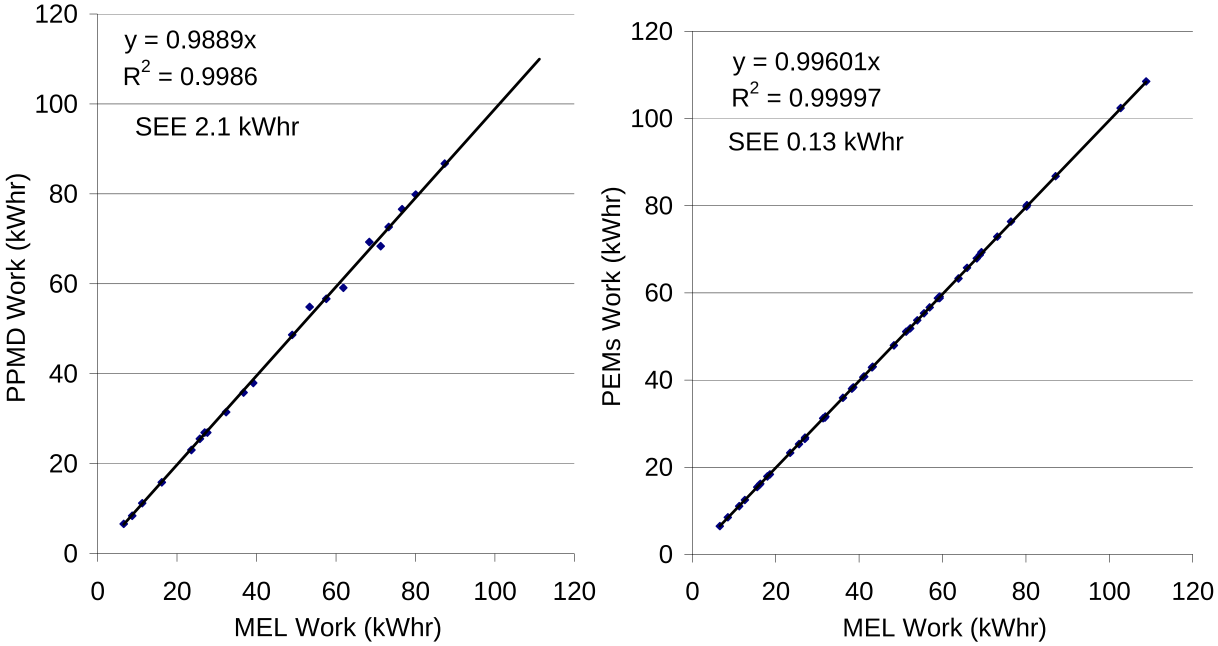


Figure 5-2 Correlation work plot between the MEL and the PEMS for the Volvo engine for both the PPMD derived work and the PEMS derived work

The correlation between the MEL and gaseous PEMS work showed an R^2 equal to 0.9999 and a slope of 1.00. The high R^2 and near 1.00 slope provide a reasonable metric that the work data between the MEL and the PEMS is not contributing to any significant errors. Work errors on a brake specific basis would be accounted for in the denominator. Given the close agreement between the MEL and PEMS denominators, one can consider any errors presented later in this report should be a result of the mass measured and not errors due to inconsistent work or difference in sample tines.

A similar R^2 and near unity slope for the Caterpillar testing was reported for the PEMS1 and PEMS2 [Durbin et al. 2009b]. Overall, the Caterpillar engine correlations plots 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, as discussed in Durbin et al [2009b].

5.3 Fuel Consumption Results

Fuel consumption results provide a measurement that can be compared with external values to provide a measure of the overall accuracy of the emissions measurements. The MEL and gaseous PEMS (available on the Cummins and Volvo tests) 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 5-3 and Figure 5-4. All the forced event tests show a good correlation between engine fuel consumption and emissions carbon balance, with the Cummins tests showed the best correlation compared to the Caterpillar and Volvo testing. The slope of 0.957 for the Caterpillar tests is similar to that found in previous MEL studies with this same engine [Cocker et al., 2004a], which adds to the confidence in the MEL repeatability.

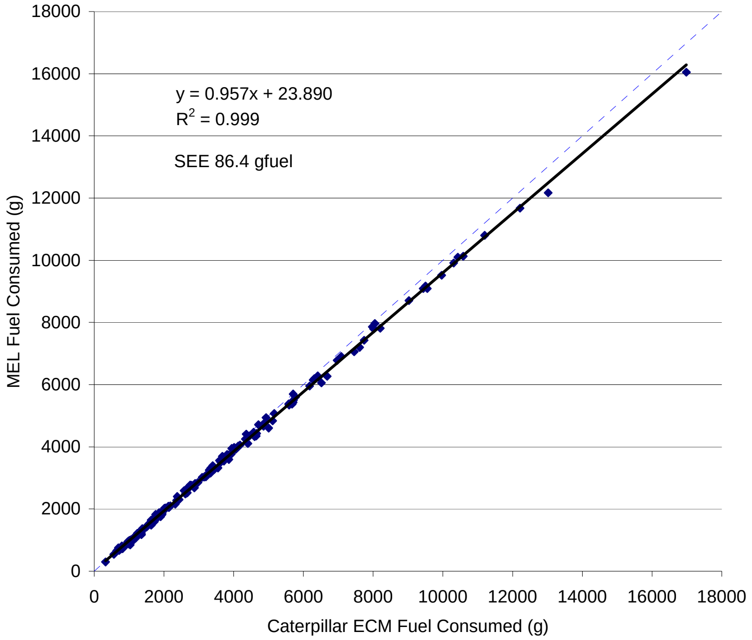
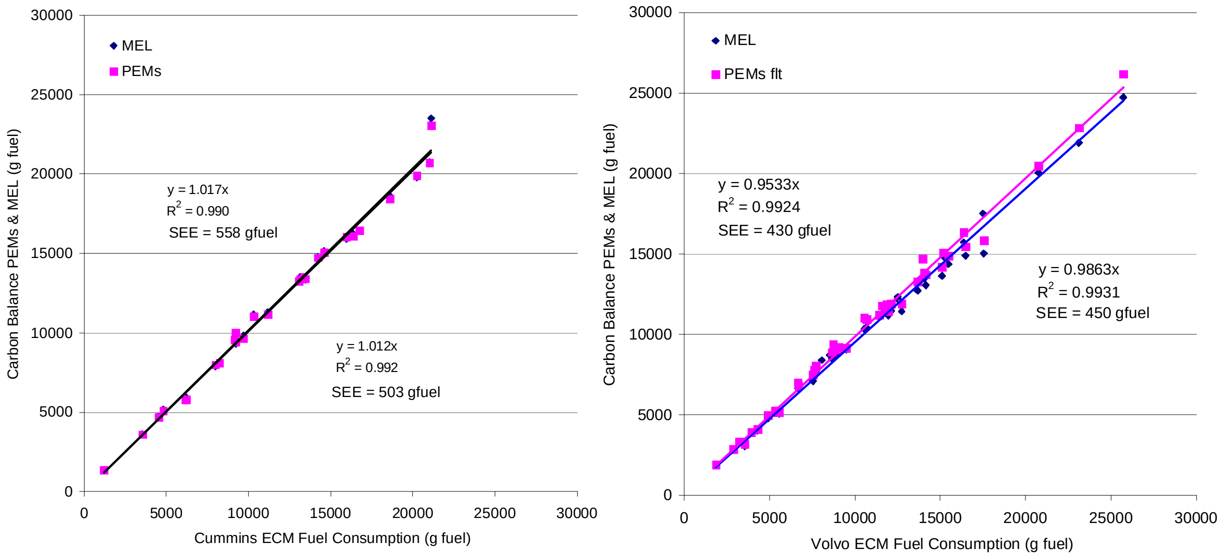


Figure 5-3 Fuel consumption correlation between the MEL carbon balance measurements and the ECM J1939 readings for the Caterpillar forced events.



(a) (b)

Figure 5-4. Fuel consumption correlation between the MEL and PEMS carbon balance measurements and the ECM J1939 readings for the Cummins and Volvo forced events

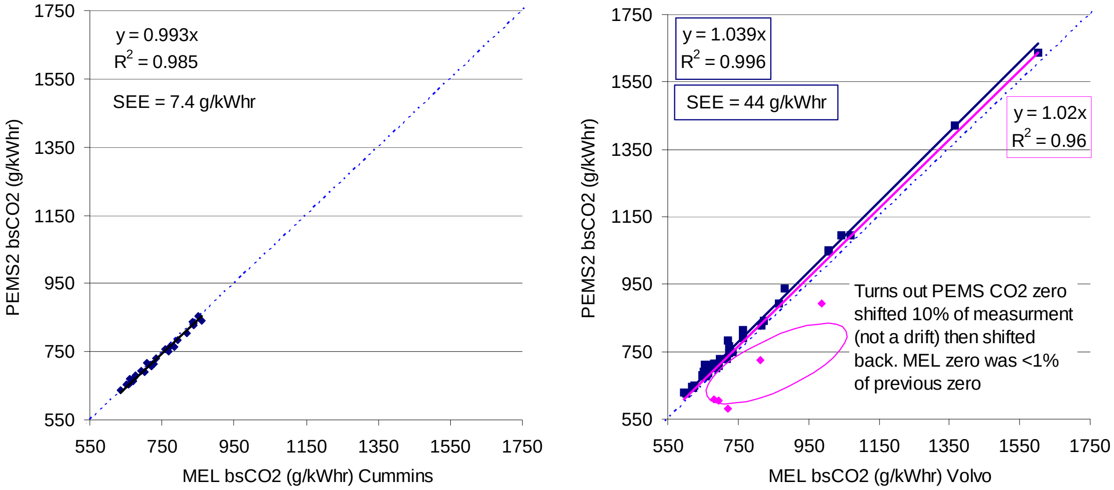
The standard error estimate is a measure of spread about the least squared line. The Caterpillar testing showed the lowest standard error estimate (SEE), which can be a result of shorter events and more time spent in the NTE engine operating zone. Longer events have the ability to go in and out of non NTE zones were the ECM fuel consumption metric is less accurate. In fact a correlation between the MEL and PEMS carbon balance showed a SEE that was around 200 for both the Cummins and Volvo tests. Also an analysis of the NTE data which is provided in the gaseous section showed that the slope and SEE were reduced for valid NTE events for both the Cummins and Volvo tests.

Overall the near unity slope and high R^2 are indicators that the on-road emissions masses are reliable and consistent within expectations. Thus the PM results presented should be reliable accurate.

5.4 Brake Specific Emissions

This section covers the gaseous brake specific emissions during the same forced events presented earlier for PM, but limited to the Cummins and Volvo tests. This section is added to give the reader a feel for the operation of the engines from a perspective of the gaseous emissions, including CO_2, NO_x, CO and NMHC. Figure 5-5 through Figure 5-8 shows the correlation of the PEMS2 gaseous results with the MEL's gaseous results for both the Cummins and Volvo engines. The Cummins tests are in figure "a" and the Volvo results are presented in figure "b".

The $bsCO_2$ emissions are shown in Figure 5-5 (a) and (b) where the correlation between the MEL and the PEMS looks good with an R^2 of 0.99 for both and a SEE of 7 and 44 g/kWhr, respectively. The slope for both were very close to unity with the Cummins was closest at 0.993 and the Volvo at 1.039 suggesting the Cummins tests showed only a slight negative bias and the Volvo tests showed a slight positive bias. Typically, a positive bias in bsCO2 corresponds directly to a bias in flow measurement. Thus, the exhaust flow bias between the MEL and the PEMS2 for the Cummins was negligible, but for the Volvo there was a slight high bias for the PEMS2.



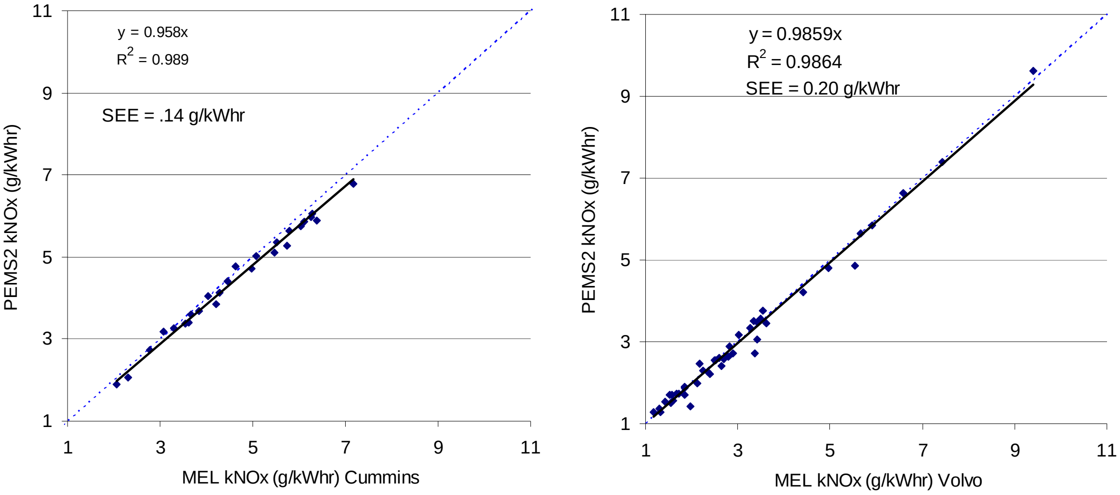
(a) **(b)**

Figure 5-5 Cummins (a) and Volvo (b) bsCO_2 emissions comparison between the MEL and PEMS2

It is interesting that the range of bsCO_2 data went from 600 to 1600 g/kWhr for the Volvo, but the Cummins was lower and ranged from 600 to 800 g/kWhr. The range of bsCO_2 is a result different ECM modifications to try and reduce bsNOx for the Volvo tests. It appears this had a significant effect on the bsCO_2 emissions or on the brake specific fuel consumption. It is unknown what affect the much higher fuel consumption had on bsPM, but it there is a possibility that the larger amounts of unburned fuel could be forming higher amounts of OC particles as indicated by the large fraction of OC for all the tests.

The five points circled in Figure 5-5 (b) are an example of an invalid PEMS2 automatic CO_2 zero that invalided a few points during the Volvo testing. It looked like the CO_2 zero shifted high then back. The high zero shifted the PEMS response low as can be seen by the points below the correlation of data. The bsCO_2 shifted around 10% of point for those points affected. The analysis presented was with this data removed since it did not pass the drift criteria in CFR40 Part 1065. It was shown here as an example of problems that occur with PEMS in-use.

Figure 5-6 (a) and (b) show the PEMS correlation to the MEL bsNO_x emissions. Both engines had a good correlation between the PEMS and the MEL where the R^2 was 0.99 and the SEE was low at 0.1 and 0.2 g/kWhr. The slope was 0.958 and 0.986 for the Cummins and Volvo engines. The lower than unity slope suggests the PEMS2 NO_x emissions were biased low compared to the MEL on the order of 2-4%. The range of bsNOx emissions was much larger for the Volvo tests where bsNO_x ranged from 1 g/kWhr to just over 9 g/kWhr. The reason for the large range of NO_x emissions was a result of the different ECM modifications and forced regenerations.

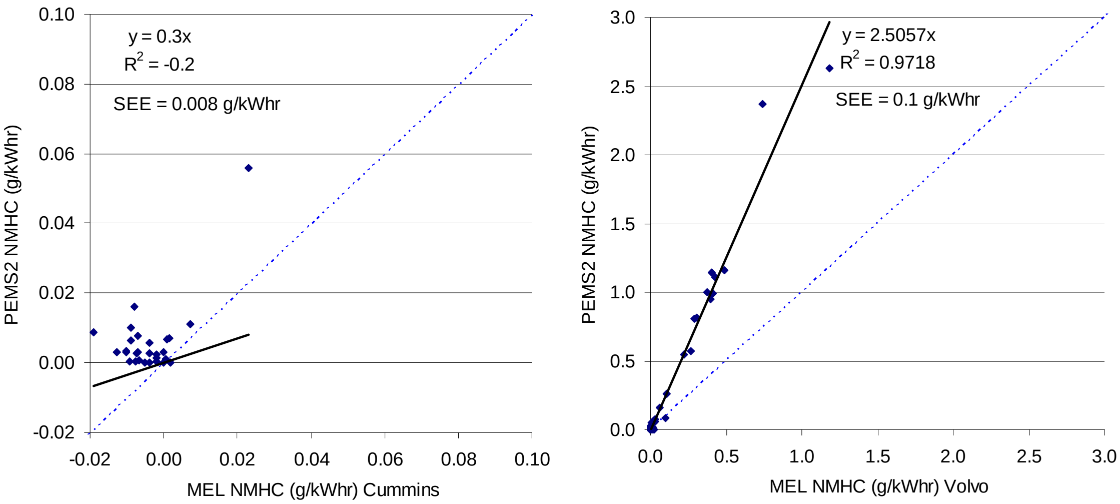


(a) **(b)**

Figure 5-6 Cummins (a) and Volvo (b) bsNO$_x$ emissions comparison between the MEL and PEMS2

If one considers the bsCO$_2$ biases as a bias in the exhaust flow measurements then the NO$_x$ bias due to NO$_x$ measurements will increase for the Cummins testing and drop for the Volvo tests. The bsNO$_x$ bias was low for both the Cummins and Volvo, but the bsCO$_2$ bias was low for the Cummins and high for the Volvo. Thus, if we assume the bsCO$_2$ bias is a result of exhaust flow then the bsNO$_x$ would get more negative for the Cummins testing and less negative for the Volvo.

Figure 5-7 shows the NMHC emissions correlation data between the PEMS and the MEL. Overall, the bsNMHC emissions were low for the Cummins tests and relatively high for the Volvo tests. The Cummins correlation between the PEMS and the MEL shows a -0.2 R^2 and a slope of 0.3. The low R^2 and low slope suggests the correlation between the PEMS and the MEL was not very good for bsNMHC. One reason for the poor Cummins correlation is most likely a result of the low mean concentrations measured by the PEMS and the MEL, as shown in Table 5-1. The PEMS and MEL mean THC concentrations were 0 and 2.4 ppm, respectively, with one standard deviation of 3.3 ppm for the PEMS and 0.26 ppm for the MEL. The large standard deviation for the PEMS at the 0 ppm mean value suggests the PEMS measurements were below the detection limits for all Cummins tests. The MEL values were above the detection limits, but were at the same level as the ambient concentrations of 2.3 ppm.



(a) **(b)**

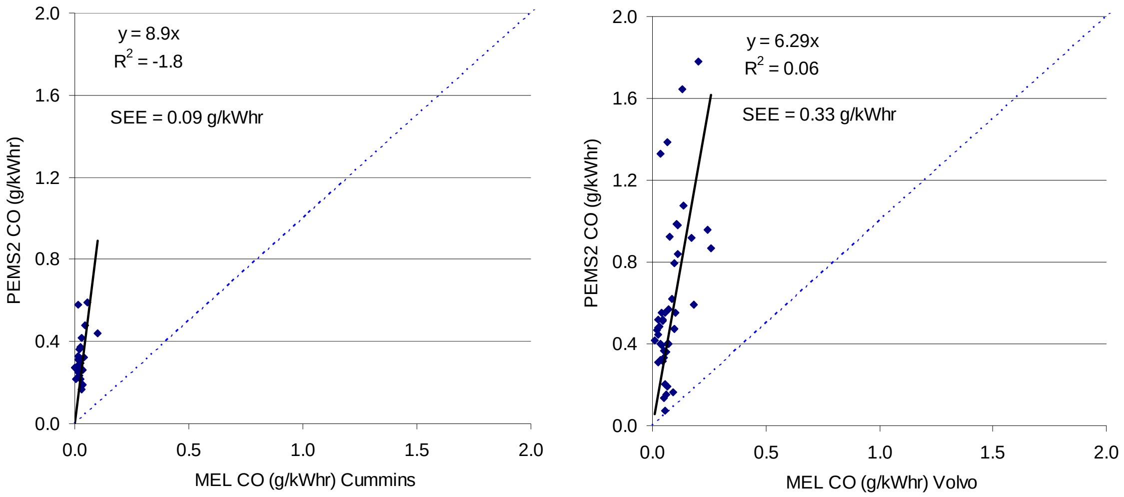
Figure 5-7 Cummins (a) and Volvo (b) bsNMHC emissions comparison between the MEL and PEMS2

The Volvo tests showed much higher NMHC emissions for both the PEMS and the MEL, where the mean concentrations were 120 and 13 ppm, respectively, see Table 5-1. The high NMHC emissions for the Volvo were most likely a result of the bypass settings and forced regenerations. The R^2 was 0.98 and a slope of 2.5 between the PEMS and the MEL. The high correlation and a greater than unity slope suggest the PEMS was measuring consistently more THC than the MEL. The high correlation, greater than unity slope, and high THC concentrations suggested either the PEMS or the MEL was not measuring the THC correctly. The MEL heated filter was discovered to be damaged after completing the Volvo testing. Typically, the MEL operation would have caught this problem during routine startup, but due to additional effort on the operation of PEMS2, the problem was missed and not discovered until the test program was complete. The PEMS data is likely more reliable than the MEL for NMHC as a result of the MEL's heated filter issue.

Figure 5-8 shows the CO emissions comparisons between the PEMS and the MEL. The correlation between the PEMS and the MEL showed a R^2 that was negative or less than 0.1 which suggests there was no correlation for both test engines. The Cummins poor correlation could be a result of the low mean concentration of 1.2 ppm and 41 ppm for the MEL and PEMS, respectively. The PEMS and MEL showed a higher mean concentration for the Volvo tests, but still a poor correlation. It is interesting that the PEMS showed more measurement range than the MEL. The Cummins average bsCO emissions were 0.03 and 0.3 g/kWhr for the MEL and PEMS, respectively. The Volvo average bsCO emissions were 0.08 and 0.6 g/kWhr for the MEL and PEMS, respectively. The Cummins and Volvo emissions were about 10 times lower for the MEL compared to the PEMS. In general, all the bsCO emissions were less than 1% of the in-use NTE standard of 20 g/kWhr.

Engine	Instrument	CO ppm	CO2 %	NO ppm	NO2 ppm	THC ppm
Caterpillar	MEL	17.0	1.4	91.6	n/a	9.8
Caterpillar	PEMS2a	n/a	n/a	n/a	n/a	n/a
Cummins	MEL	1.2	1.4	87.9	n/a	2.3
Cummins	PEMS2b	40.9	6.2	250.8	135.9	-0.1
Volvo	MEL	3.2	1.7	68.5	n/a	12.7
Volvo	PEMS2c	92.5	7.4	197.1	110.3	119.7

Table 5-1 PEMS and MEL mean concentrations percent of instrument span calibration



(a) **(b)**

Figure 5-8 Cummins (a) and Volvo (b) bsCO emissions comparison between the MEL and PEMS2

6 Lessons Learned and Operational Issues

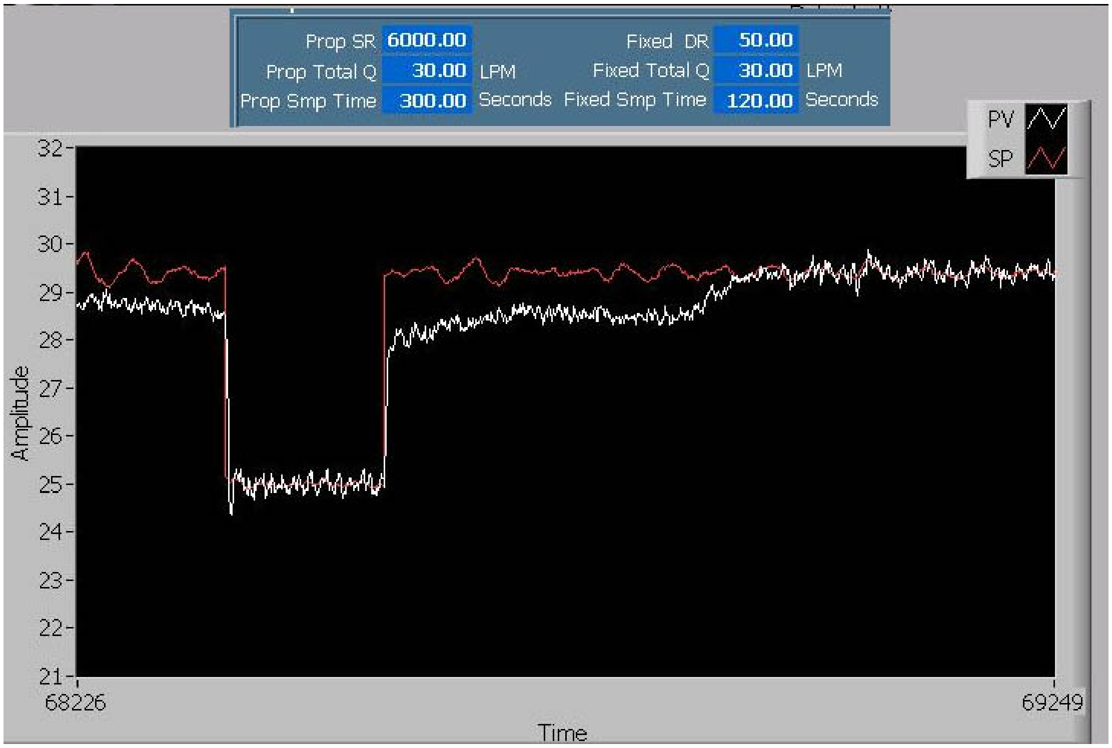
In this section PEMS problems are discussed for the Caterpillar, Cummins and Volvo tests. All the PEMS were evaluated during the Caterpillar tests, but only PEMS2 – 5 were considered for the Cummins and Volvo tests. PEMS1, 2, and 3 were mounted outside the MEL and represented a true in-use evaluation. PEMS4 and 5 were integral parts of the MEL and were not evaluated as in-use PEMS. During the Caterpillar tests, PEMS1 and 2 were operated and analyzed by the PEMS manufacturer, thus the Caterpillar problems presented here do not completely characterize what would be expected during MA testing and MA validation. UCR operated and analyzed PEMS2 during the Cummins and Volvo tests, thus a more detailed analysis is presented for this PEMS2 system. The PEMS2 additional Cummins and Volvo lessons learned include potential issues with post processor validation, crystal drift, signal spikes, sampling delay, and zero offsets in the pressure transducers. PEMS3 was operated by UCR, but due to its simplicity no additional analysis was necessary between the first and second studies.

Some of PEMS1, 2 and 3 problems were presented in the MA report [Durbin et al 2009] and are repeated hear with the newer PEMS2 and 3 issues discovered during the Cummins and Volvo testing. This section is organized by PEMS than each by engine tested. A complete description of all problems in a chronological order is available in a copy of UCR's field notes presented in Appendix H. The summary of problems presented here focuses on observations made from the both studies with feedback from the PEMS manufacturers, discussions during post-test MA meetings, and some UCR observations.

6.1 PEMS1 Caterpillar 2000 Engine Only

Manufacturer Operated PEMS1

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 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 6-1. 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 6-1 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 removing 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 caused the PEMS1 manufacturers 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.

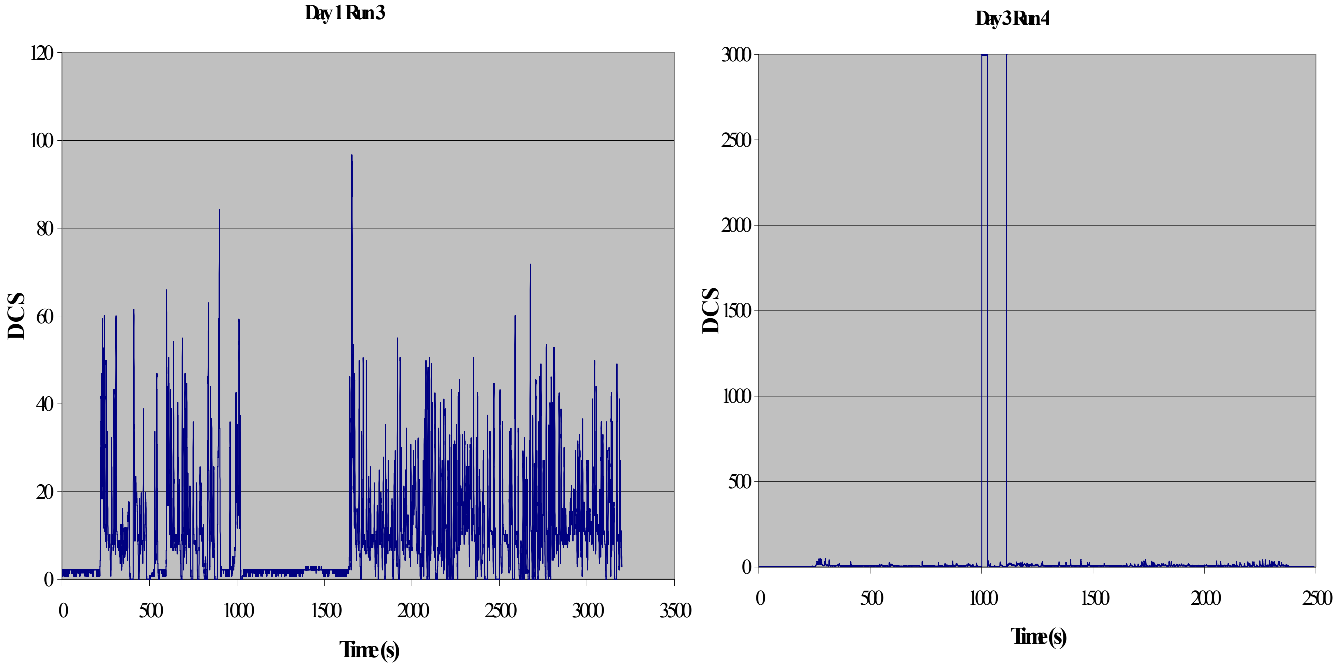


Figure 6-2 PEMS1 EAD real-time signal a) typical valid measurement b) during a communication problem

Overall, PEMS1 system is relatively simple and based on proven technologies that once integrated robustly should provide reliable information that is easy to diagnose during operation. The PEMS1 primary measurement systems depend on mass flow controllers, dilution ratio proportionality, temperature control, electrical aerosol detection and filter mass. All these technologies independently have been proven to be reliable for several years. The main challenge for PEMS1 is to integrate these signals, provide a reasonable calibration approach and switching control to manage in-use NTE's with-in the filter weight and EAD signal. The simplicity in the pieces requires only monitoring proportionality, filter temperature, filter flow and EAD signal.

In addition to operating PEMS1 there is the challenge in post processing the bsPM data. At the time of PEMS1 testing, all data was processed by the manufacturer. It is uncertain how much difficulty there is in processing the PEMS1 data. One should not consider this trivial since filter weight gain is over several PEMS1 events. The weight gain on the filter needs to be parsed for all the individual NTE's. Also, PM spiking is known to be highest at the beginning of an event where time alignment approaches can have a serious consequence to short bsPM results. Thus, post processing bsPM data for PEMS1 could vary the emissions results and post processor version numbers should be documented in order to compare PM data between different test programs.

6.2 PEMS2 Caterpillar 2000, Cummins and Volvo 2007 Engines

This section covers the problems with PEMS2 for all three test vehicles and is grouped by test vehicle. During the Caterpillar testing the manufacturer operated the PEMS2 system therefore most of the problems are based on post processed results and not obtaining those results. During the Cummins and Volvo testing, UCR technical staff operated the PEMS2 systems. Due to complexity and the need to acquire high data yield, trained engineering staff was needed to perform all PEMS2 tests.

Manufacturer operated PEMS2 Issues

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 Caterpillar testing and at the time of this study 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 6-3 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 a 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 percent of low power sample time is low.

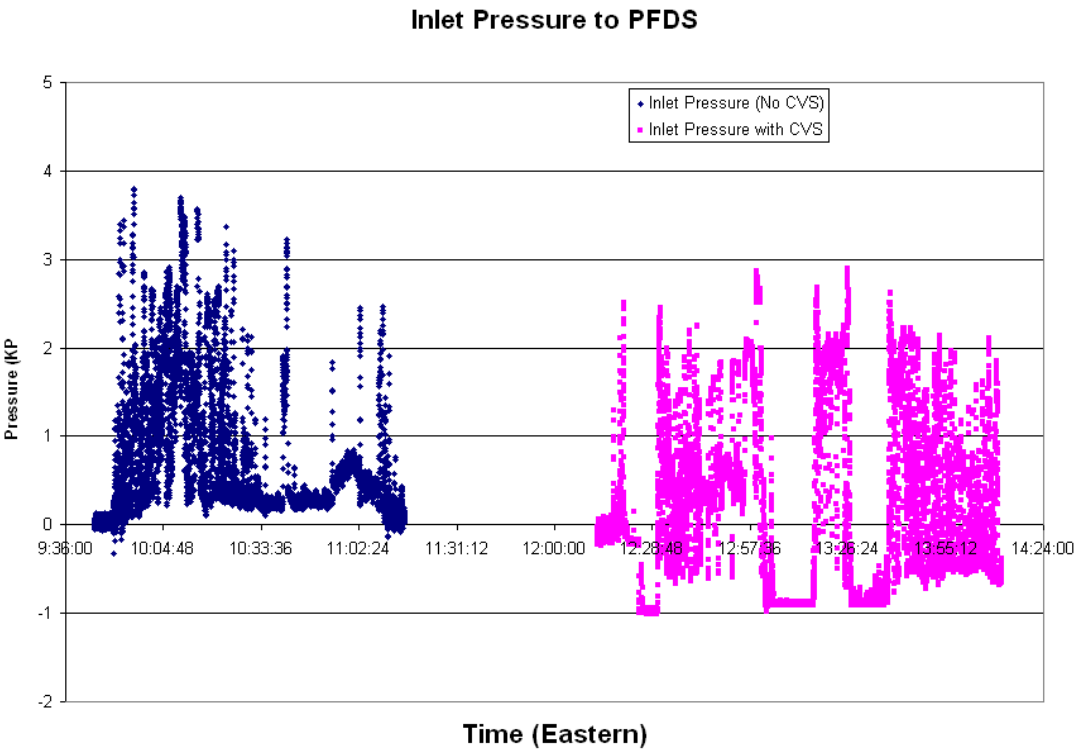


Figure 6-3 PEMS2 Sample inlet to proportional sampler with and with out CVS during (day 6)

Several discussions about PEMS2 dilution, crystal operation, and NTE triggering occurred between the EMA/EPA and the PEMS2 manufacturer 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 flow rate; combined crystals (5 min max each)
- Day 5: Single dilution, 0.25 LPM flow rate, combined crystals. Data collected differently, causes PPMD post-processor to crash.
- 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. Due to the nature of this study, with the forced 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 re-sampled 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 this EMA funded study showed that re-sampling periods on the same crystal were separated by as little as 100 seconds as described later in this section.

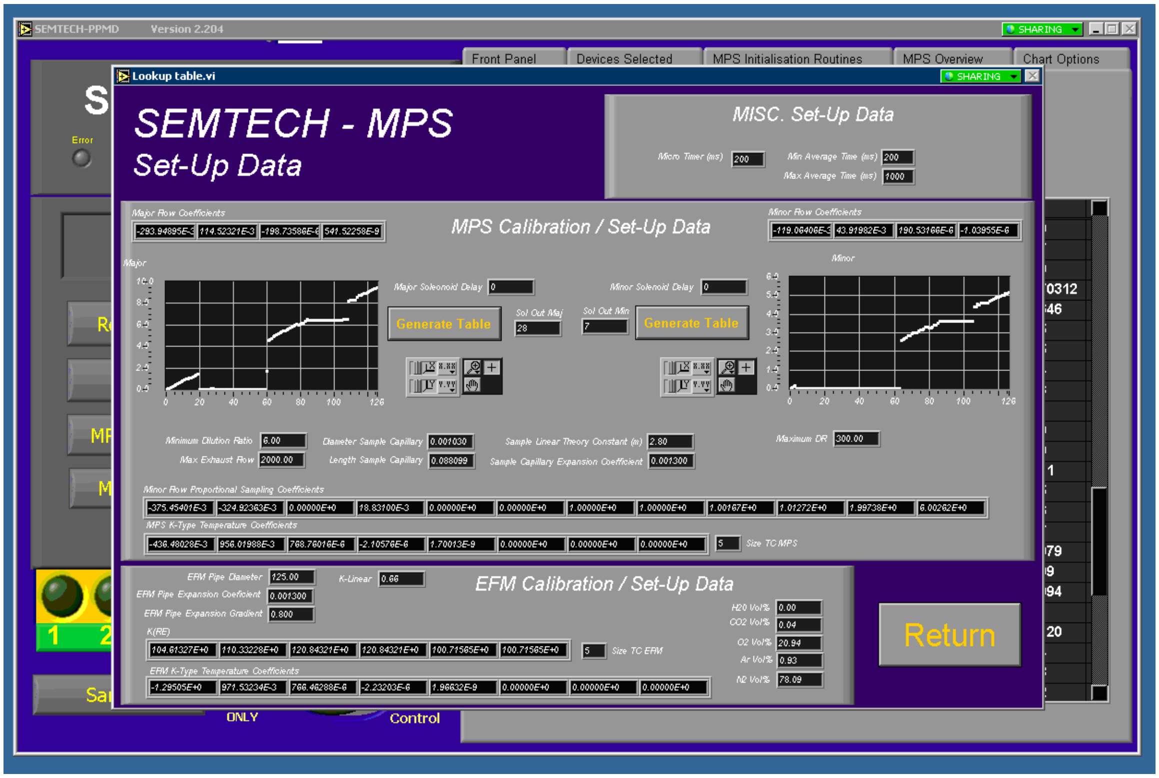
UCR Operated PEMS2 Issues

During the first PM PEMS study the manufacturer operated the PEMS for the most part and thus issues were discovered mostly in the results and not from PEMS operation. During this study, UCR operated all the PEMS and post processing where several new issues were discovered. The issues ranged from startup difficulty, faulty parameters in the code causing incorrect control, condensation in sample lines, frozen crystals still being used in sampling mode, unstable crystals thus loss of data and valve switch timing issues. A complete documentation of the field notes and problems can be found in Appendix H.

In addition to operational problems a unique post processing problem was discovered that had significant consequences to the bsPM reported by PEMS2. The PEMS2 post processor was not complete and small changes in data processing had significant affects on reported bsPM emissions as discussed earlier in the results section. These findings described within this section are complicated to understand and difficult to evaluate. It is expected by the time of this writing several new versions of the post processor will be available and a through analysis of the post processor will be out of date. Only a limited analysis on the current post processor is considered to give the reader a feel for the data sensitivity to post processing.

On average the startup of the PEMS2 PM components took over 4 hours and some times prevented going out for the day. Typically startup delays were in performing the manufacturers recommended startup procedure which entailed flow meter calibrations, crystal checks, look up table checks and sensor calibrations. Figure 6-4 shows an example of the calibration of the MPS major and minor flow systems. The discontinuity in the line informs the user that there is a problem and that the calibration needs to be repeated. This happened several times and requires a continuous repeats until a good calibration was achieved. The manufacturer explained the problem as a communication issue within one of the PEMS2 micro controller systems over their

CAN bus protocol. The data during the check was lost due to communication and thus bad values were put in the lookup tables. If this was not fixed, the proportionality would be out of control. The problems were not failures in the checks, but failures in managing the valid data from the checks.



Micro Timer (ms) 200
Min Average Time (ms) 200
Max Average Time (ms) 1000

Major Flow Coefficients
-293.94895E-3 114.52321E-3 -198.73586E-6 541.52258E-9

Minor Flow Coefficients
-119.06406E-3 43.91982E-3 190.53166E-6 -1.03955E-6

Major Solenoid Delay 0
Sol Out Maj 28
Minor Solenoid Delay 0
Sol Out Min 7

Minimum Dilution Ratio 6.00
Max Exhaust Flow 2000.00
Diameter Sample Capillary 0.001030
Length Sample Capillary 0.088099
Sample Linear Theory Constant (m) 2.80
Sample Capillary Expansion Coefficient 0.001300
Maximum DR 300.00

Minor Flow Proportional Sampling Coefficients
-375.45401E-3 -324.92363E-3 0.00000E+0 18.83100E-3 0.00000E+0 0.00000E+0 1.00000E+0 1.00000E+0 1.00167E+0 1.01272E+0 1.99738E+0 6.00262E+0

MPS K-Type Temperature Coefficients
-436.48028E-3 956.01988E-3 768.76016E-6 -2.10576E-6 1.70013E-9 0.00000E+0 0.00000E+0 0.00000E+0
5 Size TC MPS

EFM Pipe Diameter 125.00
K-Linear 0.66
EFM Pipe Expansion Coeficent 0.001300
EFM Pipe Expansion Gradient 0.800

K(RE)
104.61327E+0 110.33228E+0 120.84321E+0 120.84321E+0 100.71565E+0 100.71565E+0
5 Size TC EFM

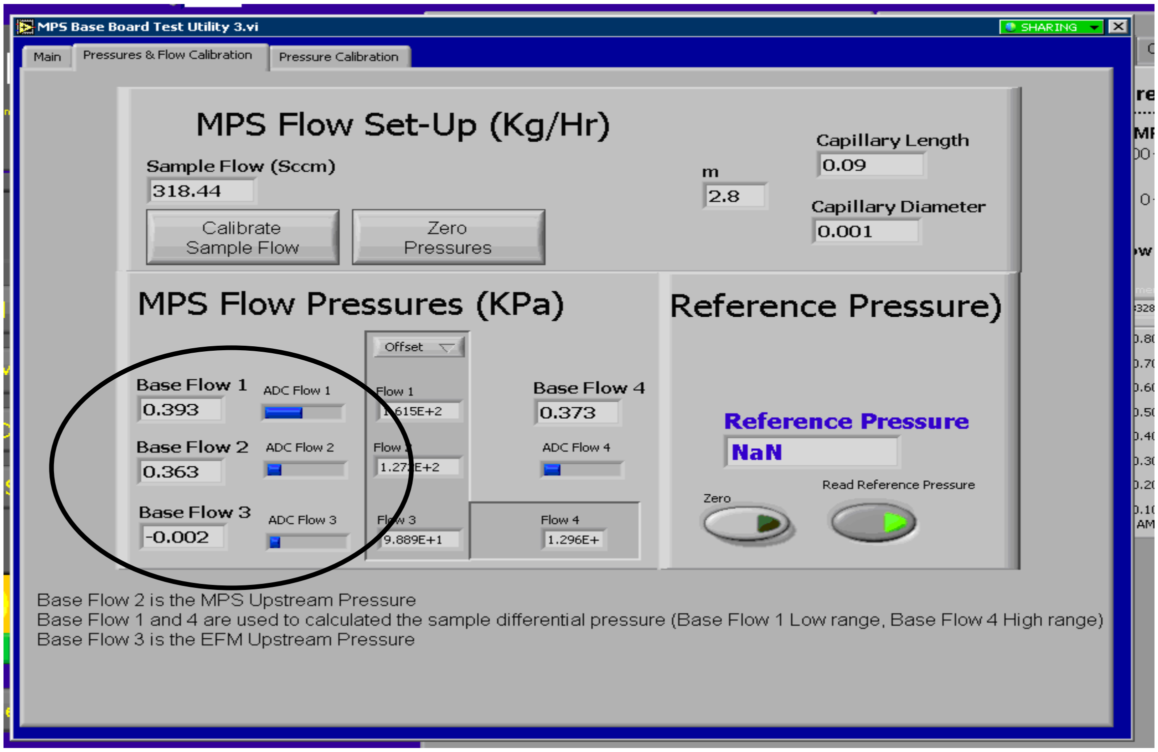
H20 Vol% 0.00
CO2 Vol% 0.04
O2 Vol% 20.94
Ar Vol% 0.93
N2 Vol% 78.09

EFM K-Type Temperature Coefficients
-1.29505E+0 971.53234E-3 766.46288E-6 -2.23203E-6 1.96632E-9 0.00000E+0 0.00000E+0 0.00000E+0

Figure 6-4 PEMS2 Proportional flow system (MPS) look-up table calibration

One of the most time consuming parts of the startup was the crystal frequency check. This procedure took about 15 minutes. Typically, the check would fail or freeze during the procedure which required the process to be repeated. Several times the procedure was repeated and took more than an hour complete. Near the end of the Cummins testing, the manufacturer gave permission to UCR to skip this procedure. A description of details of this issue and associated screen shots during repeated tests is provided in UCR's field notes provided in the Appendix H.

Figure 6-5 shows an example of a failed pressure transducer calibration during startup. The calibration process was to press the zero button on the audit software then wait for the several pressure transducers to zero. The transducers are critical for determining sample flow and proportionality calculations. One time the sample flow transducer was not zeroing, as shown in the circled area by the blue bar that should be to the left representing a zero value in Figure 6-5. This screen is not in the audit software, but in a low level version of the auditing software that was necessary to see the problem. The audit software would step through the calibration and report that all was okay, but the sample flow was reporting flow when the system was off. The non-zero flow at no flow conditions suggested there was a problem.



MPS Flow Set-Up (Kg/Hr)

Sample Flow (Sccm) 318.44

m 2.8

Capillary Length 0.09

Capillary Diameter 0.001

MPS Flow Pressures (KPa)

Base Flow 1 0.393

Base Flow 2 0.363

Base Flow 3 -0.002

Base Flow 4 0.373

Flow 1 1.615E+2

Flow 2 1.27[illegible]E+2

Flow 3 9.889E+1

Flow 4 1.296E+

Reference Pressure)

Reference Pressure NaN

Base Flow 2 is the MPS Upstream Pressure
Base Flow 1 and 4 are used to calculated the sample differential pressure (Base Flow 1 Low range, Base Flow 4 High range)
Base Flow 3 is the EFM Upstream Pressure

Figure 6-5 PEMS2 Proportional flow system (MPS) pressure calibration

After several hours of investigation with the manufacturer on the phone it was discovered that some water built up in the sample lines put a slight head pressure on the transducer thus preventing a good zero, see Figure 6-6 for location of where water collected. The sample line that had the water in it is shown by the circled area in the middle of the figure. To clear the line the automated purge pump was not enough. UCR staff had to disassemble the cover and remove the line and purge with compressed nitrogen for about 5 minutes. UCR believes during the hot gas sampling in cool high speed (convection) driving that there are areas in the PEMS2 system that could collect water. This problem did not repeat itself during the later Volvo testing on a different serial number PEMS2.

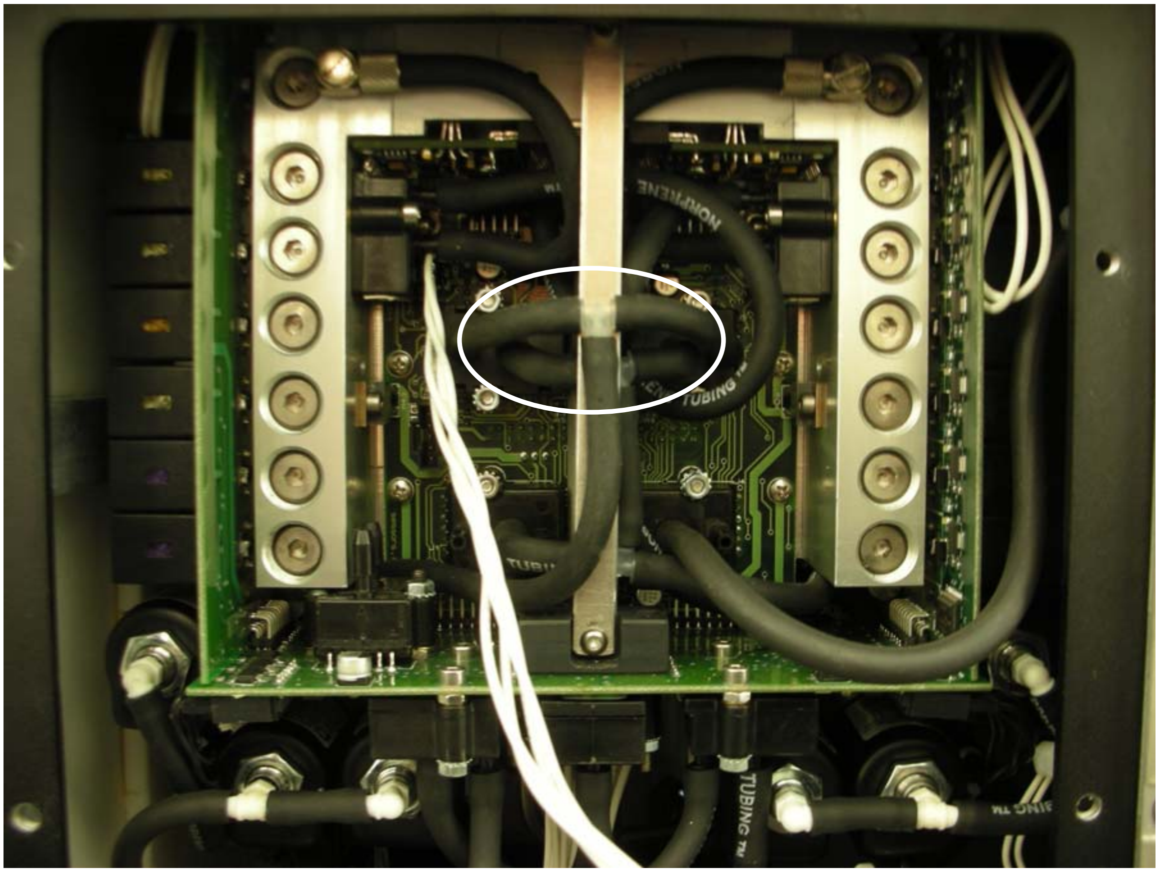


Figure 6-6 PEMS2 Proportional flow system (MPS) sample tubing and systems

During PEMS2 in-use operation it was necessary to view the low level data screens in order to determine system status. Typically one would want to verify crystals are oscillating, valves switch during an event, locked out crystals don't get used, and where the reference crystal is to make sure it doesn't get sampled. During the first test runs on the Cummins engine, the crystals were setup in a fixed sample mode where the crystals routinely rotated from crystal-to-crystal every 60 seconds regardless of event triggers. The crystal rotation prevented one full test run from getting any valid data. The problem was only discovered by reviewing the low level data and noticing crystals were engaging when no events were triggered. Untrained staff would not have caught this issue where a full day of testing could have been lost instead of one test run.

Another issue that was caught by viewing the low level data was sometimes two crystals were engaged at once. The manufacturer did not understand this problem and assumed there was something occurring during the fixed sample mode and request for a forced trigger that caused the double crystal sampling. This problem was only found on the Cummins tests and not on the Volvo tests.

Another issue that was caught by viewing the low level data was related to dilution ratio control. Figure 6-7 shows the dilution ratio set point and actual value are not in control. This is shown by the actual value remaining at zero while the set point tracks the exhaust flow. The problem was discovered by watching the values for dilution and noticing there was no change even though the exhaust was varying. It turns out there was some corrupt parameters in some of the micro controller data tables. UCR was able to re-enter these low level parameters using a host controller program and resetting the system. This issue prevented data collection on another test run of four forced events.

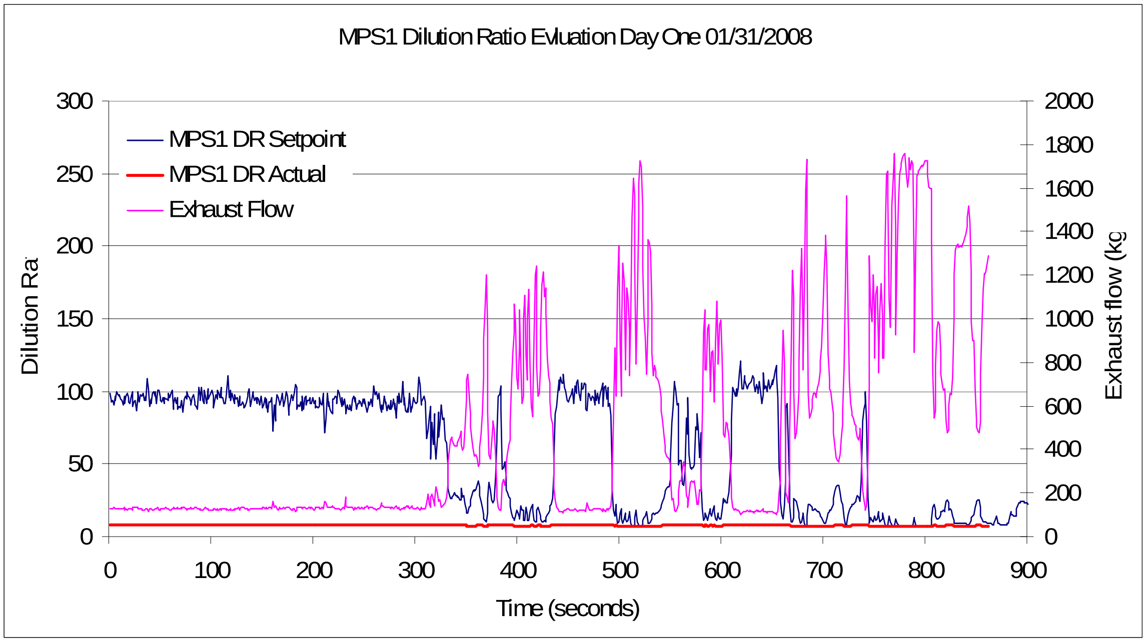


Figure 6-7 PEMS2 dilution ratio control for an early test with the Cummins engine

Several significant issues were uncovered by post processing the PEMS2 data that were not discovered during the earlier Caterpillar study. The post processor problems exposed issues such as crystal stability, valve switching, data filtering, work integration and final emissions calculations. The results behind the PEMS2 system are heavily dependent on the post processor given the decisions the post processor has to make and the impact these decisions have on the final results. The PEMS2 real-time data is not like a typical analyzer that provides a continuous stream of data in response to measurements. Instead PEMS2 signals are batch operated where the before and post event masses are decided by the post processor. The post processor decides how much time before/after an event to start, how long to average and then decide if the data is stable. The post processor has to also decide if a reference crystal should be subtracted or not.

An example of the post processor properly excluding data is shown in Figure 6-8. The crystal #2 mass gain, as shown by the circled section of data, represents the pre- and post-mass weight gains. The pre-signal looks good if you consider a 30 second average just before the event, 60 seconds before the event and 200 seconds before the event. The reason this event was discarded was due to the post filter weight gain which was not stable except for a region around 300 seconds after the event. The point here is that instability is relative to the starting point of the averaging and the duration. The figure shows clearly the data is not stable, but depending on when the filtering and decision making is made, a crystal weight gain like the one shown could be validated.

One example where the PEMS post processor validated a forced event that UCR's review process invalidated is presented here. The PEMS bsPM for this event was 0.006 g/hp-h and the MEL measured 0.001 g/hp-h. UCR removed this point because the pre-mass weight gain was during a condition where the pre-mass data was from a time interval several minutes before the sampled event. It turns out the filtering for the PEMS processor occurs first. Thus, if data before an event was removed, the post processor would average data from 60 seconds before even though the data was from several minutes before. The data was cut out and the PEMS processor used the data from 60 rows earlier not by time, but relative to the data available. This is hard to explain, but was discussed with the manufacturer as a bug in the post processing software. A more detail explanation is not provided since these issues are relative to the current version of the post processor and thus will vary greatly depending on the version. They are important though to show the sensitivity and complexity of the data processing. It also suggests the bsPM PEMS2 data is dependent on the post processor version.

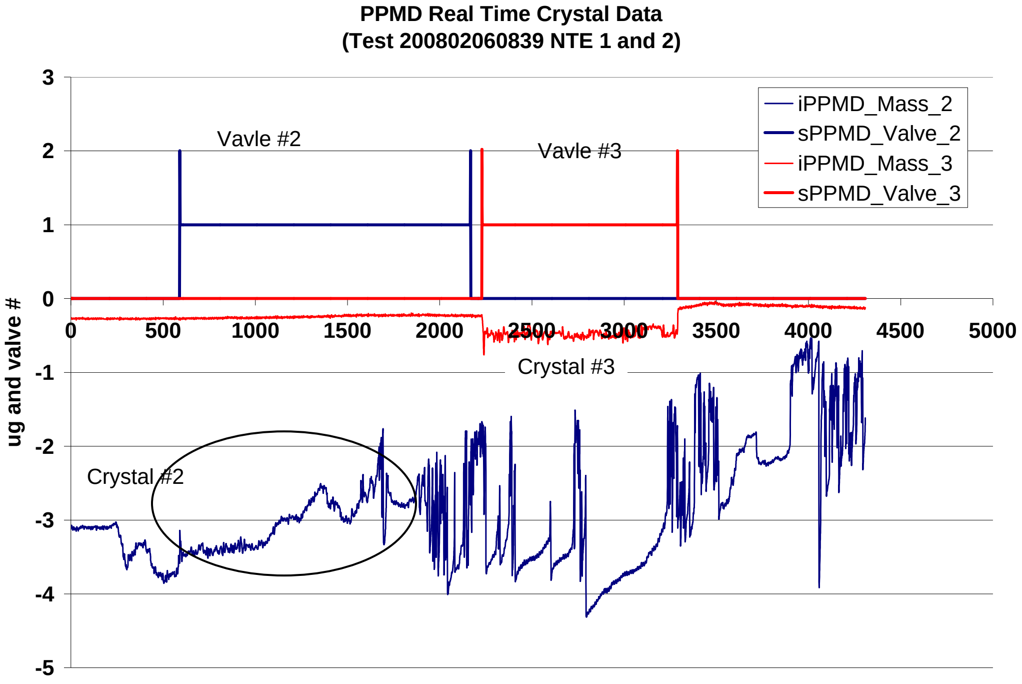


Figure 6-8 PEMS2 crystal mass gain and valve response during in-use testing Event #1 and 2

Data filtering, or the removal of data by the post processor, varied for the Cummins and Volvo tests. For the Cummins tests, most of the data filtered was due to invalid temperature, unstably crystals, and not oscillating crystals. Typical data filtering that removed data rows averaged 11% with three filtered runs at 70, 40, and 20%, and the remainder of runs having less than 5% data filtering. For the Volvo testing, the averaged filtering was higher at 38%. The Volvo data showed half of all the events with more than 50% filtering and the other half of data at less than 5% filtering. It is expected that different versions of the post processor will change the amount of filtering and thus change the bsPM reported by PEMS2. The point to make with the post processor is that the final valid data is heavily analyzed and dependent on the post processor version.

Another problem discovered with the PEMS2 operation was valve timing and crystal switching. The valve timing is best explained by Figure 6-9 where the PEMS2 valve trigger signal leads the signal that shows when the valve switches from bypass to sampling on the crystal surface. The difference in time between sampling and the trigger is 6 seconds for the example in Figure 6-9. Another good indicator of a switched valve is the slight change in sample flow as shown by the bypass flow signal in blue. Figure 6-9 shows the bypass flow delay is also about 6 seconds delayed in starting the sample on the crystal which agrees with the valve trigger signals. For all the data collected for both the Cummins and Volvo tests (over 40 tests) the average delay times was 3.5 seconds for the start and stop times and randomly varied up to 6 seconds for pre and post valve control. More details with all the delays times and figures are presented in Appendix J.

Valve timing for PEMS2 batched operation became a contentious issue for the MA committee. The problem with valve timing is that typical PM spikes can occur early in an event where, for short events on the order of 30 seconds, it is believed most of the mass would be missed by the PEMS2 valve switching. Another problem that came out of the deeper look was that work integrated with the mass loading was not integrated over the same time period. These issues are not fully resolved and will be part of this PEMS2 measurement allowance. PEMS2 manufacturer did see the valve timing as a problem and showed during SwRI testing to have reduced the variability in valve timing for MA testing. It is unclear at the time of this report if the problem will be discovered by other users of the PEMS2 instrument during in-use testing.

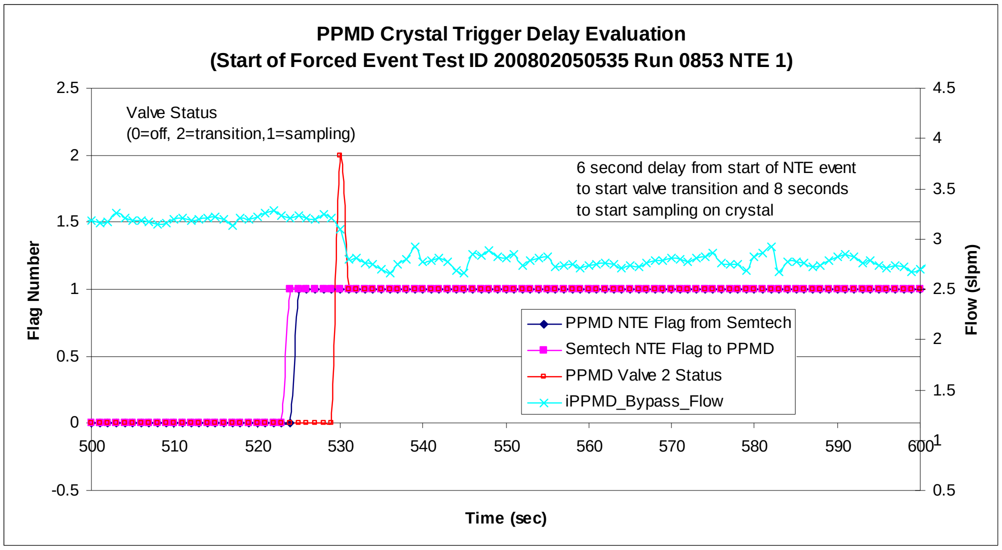


Figure 6-9 PEMS2 valve switching and sample flow on time delay from trigger on signal

The integrated work between the gaseous and PM part of the same PEMS2 systems was different and could cause PEMS2 bsPM to vary. As presented in the results section, the integrated work by the PEMS PM system and by the gaseous PEMS system varied by 1-2% even with the long forced event sampling times of 20 minutes. The gaseous PEMS and the MEL measured the same work to less than 0.1% thus the error appears to be within the PM part of the PEMS2 system. It is unclear what affect work and mass accumulation will have on short 30 second NTE's, but this uncertainty will be accounted for by the measurement allowance and is part of the PEMS black box result.

During the last day of Volvo testing, UCR attempted to perform true NTE operation to evaluate bsPM emissions over short real NTE's. The goal was to operate the Volvo engine with no regenerations and use one bypass setting to see the variability in real-time bsPM and the PEMS2 ability to operate in true NTE mode. The MEL was operated using forced events for PEMS3, 4 and 5 which gave a feel for the bsPM over NTE and non-NTE operation. The real-time PEMS3, 4, and 5 could then be used to provide a feel for the NTE bsPM emissions over the same events as PEMS2. At first, the real-time NTE operation did not work with the PEMS2 firmware. The manufacturer was contacted and a beta version of the software was used to get some valid NTE bsPM data for the last day of testing.

Figure 6-10 shows the PEMS2 real-time NTE PEMS2 results. The PEMS2 NTE was triggered by the ECM during in-use operation which simulates what would happen during typical in-use testing. A total of 17 valid NTE points were identified by the PM PEMS and its post processor. The nominal PEMS2 NTE bsPM was 0.001 g/hp-h (excluding visible outliers). The MEL reference bsPM, during NTE and non NTE operation, showed a bsPM of 0.002 g/hp-h with a standard deviation of 0.001 g/hp-h. PEMS3 showed an NTE bsPM value of 0.0005 g/hp-h for the same events with out any outliers. Given the MEL nominal bsPM was 0.002, PEMS2 bsPM over 0.01 or large negative values could be outliers. Given these are outliers, 7 of the 17 NTE's would represent 40% of the collected data being outliers. More analysis is necessary to understand the cause for the data variability and to confirm if these points are truly outliers.

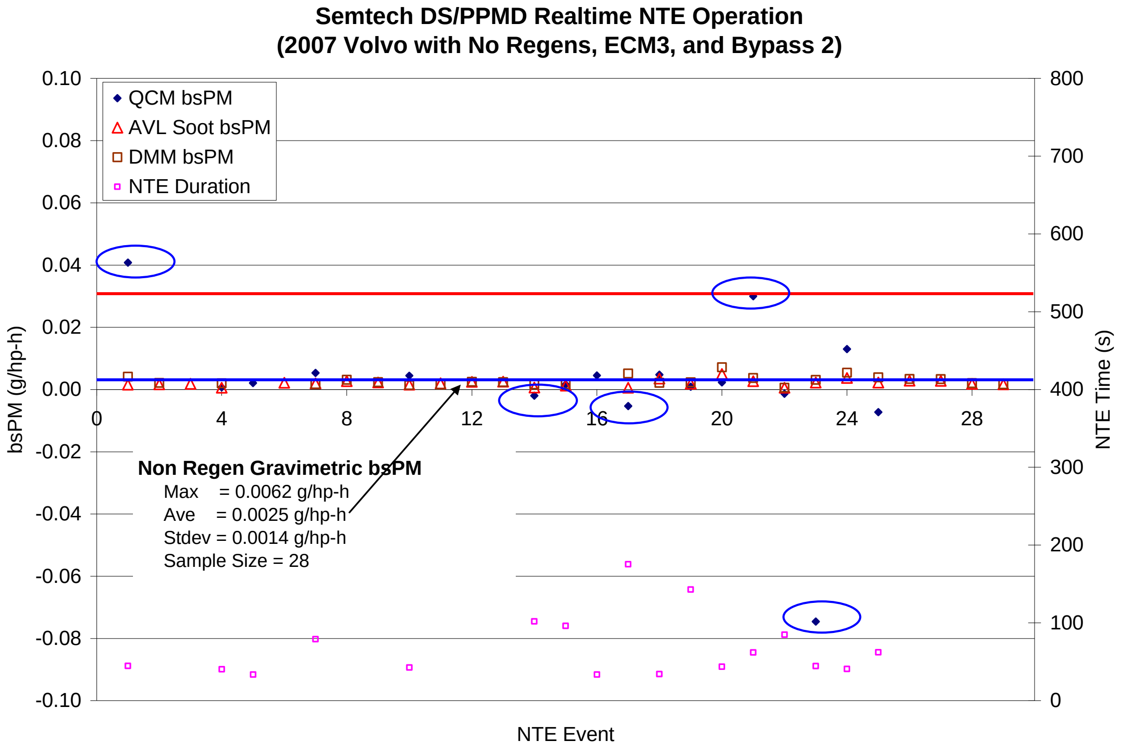


Figure 6-10 Volvo PEMS2c in real NTE mode during MEL forced filter events

Another significant issue discovered while operating the PEMS in real-time NTE operation was found by the identification of NTE's between the gaseous part of PEMS2 and the PM part of

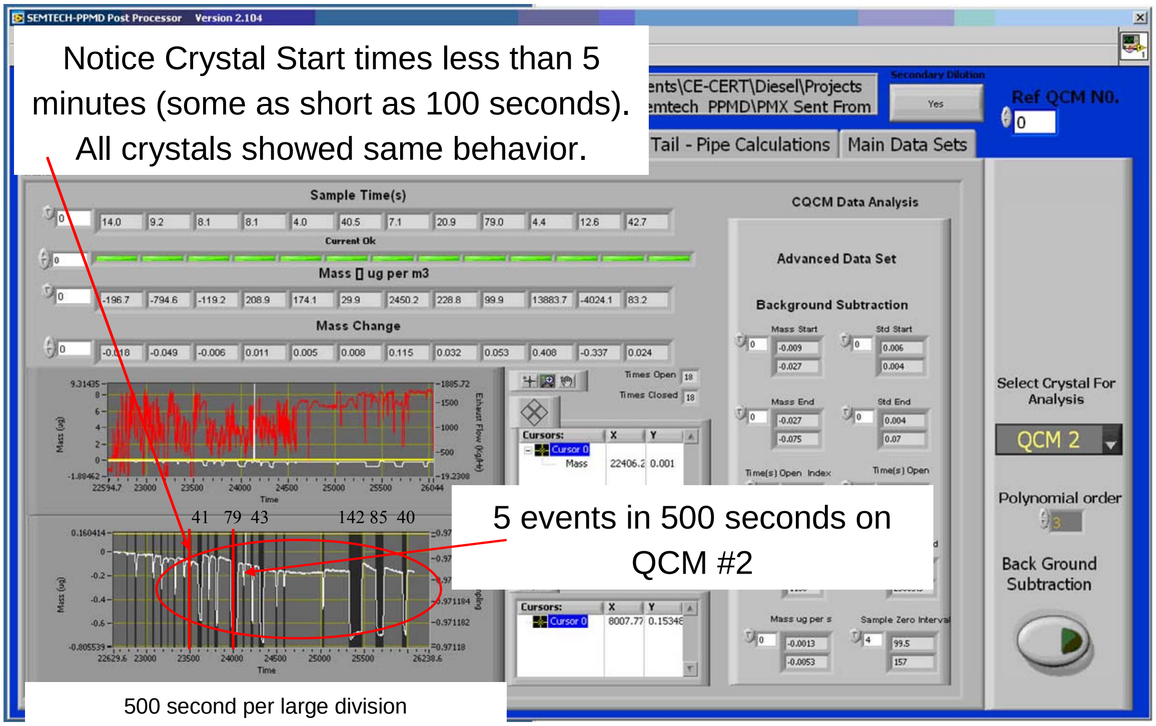
PEMS2. Table 6-1 shows the NTE events identified during the final day of Volvo testing. A total of 29 events were identified by the gaseous PEMS and only 17 were identified by the PM PEMS part. Of the 17 events, PM PEMS identified only 6 NTE's with start and stop times that were less than 10 seconds. This was very contentious issue for the MA committee and resulted in a requirement for PEMS2 to demonstrate that future NTE operation would improve the identification of the NTE events. A deeper analysis of the reason for this was not considered since it is expected future versions of the PM PEMS software would fix these problems.

Semtech vs PPMD Start Stop Times for QCM for real time NTEs on Volvo 2007 Engine

Common NTE	Semtech Evaluated NTE				PPMD Evaluated NTE				Time Deltas	
Events	Event	Start	Stop	Duration	Event #	Start	Stop	Duration	start	stop
1	1	11:20:55	11:21:38	43	1	11:20:57	11:21:41	45	1.3	3.0
2	2	11:24:05	11:24:39	34						
3	3	11:26:55	11:27:28	33						
4	4	11:32:08	11:33:16	68	2	11:32:36	11:33:17	41	27.8	0.3
5					3	11:36:42	11:37:15	34		
6	5	11:37:35	11:38:27	52						
7	6	11:38:34	11:40:01	87	4	11:38:46	11:40:05	79	12.2	4.2
8	7	11:40:31	11:41:03	32						
9	8	11:42:00	11:42:44	44						
10	9	11:43:41	11:45:00	79	5	11:44:19	11:45:02	43	37.8	1.5
11	10	11:45:44	11:46:14	30						
12	11	11:46:18	11:46:55	37						
13	12	11:48:17	11:48:52	35						
14	13	11:49:08	11:51:16	128	6	11:49:36	11:51:18	102	27.6	1.5
15	14	11:51:25	11:57:04	339	7	11:51:28	11:53:04	96	2.4	-240.3
16					8	11:56:32	11:57:06	34		
17	15	11:57:05	12:00:01	176	9	11:57:08	12:00:03	176	2.3	1.8
18	16	12:00:02	12:01:17	75	10	12:00:05	12:00:39	34	2.6	-38.1
19	17	12:01:21	12:03:46	145	11	12:01:26	12:03:49	143	4.4	2.2
20	18	12:03:48	12:04:33	45	12	12:03:50	12:04:34	44	2.0	0.6
21	19	12:04:35	12:06:26	111	13	12:04:37	12:05:39	62	2.0	-47.1
22	20	12:06:30	12:07:55	85	14	12:06:32	12:07:57	85	2.0	2.0
23	21	12:08:16	12:09:05	49	15	12:08:24	12:09:08	45	7.3	2.9
24	22	12:09:06	12:13:19	253	16	12:11:38	12:12:19	41	152.0	-60.3
25	23	12:15:24	12:16:58	94	17	12:12:19	12:13:21	62		
26	24	12:18:50	12:19:26	36						
27	25	12:19:45	12:20:56	71						
28	26	12:20:57	12:23:05	128						
29	27	12:23:06	12:23:42	36						

Table 6-1 Real NTE operation for the PEMS2 gaseous and PM systems on the Volvo tests

During the deeper analysis of the PEMS2 post processed data, it was discovered that the PEMS2 was not stabilizing for the 5 minutes as stated in the manual and recommended by the manufacturer. Figure 6-11 shows several real-time NTE events resampling on crystal #2 as soon as 100 seconds. After discussion with the manufacturer and the MA committee, PEMS2 manufacturer was instructed to lock down this parameter, which subsequent testing at SwRI has confirmed that the 5 minutes stabilization is now operating properly.



Notice Crystal Start times less than 5 minutes (some as short as 100 seconds). All crystals showed same behavior.

5 events in 500 seconds on QCM #2

500 second per large division

Figure 6-11 PEMS2 crystal stabilization time are not waiting 5 minutes

Given limited funding and the depth of possible problems for PEMS2 system, a more through investigation was not possible. It is expected that other unique features may be exposed given more time with the data. The PEMS2 system is complex and manages more than three microcontroller communications over local networks with hundreds of system specific parameters. Even though the number of microcontrollers and the number of parameters are much less than the efforts of a common heavy duty diesel ECU communication network, they are substantial given the level of instrument maturity.

6.3 PEMS3 Caterpillar, Cummins and Volvo Engines

PEMS3 was operated by the manufacturer at the beginning of the Caterpillar testing, but UCR was able to take over operation by the middle of first round of Caterpillar testing due to its simplicity. All the PEMS3 data for the Caterpillar testing was processed by the manufacturer, but during the Volvo and Cummins testing this data was analyzed as part of the PEMS2 post processor. UCR in addition considered some PEMS3 points using the PEMS3 post processed results. No post processor difficulties were identified for PEMS3.

PEMS3 problems were primarily electronics overheating issues for the Caterpillar testing, some unusual signal noise during Cummins testing and no issues during the Volvo testing. PEMS3 was located closest to the engine heat and just below the exhaust system for the Caterpillar testing. During MA temperature profile discussions the PEMS3 location was 40°C hotter than the behind the cab location where PEMS1 and 2 were located. 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.

During the Cummins testing, it was discovered during a post test review of the data that there were some large noise issues for PEMS3. The noise was on the main concentration signal where the nominal measured value was 0.3 mg/m^3 with noise at ± 0.5 mg/m^3, as shown in Figure 6-12 Case A. At first, it was thought the problem was due to vibration issues. Two additional cases were tried to eliminate the noisy signal and denoted as case A, B, and C. Case A was the manufacturer recommended mounting system using PEMS3a mounted to the frame. It was believed the PEMS3a was the problem so PEMS3b was installed using the same mount as case A. The problem was still present, but with less magnitude, as shown in Figure 6-12 Case B. Lastly, Case C was tried with same PEMS3b, but this time the PEMS was moved inside MEL laboratory using insulating foam for the vibration mounts, see Figure 6-13. It appears the new location eliminated the noisy PEMS3b concentration signal as shown by Figure 6-12 Case C.

In addition to moving the PEMS3 instrument, the sample probe was moved due to constraints of sample length and articulation of the truck during in-use testing. The PEMS3 manufacturer said that the reduction in vibration from A & B to C has been seen in the past and could be associated to pressure pulsations within the exhaust pipe. The cause of these pulsations, as explained by the manufacturer, is a result of the PEMS location and the length of pipe used to tune the pulsations (the pulses were magnified as a result of the CVS connection).

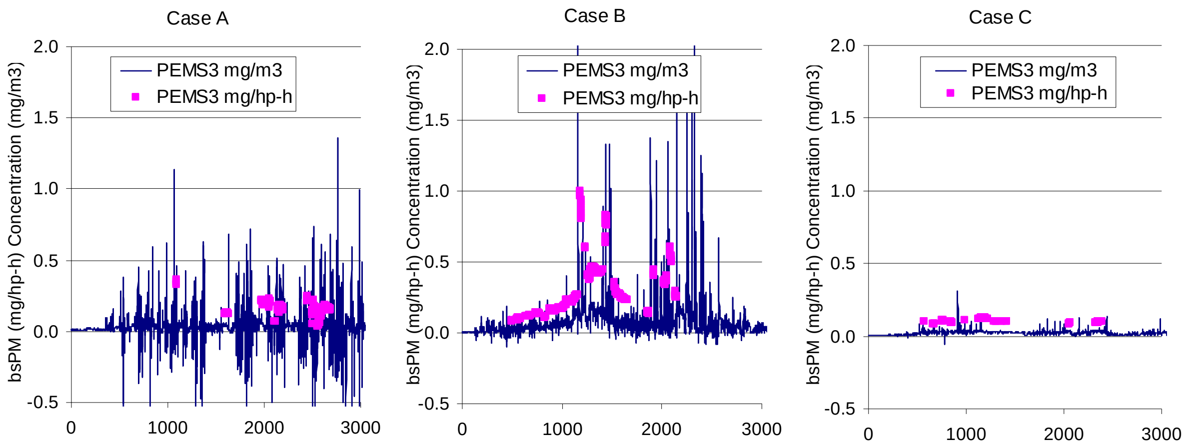


Figure 6-12 PEMS3 Instrument signal noise issue for Case A (1/31/2008), Case B (2/5/2008), and Case C (2/6/2008) while sampling the Cummins raw exhaust

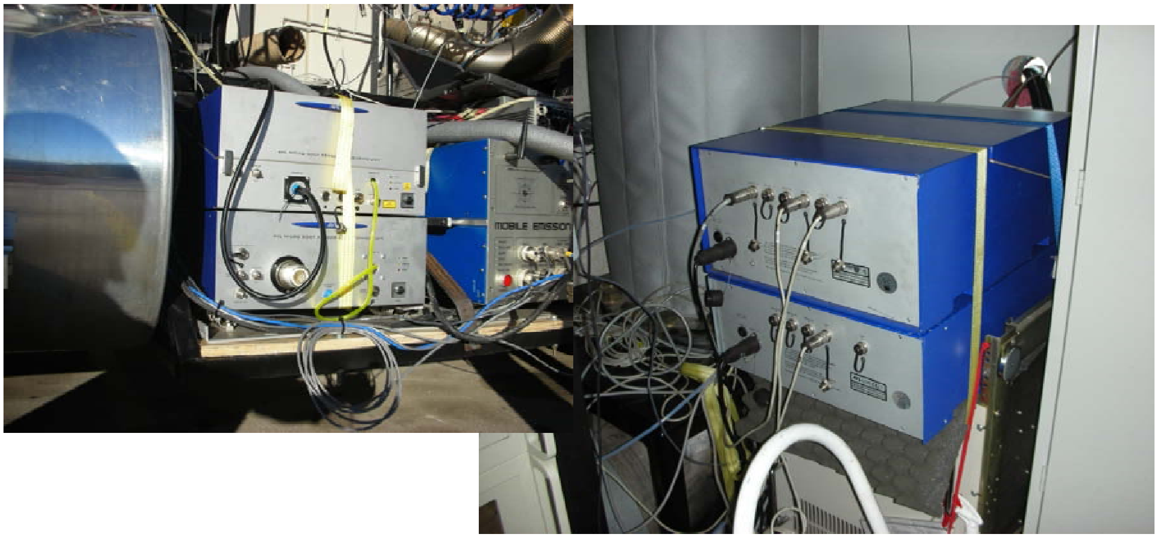


Figure 6-13 PEMS3 external and internal mounting while investigating the PEMS3 noise

Additional testing was performed to try and eliminate the exhaust pulsations and evaluate the claim by the PEMS3 manufacturer. To evaluate the theory, UCR and Caterpillar representatives installed a second PEMS3a and sampled ambient air and Hepa-filtered air while PEMS3a was mounted on the vehicle frame, as represented by Case A. The idea was if the noise was still present while sampling non pulsating air with the same mounting location then the noise was not due to exhaust pulsations. The noisy concentration signal was still present for both the ambient air sample and Hepa filter sample, see Figure 6-14. The fact that the noise was still present suggests that the noise was not an exhaust pulsation issue, but from some other source.

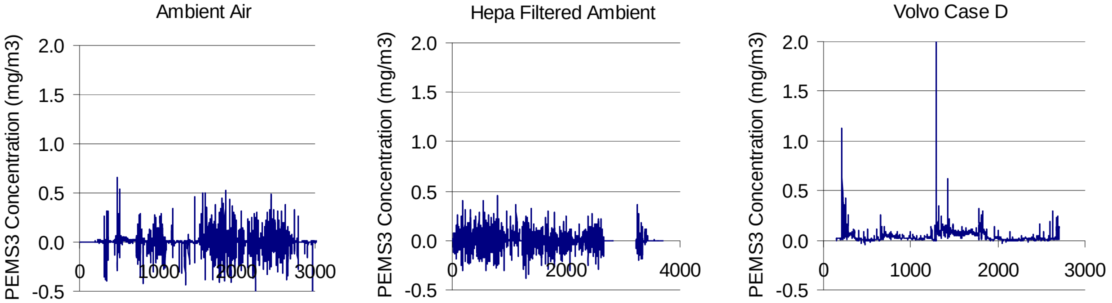


Figure 6-14 PEMS3 Instrument signal noise issue for direct ambient sampling Case A (2/7/2008), hepa filtered ambient sampling Case A (2/7/2008), and Volvo exhaust sampling Case D (3/20/2008)

One other suggestion that could explain the noise is from some acoustical noise generated from the engine or vehicle. It was noted during the Cummins testing that a unique noise was generated from the vehicle chassis that was not from the engine, but from new tires (knobby tire tread). The noise was loud enough to be difficult to talk in the cab of the test vehicle. The manufacturer had not heard of this problem before, but it was considered possible that this noise could be an interferent with the measurement principle of the PEMS3 detection method.

PEMS3b remained in the MEL from February 6th through the end of the Cummins testing. For the Volvo testing PEMS3 was mounted back on the frame and no issues were experienced with sound, vibration or exhaust pulsations. Even though the PEMS3 noise was significant on a second by second basis, the overall average bsPM NTE and forced events were not affected. Thus, this error is noted, but does not appear to affect bsPM at the event durations or the short NTE durations.

6.4 PEMS4, 5 and MEL Caterpillar, Cummins and Volvo Engines

PEMS4 and 5 were integrated 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 5.

PEMS4 required daily cleaning and higher dilution rations to prevent over ranging during the Caterpillar testing. Daily cleaning for PEMS5 was not necessary, only routine weekly cleaning. PEMS4 and 5 were in a laboratory setting except for altitude changes. Road vibration and thermal effects were isolated by laboratory air conditions and several forms of vibration isolation from the trailer air ride, bench air ride, and individual instrument rubber feet isolation. The only true in-use disturbance was altitude affects such as barometric pressure changes. Barometric changes can cause some minor flow rate corrections that can affect the PEMS4 impaction cut sizes and overall concentration effect. No known barometric affect is expected for PEMS5.

The MEL reference system had some operational issues during the beginning of the Caterpillar test program. 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.

7 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 section, 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.

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.

Regeneration is potentially a serious problem for all PEMS, including the PEMS1 gravimetric filter reapportionment method and PEMS2 quartz surface detection. In-use regulations may not exclude regeneration operation, thus it is important for the PEMS users to understand the PEMS responses during regenerations.

The fundamental sources of error are considered for PEMS1 and 2. PEMS3, 4, and 5 were not considered due to their level of acceptance by EPA as part of the MA program. PEMS3 was considered at one time as a possible alternative, but PEMS4 and 5 are not being considered. Thus, the sources of error are focused on PEMS1 and 2.

7.1 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 earlier, so this section 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 of magnitude higher concentrations of small particles in the size range just greater than 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 (free molecular, transition and continuum regimes) . Two prior studies [Jung and Kittelson, 2005; Fissan et al., 2007] have characterized the EAD up to 150 nm, where most of particle number exists, and their calibration curves ($d_p^{1.13}$) match well with the manufacturer's that cover 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 measurements 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. It is also worth noting that the European Particle Measurement Program (PMP) is another methodology used for regulations, which utilizes the measurement of "solid" particle number counts (d_p^0).
- 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]. A nucleation event can appear seconds after a rapid deceleration (such as switching gears). This could be seen during 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.

7.2 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 earlier, so this discussion 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]. There has been some indication that corona charging can change gas phase composition, 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.
- Water bound to sulfate particles will vary between the Teflon filter and the quartz crystal surface due to the different conditioning with humidity, temperature and stability time. For the Teflon filter the conditioning is controlled as per 1065 at 21°C, 45% RH and several hours stabilizing at these conditions. For the PEMS, the conditioning is at 47°C, at the humidity at the time of sampling, and stabilizing times on the order of a few minutes.
- 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.

8 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 and the associated earlier program were conducted as preliminary investigations 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 these two pilot programs, PM PEMS were directly compared with the UCR Mobile Emissions Laboratory (MEL) under on-the-road driving conditions. The MEL is a full 1065 compliant constant volume sampling system (CVS) with gravimetric PM measurements. Measurements were made from three class 8 trucks over a series of different on-road driving conditions. The trucks were selected to achieve a range of PM mass loadings from above the in-use PM standard of 0.03 g/hp-h to less than the certification standard of 0.01 g/hp-h. One truck had 2000 Caterpillar engine without a DPF and the other two were equipped with OEM DPFs, one from Cummins and the other from Volvo. Each of the 2007 vehicles was modified to vary their emission levels using regeneration and a bypass. 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.

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 events were utilized to target filter masses between 50 and 200 µg. The results show that the filter masses ranged from approximately 5 µg to over 400 µg, with most of the test filter mass values within the targeted 50-200 µg range.

- Brake specific PM emissions varied from 0.1 g/hp-h to 0.0003 g/hp-h over the different vehicles and operating conditions. The composition of the particles also varied from vehicle to vehicle, with one vehicle having high EC, one having high OC, and another having a substantial amount of sulfate.

- PEMS1 was one of the primary PM PEMS being considered for the PM measurement allowance program. PEMS1 was tested only on the 2000 Caterpillar vehicle. The correlation for PEMS1 on this vehicle 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.

  Estimates of the 5th and 95th percentile confidence limits at the 0.03 g/hp-h emissions level and incorporating any biases provided a range from -0.039 to 0.068 g/hp-h for the full data set and -0.013 to 0.045 g/hp-h for the final day of testing. The 90% confidence interval was 0.053 g/hp-h for the full data set and 0.029 g/hp-h for the last day.

- PEMS2 was one of the primary PEMS being considered for the PM measurement allowance program. It was tested on all three vehicles. For the 2000 Caterpillar vehicle, the correlation for 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. For the 2007 Cummins vehicle, PEMS2 showed a poor correlation (R^2 = 0.1), low slope (0.1), and positive zero intercept (0.001 g/hp-h). For the 2007 Volvo vehicle, PEMS3 showed better results with a correlation of R^2 = 0.9, a slope of 0.84, and positive zero intercept of 0.001 g/hp-h.

  It should be noted that subsequently, the PEMS2 instrument manufacturer indicated a change in the QCM instrument sensitivity that would further increase PEMS results by 1.25 times. The original data were not updated in the present report for this change. This new factor would make the PEMS2 correlation worse for the Caterpillar tests, but improve it for both the Cummins and Volvo tests.

  Estimates of the 5th and 95th percentile confidence limits at the 0.03 g/hp-h emissions level and incorporating any biases provided a range from -0.011 to 0.068 g/hp-h for all the vehicles and from 0.007 to -0.004 g/hp-h for the 2007 engines. The 90% confidence interval was 0.04 g/hp-h for the full data set and 0.006 g/hp-h for the 2007 vehicles.

- 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 was tested on all three vehicles. For the non-DPF equipped, 2000 Caterpillar vehicle, 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 performance of PEMS3 for the DPF-equipped, 2007 Cummins and Volvo vehicles was much worse. For the Cummins vehicle, the correlation was R^2 = 0.45, the slope was 0.04, and the zero intercept was 0.000 g/hp-h. For the Volvo vehicle, the correlation was R^2 = 0.52, the slope was 0.1, and the zero intercept was 0.001 g/hp-h. The composition of the PM was predominantly sulfate for the Cummins vehicle and OC for the Volvo vehicle. The low correlations and biases for these vehicles is consistent with the PEMS3 instrument. PEMS3 is not as effective for the DPF-equipped vehicles with low mass levels and particles that are predominantly not EC in nature (e.g., sulfate or OC).

  The manufacturer performed a separate analysis utilizing a total PM model to account for SOF using the hydrocarbon, soot concentrations and the sampling conditions, sulfate using catalytic conditions, and thermophoretic losses. With the application of this model for the 2000 Caterpillar, the good correlation (R^2 = 0.94) was maintained, but the bias was essentially eliminated. The model improved the Volvo correlation, which was predominantly OC PM, with an R^2 increasing from 0.52 to 0.82 and the slope from 0.1 to 0.6, but still showed a negative bias. For the 2007 Cummins, the model improved the slope somewhat from 0.04 to 0.34, but was still biased negatively. Also, the correlation did not significantly improve (R^2 = 0.43). Since the composition of these particles was predominantly sulfate (Cummins) and organic (Volvo), additional information is probably needed to improve the model to account for the contribution of sulfate and SOF.

Estimates of the 5th and 95th percentile confidence limits at the 0.03 g/hp-h emissions level and incorporating any biases provided a range from -0.018 to -0.001 g/hp-h for the direct PEMS3 measurements and from -0.008 to 0.010 for the total PM PEMS3 modeled results. The 90% confidence interval was 0.008 g/hp-h and did not change significantly for the modeled results.

PEMS3 experienced some issues with electrical overheating due to the proximity of the instrument placement to the engine for some tests. Also, for one engine, the 2007 Cummins, PEMS3 experience considerable system noise, the source of which was not fully identified, but could be due to tire tread noise after a process of elimination.

- Two other PM-only PEMS were evaluated (PEMS4 and PEMS5). These PEMS are both used in semi-regular operation in the MEL. PEMS4 showed a reasonable correlation of R^2=0.77 and a slope 0.9 for the 2000 Caterpillar. For the 2007 Cummins vehicle, PEMS4 showed a good correlation with an R^2 of 0.8, but a slope of only 0.15, indicating this PEMS had difficulty with quantifying the mass levels for this vehicle. For the 2007 Volvo vehicle, PEMS4 showed a good correlation with an R^2 of 0.77 and a slope of 0.48, indicating the PEMS had some correlation with the MEL but underestimated the PM mass.

  PEMS5 showed a good correlation of R^2=0.88 and a slope near unity of 0.97 for the 2000 Caterpillar. This correlation is due in large part to the fact that this instrument calibrated against MEL gravimetric PM measurements, so it does not represent an independent measure of PM. For the 2007 Cummins vehicle, PEMS5 showed a poor correlation with an R^2 of 0.38 and a slope of only 0.07. Similarly, for the 2007 Volvo vehicle, PEMS5 showed a poor correlation with an R^2 of 0.4 and a slope of 0.35. This indicates that PEMS5 has difficulty with quantifying the PM mass levels for DPF-equipped engines and tends to underestimate the mass for these engines. Thus, the calibration that works effectively at the higher PM mass levels would need to be redone for the lower PM levels.

  Estimates of the 5th and 95th percentile confidence limits at the 0.03 g/hp-h emissions level and incorporating any biases provided a range from -0.026 to 0.004 g/hp-h for PEMS4 and from -0.016 to 0.005 for PEMS5.

- All PEMS under reported the measurement of the Cummins small nano-particles which were predominantly composed of sulfate. The magnitude of the under reporting is not known, but is around 80-90% of the reference mass. More measurements are needed to quantify this better for some PEMS. As a note PEMS1 was not evaluated on the Cummins vehicles so PEMS1 ability to measure these particles is not known.

- 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 a number of problems both when operated by the manufacturer and when operated by UCR. During the tests where the instrument was operated by the manufacturer, some of the problems related to lack of in-use operational experience and not performing routine checks that limited data collection. The operation of the PEMS2 software at that point 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. During the portion of the testing when UCR operated PEMS2, several additional issues were identified, ranging from startup difficulties that on average took over 4 hours, problems with sensors, faulty parameters in the code causing incorrect control, condensation in sample lines, frozen crystals still being used in sampling mode, unstable crystals thus loss of data, and valve switch timing issues. Problems with the post processing were also identified, including issues with crystal stability, valve switching, data filtering, work integration, ambient correction, NTE identification, and final emissions calculations.

- Since forced 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 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.

- Given the operational issues and measurement inaccuracies, that can exceed 100% at the relevant emissions levels, it is suggested that in addition to the MA rigorous evaluation of the sources of measurement error, there should be an evaluation of the PEMS operational and data processing issues. A new program with a focus on operating the PM PEMS in such a way that the PEMS will detect issues with their instruments that affect bsPM could be conducted based on expectations from PM measurement practices. Such a program exists at EPA and is part of their verification new environmental technology and is called EPA's Environmental Verification Technology Program (ETV) [http://www.epa.gov/etv/]. The goal of this program is to create an objective and fair evaluation of new environmental test equipment. The ETV program should include an evaluation of operating procedures to evaluate the ability of the PEMS to detect a failure/drift and should be designed to evaluate all operations that will affect their bsPM emissions.

- The MEL passed all audit checks and the system was found to be in compliance with 40CFR Part 1065 for PM measurements.

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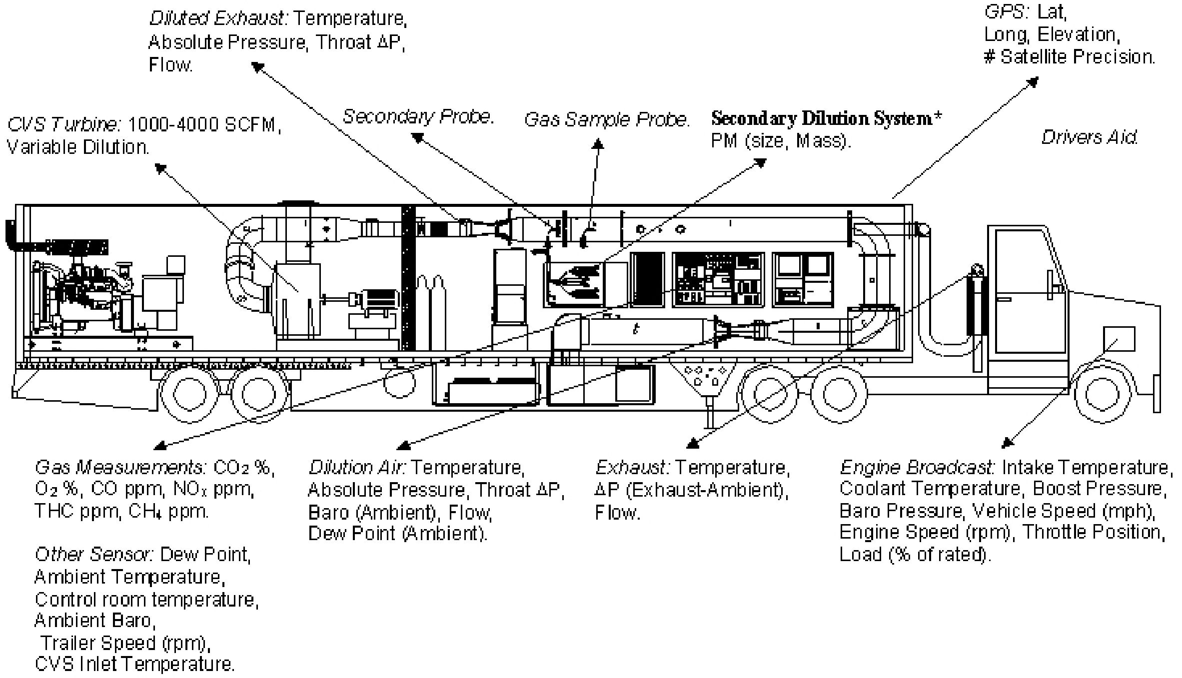
Appendix A – Background Information on UCR's Mobile Emission Lab

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)	Heated FID

Table A-A1 Summary of gas-phase instrumentation in MEL

Quality Assurance and Quality Control Requirements

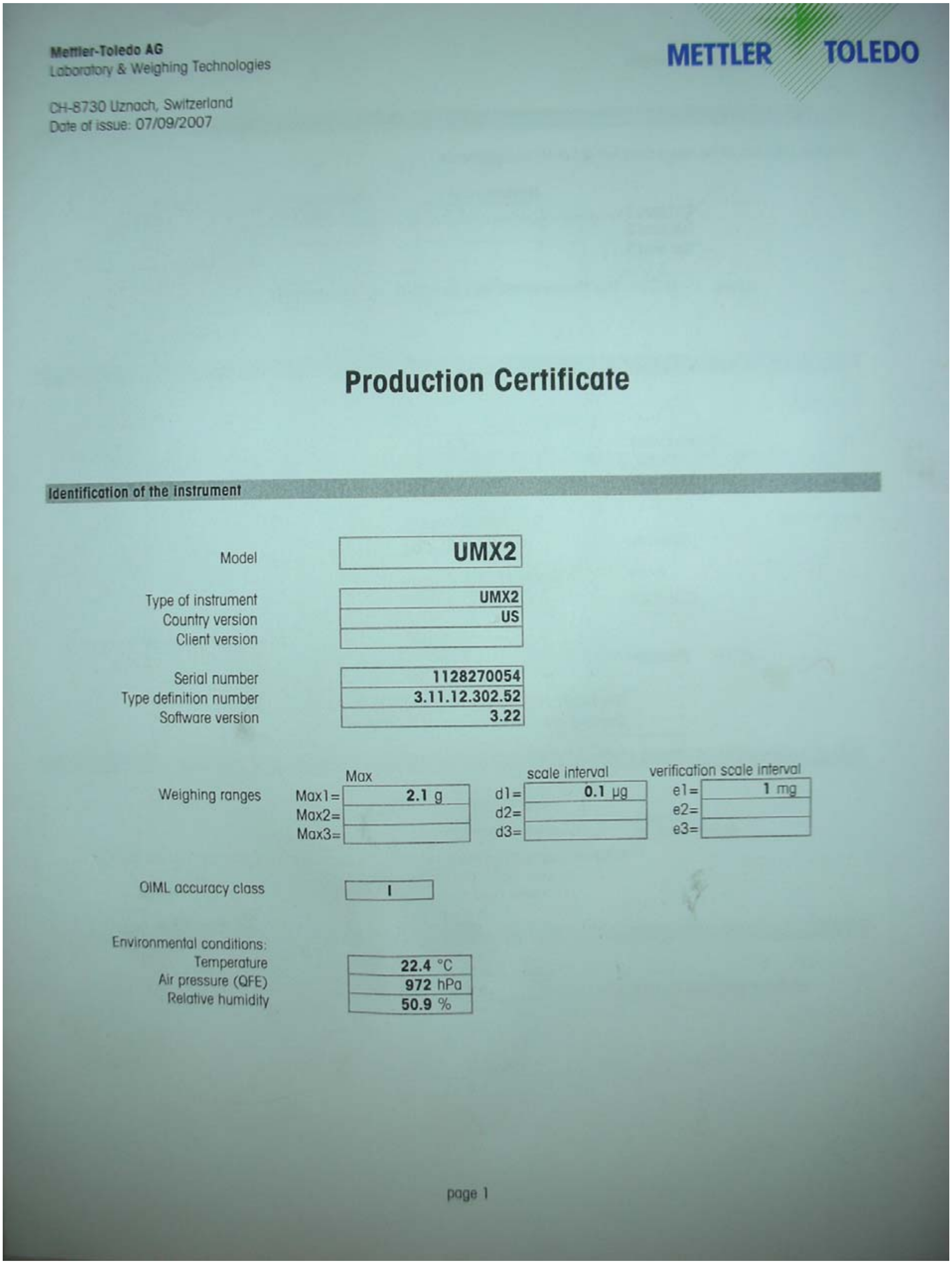
Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL staff as part of the data quality assurance/quality control program is listed in the table below. The MEL uses precision gas blending to 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.

8.1.1.1 EQUIPMENT	8.1.1.2 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$_2$0	
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

Table A-A2Sample 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

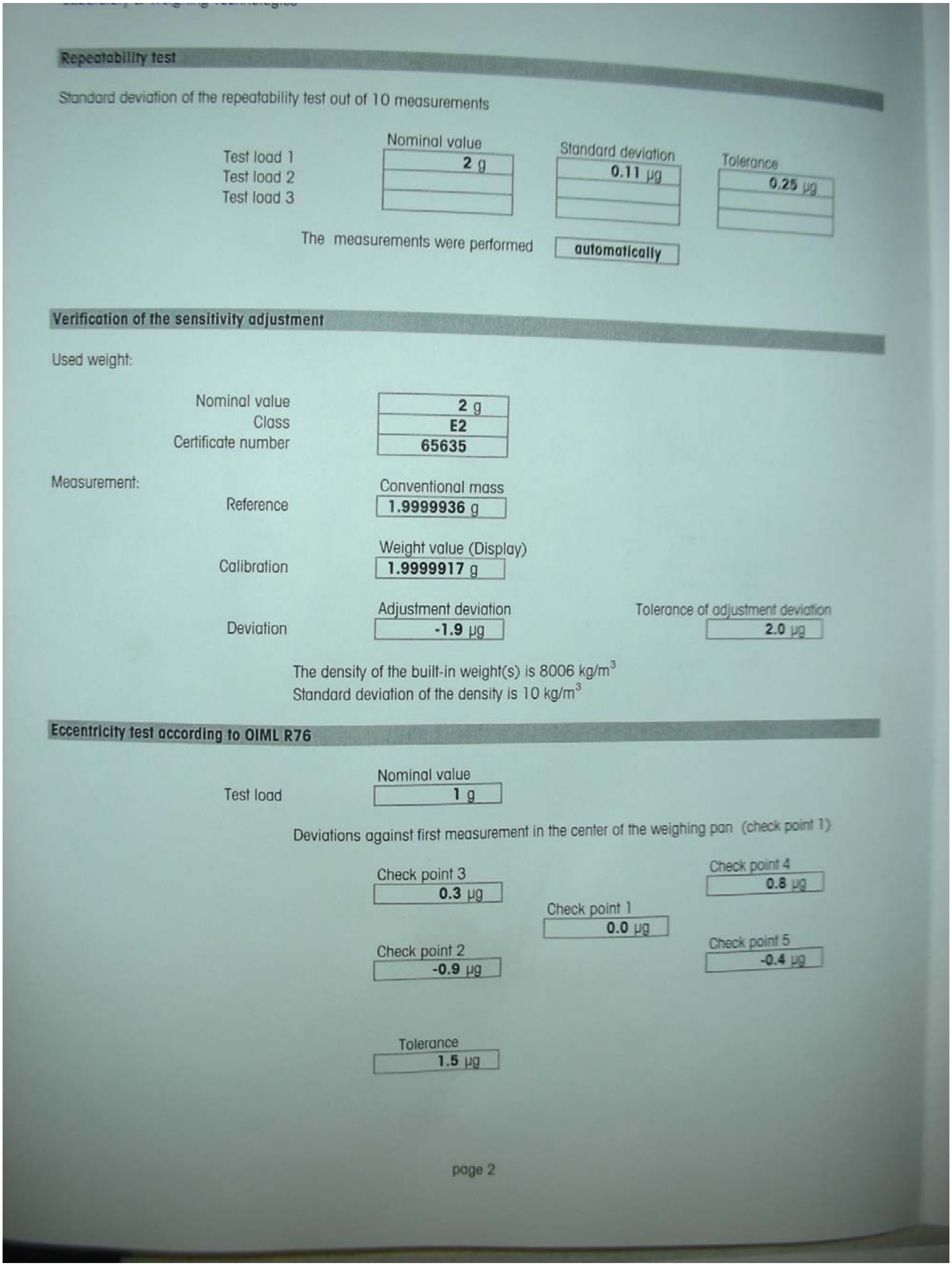
	Max		scale interval		verification scale interval
Max1=	2.1 g	d1=	0.1 µg	e1=	1 mg
Max2=		d2=		e2=	
Max3=		d3=		e3=	

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

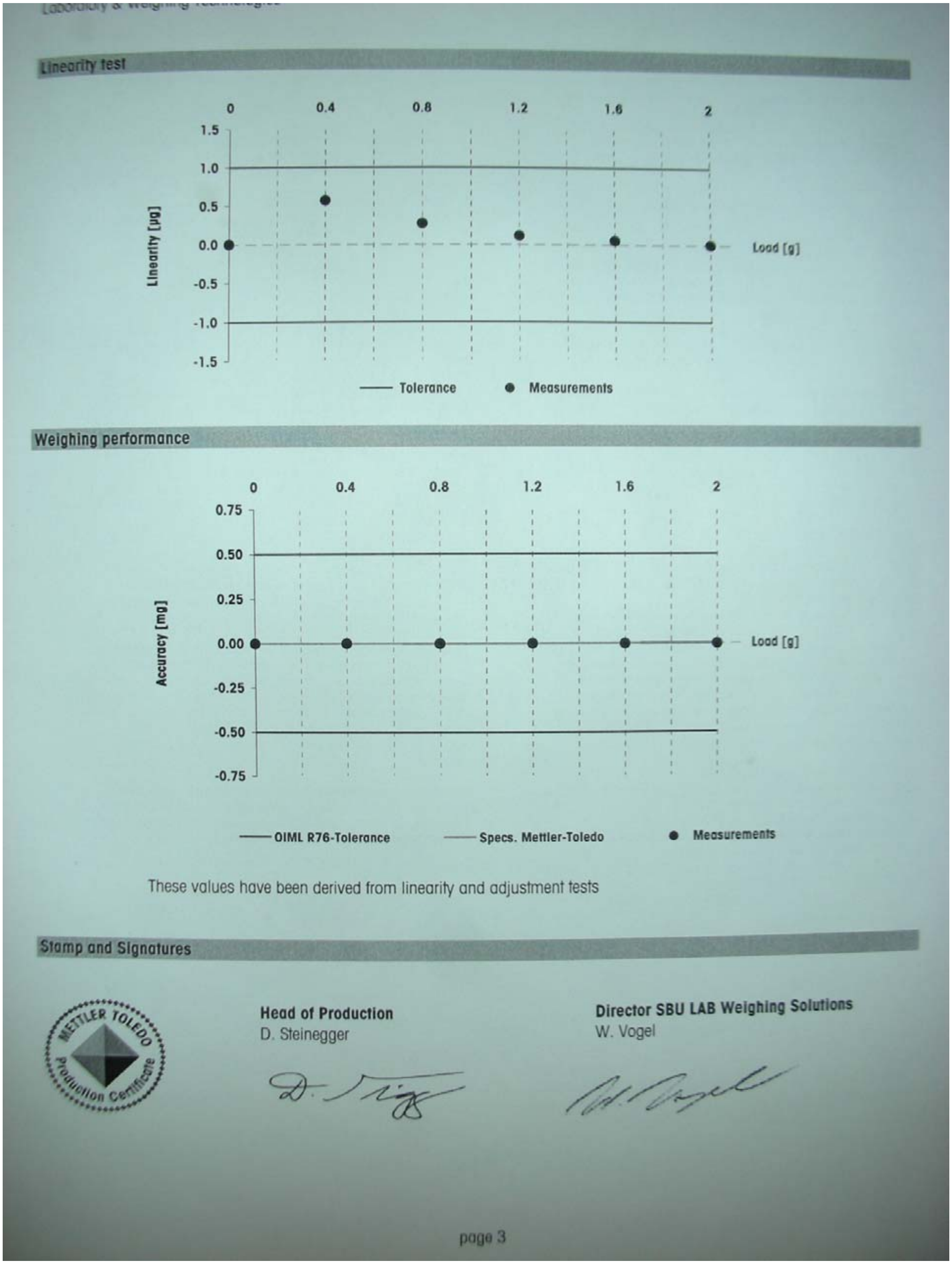
Test load: Nominal value **1** g

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

page 2



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

Appendix C – PEMS4 Description and Startup Procedure

The Dekati DMM measures PM mass concentrations through a combination of an electrical mobility diameter via particle charging and an aerodynamic diameter via inertial impaction over six stages of electrometers [Lehmann, et al., 2004]. The combination of mobility diameter and number averaged aerodynamic particle diameter allows estimation of particle mass with the assumption of a log normal distribution. The aerodynamic diameters are estimated from six impactor electrometers that range from 0.030 um to 0.532 µm, as shown in Table A-D1 and Figure A-D1. The mobility diameter estimates the sub 30 nm particle diameters. If the distribution is bimodal, the DMM assumes an average density of 1 g/cm^3. The DMM also has an inlet precut classifier set around 1.32 µm. The DMM was operated on the faster response option, as opposed to the lower detection option. The faster response setting is more typical for transient emission testing.

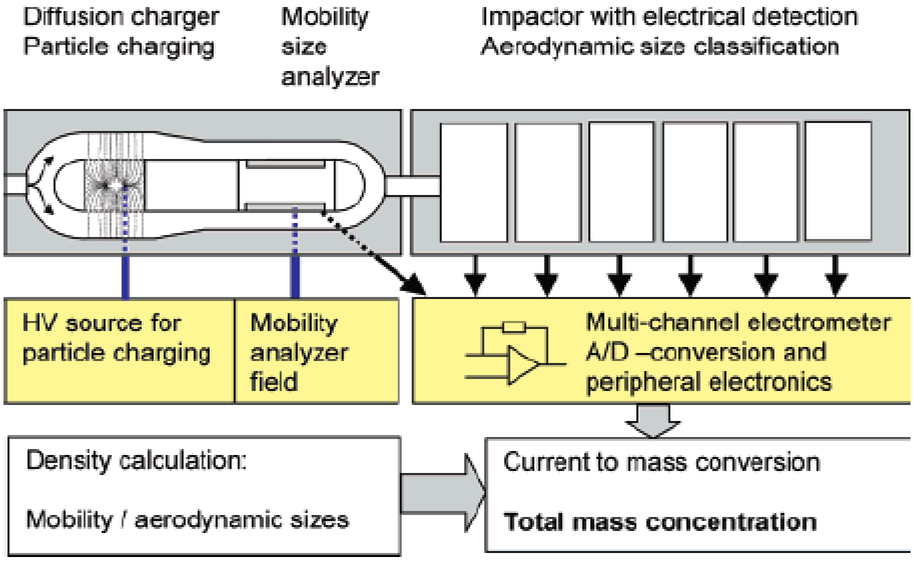


Figure A-D1 Principle of the Dektai mass monitor (DMM)

$$d_p = 59\left(\frac{0.938}{\frac{I_{\text{mob}}}{I_{\text{tot}}} - 0.124} - 1\right)^{(1/2.13)}$$

Table A-D1. Dekati DMM aerodynamic impaction stages.

Aerodynamic Impactor Diameters D_{50} (um)					
Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
0.030	0.052	0.086	0.114	0.237	0.532

Some issues that need to be addressed when operating the DMM are flow compensation and digital to analog conversion. The DMM operates at a constant flow and assumes a nominal flow of 10 lpm, but the actual flow is a function of standard conditions and installation practices. At the time of this testing, the DMM was operated where the nominal flows was around 9.6 standard liter per minute (at 20°C and 1atm) or about 4% lower than designed. The mass concentration should be corrected up by this amount in order to account for the denominator in the DMM output concentration. In addition to this nominal flow correction, one would also need to correct in real-time for elevation changes which will affect flow by the ratio of absolute pressure divided by standard pressure. The MEL is mobile and went up and down in elevation during some of the test runs, so the correction would need to be made on a second by second basis. The total flow correction at the highest elevations can be as much as 20%. The DMM does not provide flow corrected results for elevation changes or deviations from nominal flow, so these corrections are the responsibility of the operator. Additionally, the small change in nominal flow may also slightly impact the size distribution. These corrections were not performed for the data presented here. These corrections are small, however, and on the order of 5-20%, and are not significant at the post DPF levels discussed here.

Another problem with operating the DMM near zero is that the analog signal at 5 $\mu g/m^3$ is not accurate. The analog signal of a 5 $\mu g/m^3$ concentration is 5 mv and it varies by 1 mV and does not reflect the actual level digitally from a DMM file. The problem could be the digital to analog conversion in the DMM, ground loop affects between the DMM and the MEL, or analog to digital conversion in the MEL system. Due to the complexity of design behind the PMP program and many of the MEL test operations, the DMM instrument was setup to record the DMM analog signal as a primary data channel and the DMM digital file as a back up. Data can be recorded from the DMM digitally through direct RS232, but then there is only access to impactor and mobility currents plus some status information. Mass concentration is only an output from the DMM instrument via an analog connection. CE-CERT did record the DMM logged file through the DMM software and can make comparisons back to the DMM analog data by hand, but the general conclusions should be the same that is given by the analog data.

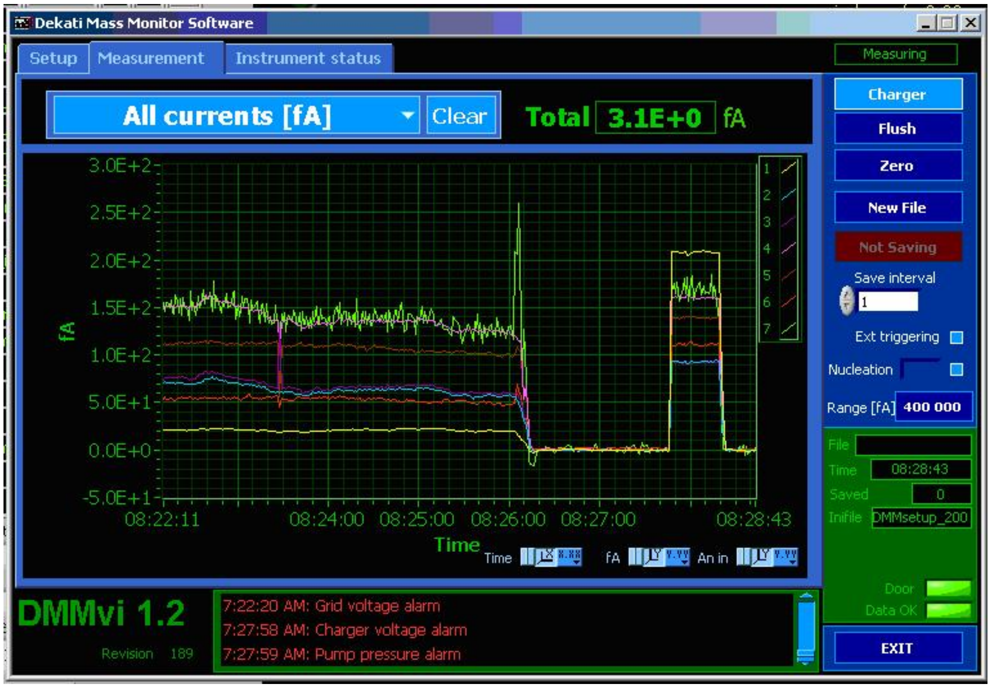
SOP DMM startup

1. **Power DMM instrument if not on and DMM pump (see toggles)**
2. **Start DMM software (Diesel 5, "DMM 1.2")**
3. **At the first screen, press "Start" then press "cancel" when it asks you to replace existing file**
4. **Instrument is now on and needs 30 minutes to warm up before zeroing. Zero required before test day and checking through day**

SOP DMM Zeroing

1. **Remove sample line from probe and insert hepa filter (in tool box, 4th drawer)**
2. **Let stabilize for 1 minute (or leave on during 30 min warm up) and enter pre zero value ____ $\mu g/m^3$ (Record value on checklist)**
3. **On "DMM 1.2" software, press "Zero" on the right side on measurement tab**
4. **A successful zero looks like figure 1. Enter post zero value ____ $\mu g/m^3$ ("Total Mass [$\mu g/m^3$]" pull down as in figure 2, record value on checklist)**

5. **Switch screens back to "Total Mass [µg/m^3]"**
6. **Remove filter and record response measuring air. ____ µg/m^3. Should be ~ 5 µg/m^3 ± 5 µg/m^3 (Record value on checklist)**
7. **Put sample line back as it was found.**



All currents [fA]

Total 3.1E+0 fA

Save interval 1

Ext triggering ☐

Nucleation ☐

Range [fA] 400 000

File

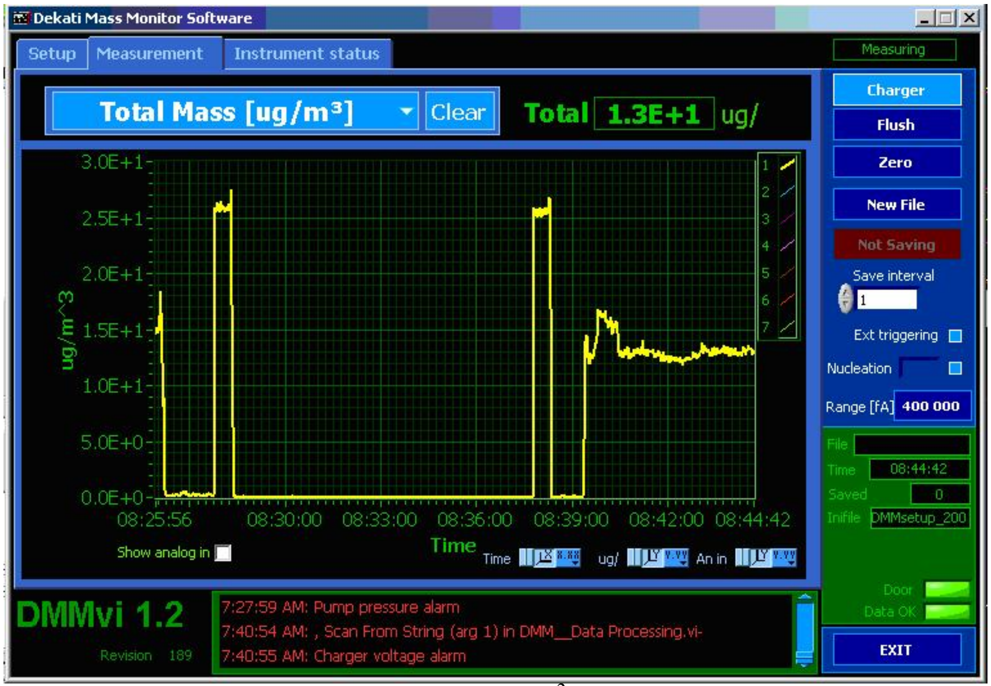
Time 08:28:43

Saved 0

Inifile DMMsetup_200

```
7:22:20 AM: Grid voltage alarm
7:27:58 AM: Charger voltage alarm
7:27:59 AM: Pump pressure alarm
```

Figure A-D1 – Typical DMM zero in fempto amps



Total Mass [ug/m³]

Total 1.3E+1 ug/

Show analog in ☐

Save interval 1

Ext triggering ☐

Nucleation ☐

Range [fA] 400 000

File

Time 08:44:42

Saved 0

Inifile DMMsetup_200

```
7:27:59 AM: Pump pressure alarm
7:40:54 AM: , Scan From String (arg 1) in DMM__Data Processing.vi-
7:40:55 AM: Charger voltage alarm
```

Figure A-D3 – Typical DMM zero in µg/m^3

Appendix D – PEMS3 Daily Startup Procedure

Written By: Joel Squire
Reviewed By: Mike Viergutz
Date Written: 19-Mar-07
Date Revised: 7-May-07

Contacts:

Joel Squire: 578-8631 or 303-2431
Mike Viergutz: 578-5718 or 303-6619
Lee Purdy (AVL Hotline): 734-446-4178

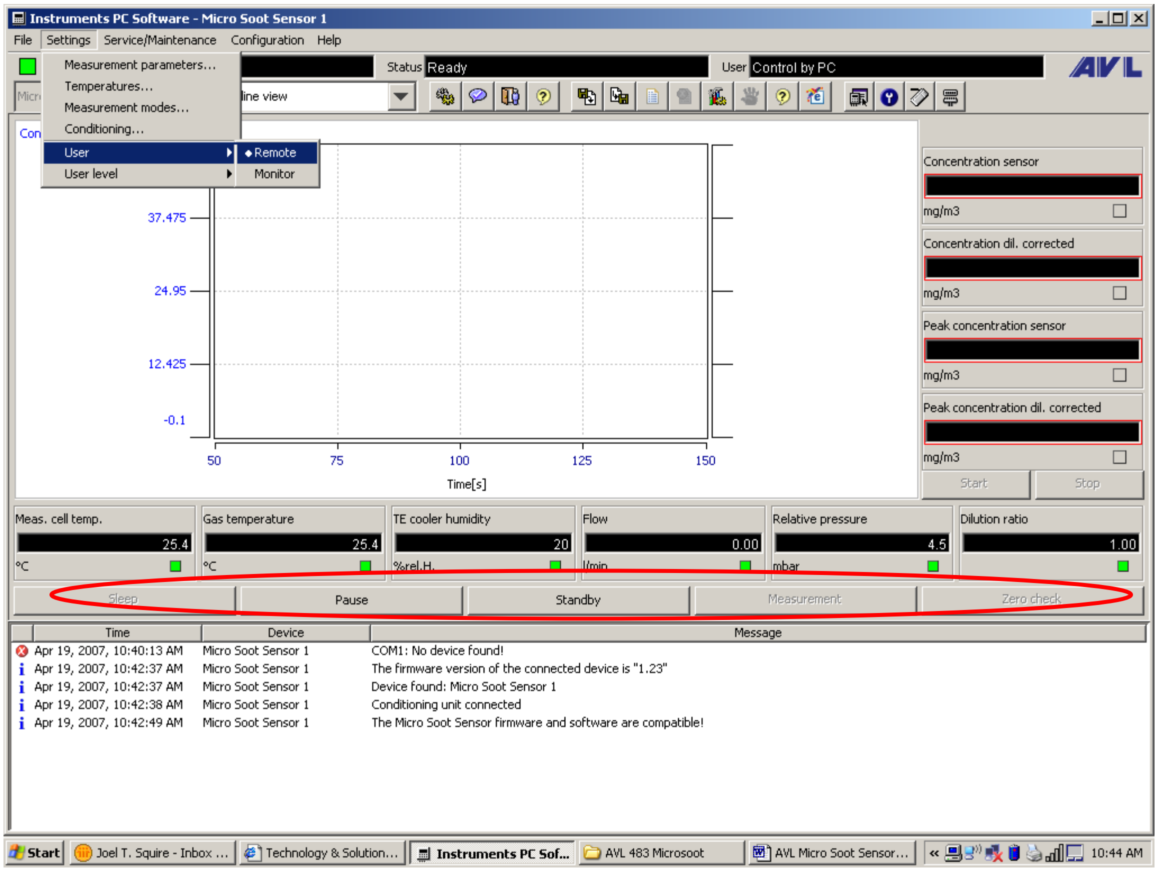
AVL 483 Micro Soot Sensor Daily Support Procedure

Equipment

1. Laptop Computer with AVL Instruments PC Software installed
2. Serial Cable to connect laptop to AVL 483.
3. Phillips #2 screwdriver
4. 2 crescent wrenches
5. Metric nut driver

I. Connecting to the AVL 483

1. Connect the laptop to COM 1 or Com 2 on the AVL 483 and run the AVL Instruments PC Software.
2. Ensure that the unit is in **Sleep** or **Pause** mode. The test cell operator should always leave the AVL in these modes when not operating to minimize the operating hours of the pump and measurement cell. Please notify the operator of this requirement if he/she is not doing this at the end of each shift/day.
3. To gain control of the AVL 483, click **Settings>User>Remote**. Should now be able to change modes in the AVL Software.



Status Ready

User Control by PC

Meas. cell temp. 25.4 °C

Gas temperature 25.4 °C

TE cooler humidity 20 %rel.H.

Flow 0.00 l/min

Relative pressure 4.5 mbar

Dilution ratio 1.00

Time	Device	Message
Apr 19, 2007, 10:40:13 AM	Micro Soot Sensor 1	COM1: No device found!
Apr 19, 2007, 10:42:37 AM	Micro Soot Sensor 1	The firmware version of the connected device is "1.23"
Apr 19, 2007, 10:42:37 AM	Micro Soot Sensor 1	Device found: Micro Soot Sensor 1
Apr 19, 2007, 10:42:38 AM	Micro Soot Sensor 1	Conditioning unit connected
Apr 19, 2007, 10:42:49 AM	Micro Soot Sensor 1	The Micro Soot Sensor firmware and software are compatible!

II. Purging

4. Click the **Sleep** button to put the unit into Sleep Mode.
5. Purge the unit. To purge, select **Service/Maintenance>Service Tests>Purging** and click the start purge button

6. From the **Sleep** mode, put the unit in **pause** mode. This may take up to 30 min to completely stabilize in pause mode.

III. Checking for Diagnostics

7. After the unit shows **Ready** in Pause Mode, check the diagnostics screen at the bottom for any new errors or warnings. Note that the Status light should be green when Pause mode has completed. **Validate** and **Correct** any errors or warnings that appear on the Diagnostic screen. Record any errors or warnings, and what was done to correct them, in the Daily Log Sheet.

IV. Checking the Zero Signal

8. Put the unit into **Standby** Mode. The unit will take 1 min. to complete Standby. During this time, the AVL re-zero's itself. Switch views in the Software by pulling down the menu showing the Online view. Select **Service view numerical**. In this view , you can check the Zero signal. If the zero signal is ~1.000 mV, then the unit must be cleaned. Record the "As Found" Zero Signal in the Daily Log Sheet. Below the Zero Signal reference is the Resonance Check window. Record the frequency, Max signal and measuring Cell temp.
9. Refer to the AVL 483 Manual for cleaning instructions. If the unit requires cleaning, the <u>filters must also be changed.</u>
10. Once the unit is cleaned, you must put perform another zero to ensure the cleaning was sufficient. Zero signal should be <.100 mV for a clean measurement chamber. Record the "As Left" Zero signal in the Daily Log Sheet
11. Perform a leak check. **Click Service/Maintenance>Service Tests>Leak Check**. Cap the end of the Sample line as shown below. Click **Start Leak Check**. If leak check passes, both lights will turn green, if leak check fails, lights will turn red and the leak will have to be found and fixed. Record leak rate in the Daily Log Sheet.

V. Performing Linearity Checks

12. Put the Unit back into **Sleep** mode.
13. Select **Service/Maintenance>linearity checks>microphone Linearity Check**
14. Click the start button to start the microphone linearity check.
15. Record the result in the daily log sheet. Value should be ~ 1 +/- .05 threshold. If the value is outside the threshold. Notify the responsible support person.
16. For the Laser Linearity check, the Absorber window must be installed on the Measuring cell. Refer to the manual on how to do this.
17. Once the absorber window is installed and the measurement chamber is closed, perform the Laser linearity check in the same manner as the microphone.
18. Record the result from the Laser Linearity check in the daily log sheet. Value and tolerances are same as microphone.

VI. Calibration Check.

19. Calibration check is also performed with the absorber window attached.
20. From the sleep mode, select **Service/Maintenance>Calibration check>Start Calibration check.**
21. The results should not deviate by more than 5% from the reference value. If the calibration check returns a positive deviation, contact the responsible support person. If the calibration check returns a negative deviation, adjust the calibration as follows:

    a. **Click on Service/Maintenance>Calibration of Measurement Value**. Adjust the calibration factor up by the percent deviation. The formula used is:
    (Cal. Factor * % Deviation) + Cal. Factor.
    b. Perform another calibration check to verify that the deviation is within 5%.

The Cal. Factor can be adjusted up until it reaches a value of 3. after that, a new measuring cell must be installed in the unit.

23. Record the results in the log book. Also note the Cal. Factor change.

II. Recommended Service Intervals

1. Calibration Check: Weekly. Refer to the AVL Manual to perform the calibration checks.
2. Measuring cell cleaning: @ 1.00 mV Zero Signal. Refer to the Manual for cleaning procedure.
3. **3.** Pressure Reducing Unit and Sample line cleaning: Every 300 hours of Exhaust operation. Refer to the manual for cleaning the pressure reducing unit. Dilution cell also needs to be cleaned. Sample line should not be cleaned but should be re-cored.
4. **4.** 1000 Hr. Service: Every 1000 Hrs since last service. Refer to the 1000 Hr. service procedure on the emissions shared drive.

Appendix E – PM Composition Description

The appendix describes the PM composition measurements in greater detail. PM composition was evaluated via EC/OC analysis using the NIOSH method from quartz fiber filters. Sulfate was analyzed using Ion Chromatography on the same Teflon filters used for the gravimetric analysis.

Typically, total PM is consistent with the addition of EC + OC + SO_4 with some underlying assumptions about the structure of the OC and SO_4 species. For our OC and SO_4 the following formula is used for total PM = EC+ 1.4*OC+2*SO_4. Using this formula very good agreement was found on the Cummins data, but this did not hold true for the Volvo data. The Volvo data showed total PM much greater at times than the gravimetric data. In fact, some OC measurements were greater than the gravimetric PM measurements. The EC/OC, sulfate and gravimetric sample media are both contained in the same 1065 sample conditioning system so there should be no dilution or aging differences. The quartz filters used for EC/OC sampling have a greater absorption artifact factor compared to the Teflo gravimetric sample media. The absorption differences between quartz and Teflo may explain why the total PM balance did not have as good agreement as the Cummins engine data.

For sulfate PM, it is useful to discuss the assumptions used to derive the sulfate mass. SO_4- ions are measured using ion chromatograph. In order to get to sulfate mass, one must then make an assumption of the form of the particle. For this analysis, the assumption was the particle was sulfuric acid (H_2SO_4). In order to determine the mass of the particle one must assume how much water mass is bound up in the H_2SO_4. The assumption in this work is a factor of two which is consistent with the value used by others. The water mass in the H_2SO_4 particle is a result of the humidity of the sample conditioning, which is stabilized for several hours at a dewpoint temperature of 9.5°C as per CFR40 1065.

The PEMS instruments will not have the same amount of water hydration in the sulfate PM where each PEMS will vary based on their dilution and detection methods. PEMS1 measures the particles similarly to the reference so the issue about sulfate PM hydration should not be a source of error. PEMS2 sulfate derived PM depends on the particle crystal impaction, conditioning times (<5 min) and a variable humidity at 47°C. If one only considers the only the error in hydrating the PM, the largest difference for PEMS2 should be at most a factor of two lower. PEMS3 measurement principle does not detect sulfate so their dilution method is not considered and PEMS4 and 5 are both heavily dependent on particle size so they are not considered. Thus, it is expected the PEMS2 should at most vary in PM mass, for sulfate dominated PM, by no more than a factor of two. It is interesting to point out all the PEMS, including PEMS2, was low by approximately an order of magnitude compared to the reference method. Thus it appears there is some element of sulfate particles either size and or composition that is not detected by the PEMS2 measurement principle.

Many of the measurements were near the detection limits for the EC/OC and sulfate instruments. Detection limits for gravimetric, EC/OC and sulfate IC analysis are based on instrument detection and media blanks used during gravimetric tunnel blank operations. Based on past experience, the instrument detection limits are lower than the operational tunnel blank responses.

The gravimetric, EC/OC and sulfate tunnel blanks are typically reported as 5, 0.5, 5, and 3 µg/fliter for 1 m^3 of volume passing through the filter.

The Caterpillar samples showed very little sulfate mass, with most of the measurements near the detection limits for the IC instrument. The Cummins vehicle showed a significant fraction of the total PM came from sulfate and a lesser amount from OC. The EC measurements for the Cummins were low and mostly near detection limits except for a few samples. The fact that a large fraction of the PM was coming from sulfate agrees with our understanding of filter regenerations on ULSD fuel. The Volvo engine showed a different outcome where most of the PM was OC and very little sulfate and a small, but measurable amount of EC. It appears that the bypass allowed enough EC and large amounts of volatile HC species around the DPF that could absorb to the EC and then ultimately on the PM sample media.

It is suggested that the poor correlation between the gravimetric and composition masses is a result of possible artifact differences between a Teflon surface and a quartz fiber surface. Teflon surfaces have a lower tendency for HC absorption than quartz surfaces, thus one would expect the mass on the quartz surface to be larger than the Teflon surface. This ratio could vary with HC concentration and other variables. It was estimated that 40% of the OC on the quartz was represented on the Teflon surface. The equation used for the Volvo engine for total mass was EC+0.4*1.4*OC+2*SO4.

Figure A-E1 shows a comparison between gravimetric PM (x-axis) and the summation of PM compositions (y-axis). The figure shows that using these assumptions a good correlation between gravimetric mass and the summation of the compositions is achieved.

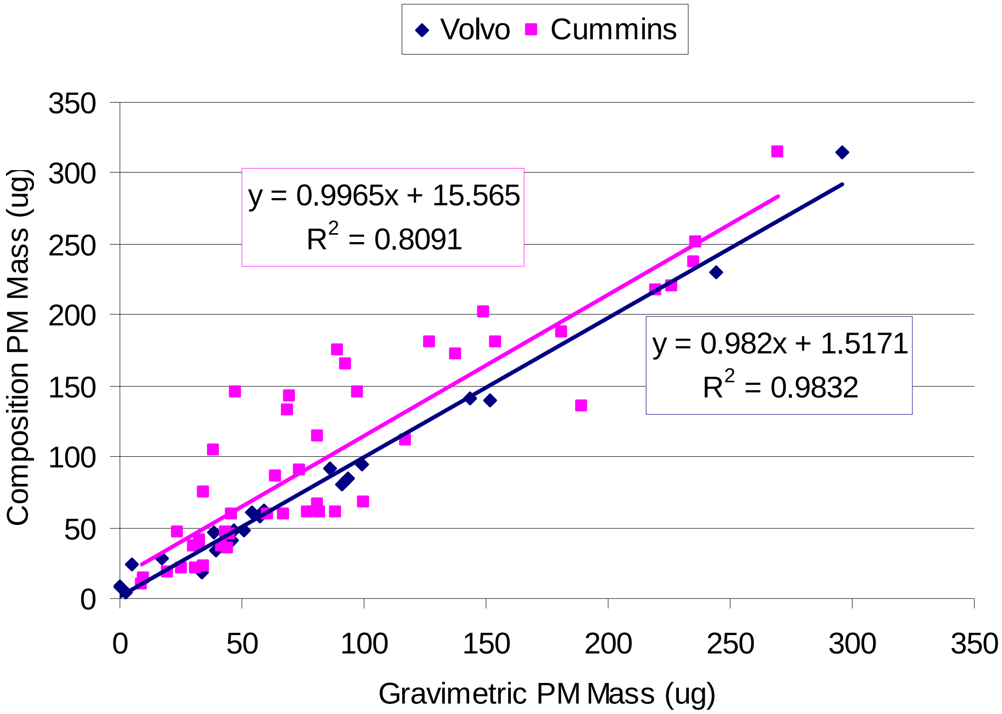


Figure A-E1 Gravimetric PM compared to total PM from EC+xOC+ySO_4^- (Volvo and Cummins)

Figure A-E2 (a) shows the raw THC concentration measured by the PEMS at the tailpipe as a function of the MEL calculated gravimetric PM concentration at the tail pipe. The R^2 is 0.8 suggesting a strong correlation to THC and PM emissions. The high THC concentration also correlates well with regeneration percent as shown in Figure A-E2 (b) where the R^2 is 0.8. At high regeneration levels, the THC concentration increased due to the DPF fuel management system and the bypass system. This high THC concentration surrounded by available soot particles and absorbing Teflon surface appear to provide a mechanism for the bsPM to be dominated by OC for the Volvo testing. The high concentration of THC does not represent an expected DPF failure (cracked in DPF with a dysfunctional DOC), but it does demonstrate the PEMS ability to measure PM of this composition and size distribution.

Figure A-E3 shows the OC mass quantified on the sample media. Notice how most of the OC was generated during the first two regenerations. After the first two regenerations, there appeared to be no more OC mass remaining on the DPF surfaces. Thus, the subsequent masses were dominated by sulfate generated on the catalytic surface.

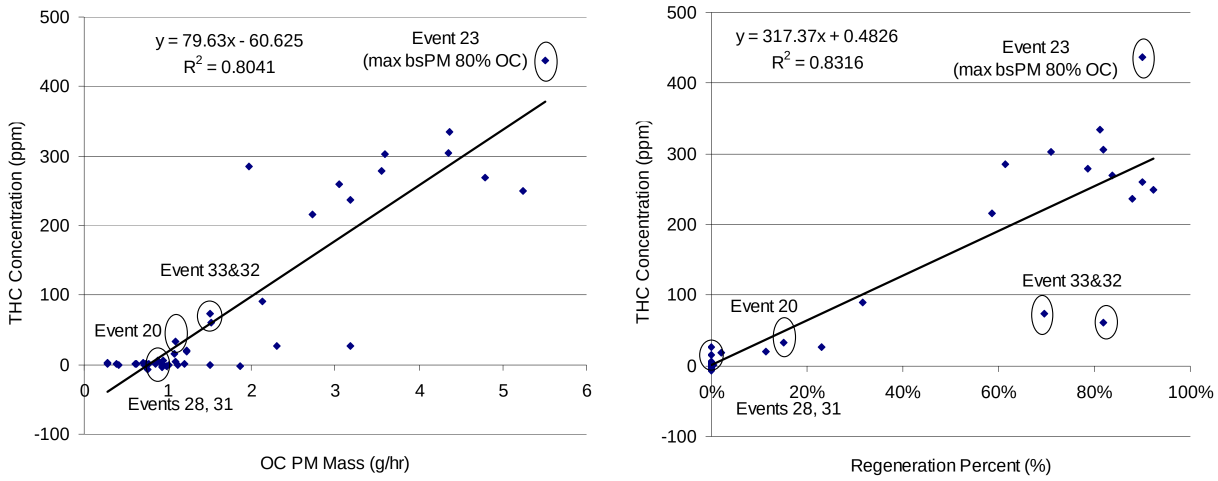


Figure A-E2 THC concentration as a function of MEL calculated raw PM concentration (a) and regeneration (b) for the Volvo engine

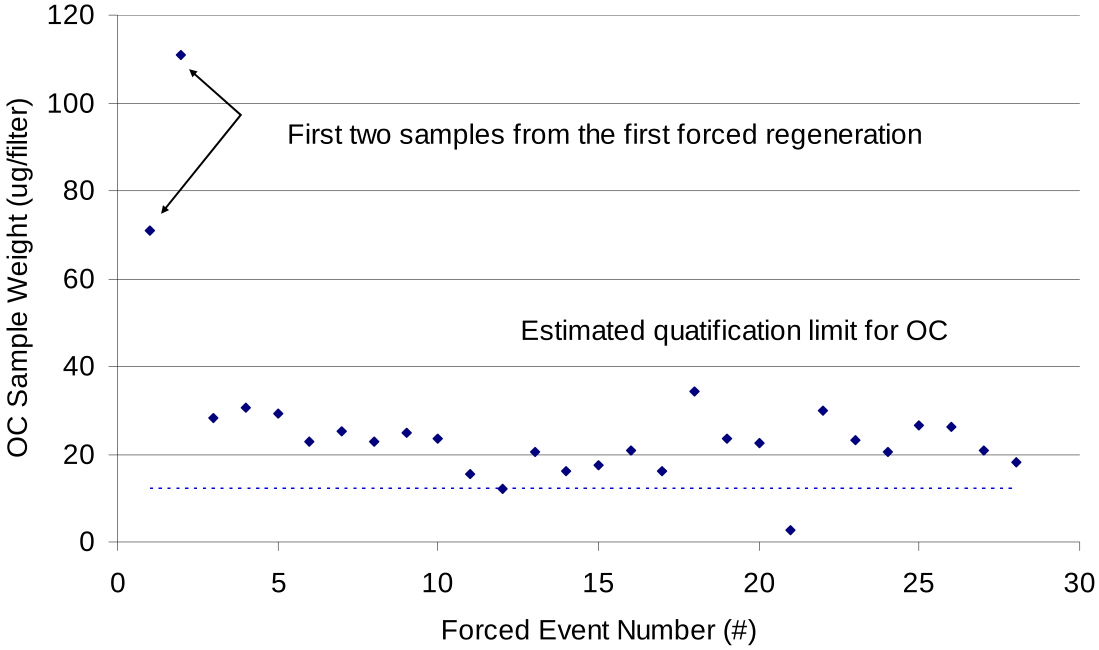


Figure A-E3 Organic carbon (OC) sample weight mass in units of ug/filter (Cummins)

Appendix F – Size Distribution and Particle Count Measurement

Particle size and count are informative for characterizing the particles behavior and growth. Typically one measures size distribution and particle count to characterize particle size properties. Size distributions were analyzed using CE-CERT in-house fast scan mobility particle sizers (fSMPS) and particle counts were sampled using a TSI condensation particle counter (CPC) 3760 which has a 50% cut point (D50) of 11 nm.

The size distribution in Figure AF-1 shows that Event #1 was mostly below 1x10^2 except for a short burst of data that coincided with a regeneration event. This filter showed a substation amount of sulfate mass and organic mass. The nominal particle size is 30 nm for event #1 and around 10 nm for event #2. Both events show large particle concentrations at small particle diameters. Typical combustion soot particles are at 100 nm.

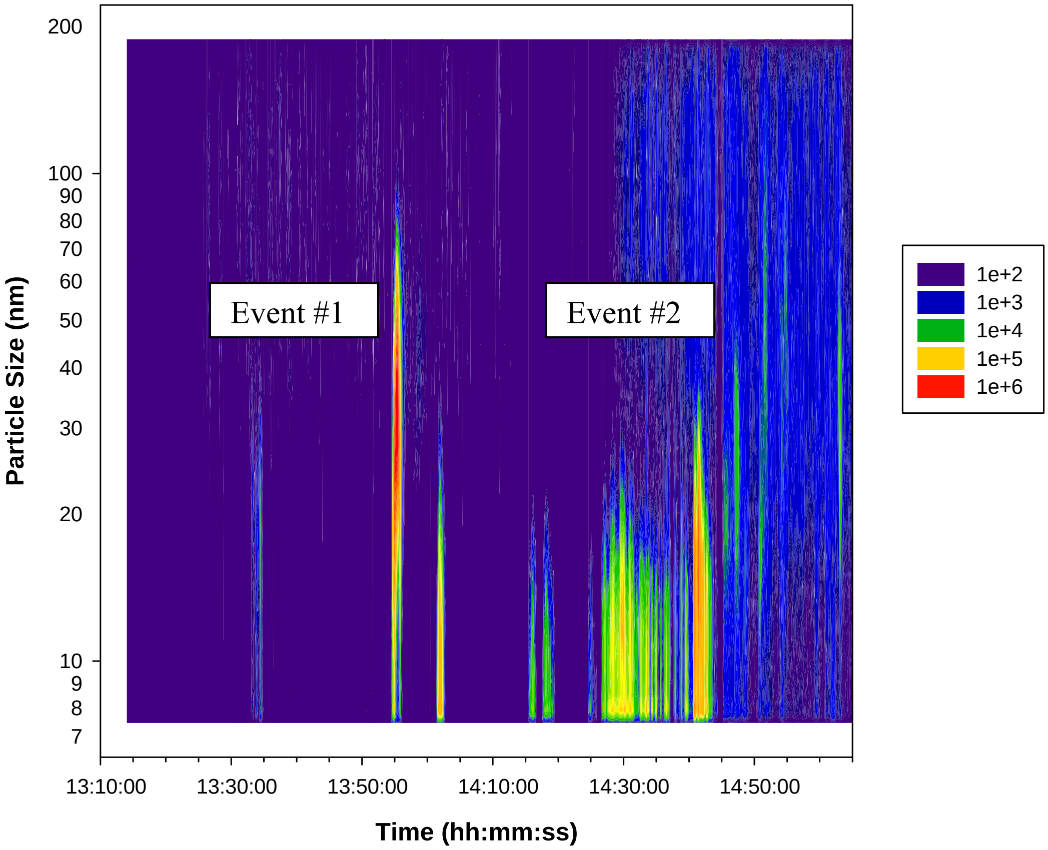


Figure A-F1 PM size distribution for forced event number 1 and 2 (Cummins)

Appendix G – Supplemental Real-Time Tables and Figures

Cummins Regeneration Effectiveness

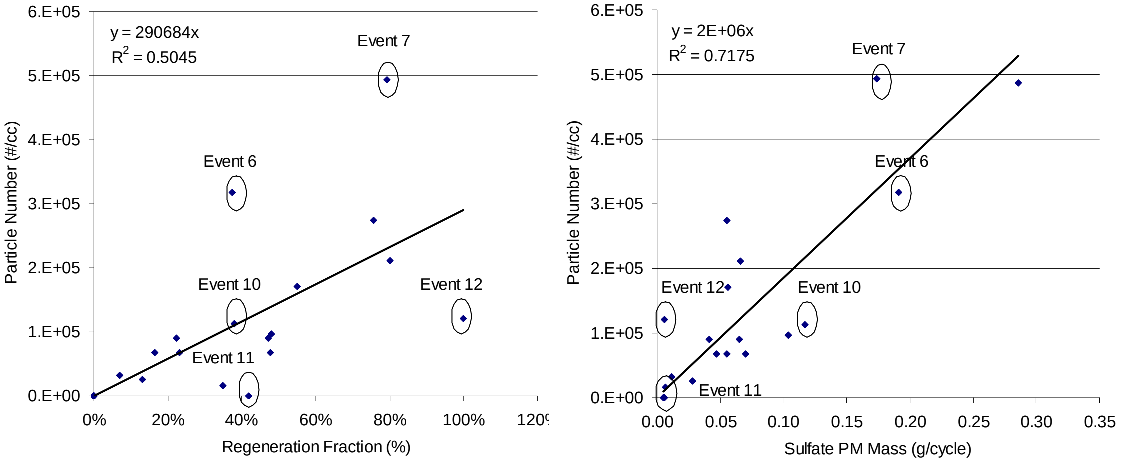


Figure A-G1 CVS dilute particle number vs regeneration fraction (a) and sulfate PM (b) mass (Cummins)

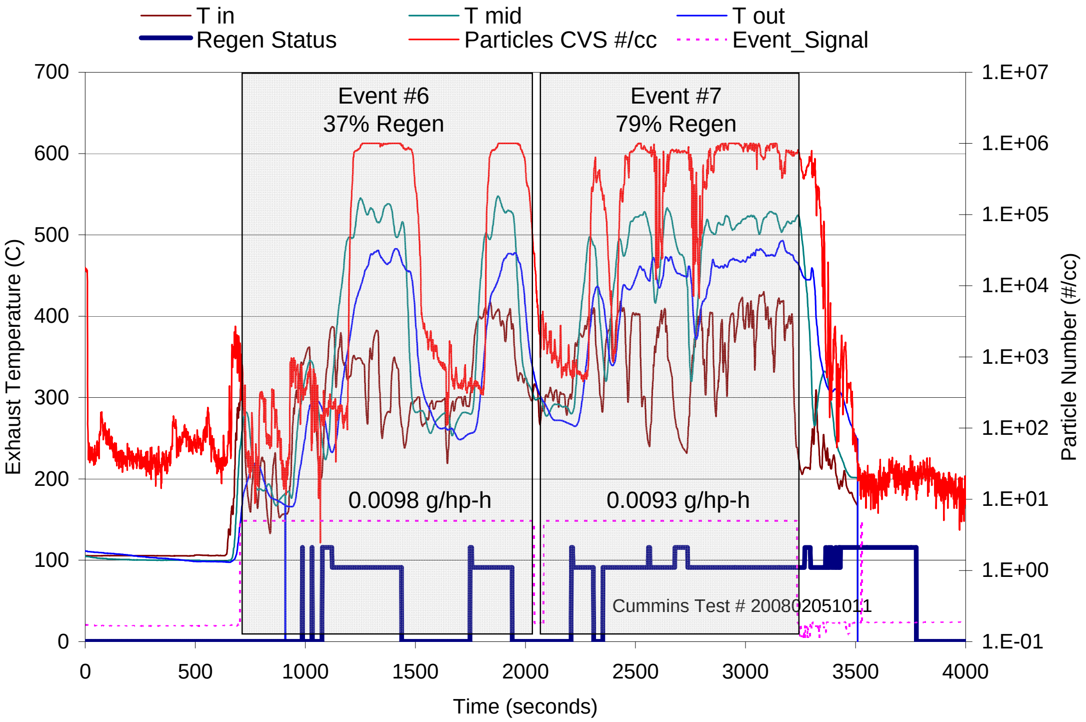


Figure A-G2 Exhaust temperatures, particle number and regen PID for events #6 and 7 (Cummins)

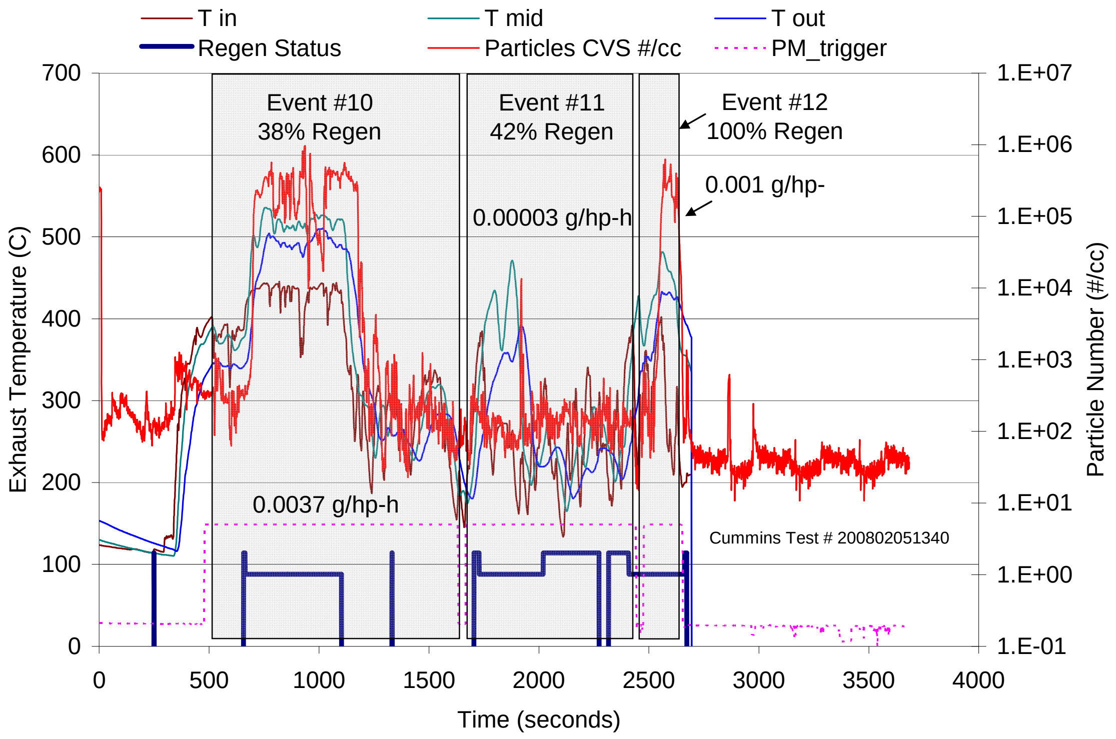


Figure A-G3 Exhaust temperatures, particle number and regen PID for events #10, 11, and 12 (Cummins)

Volvo Regeneration Effectiveness

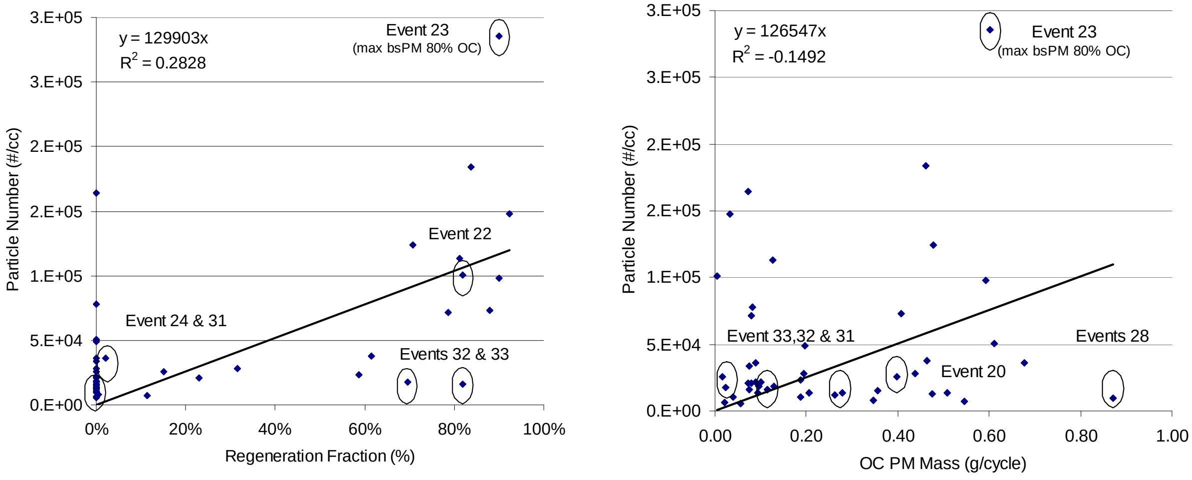


Figure A-G4 CVS dilute particle number vs regeneration fraction (a) and OC PM (b) mass (Volvo)

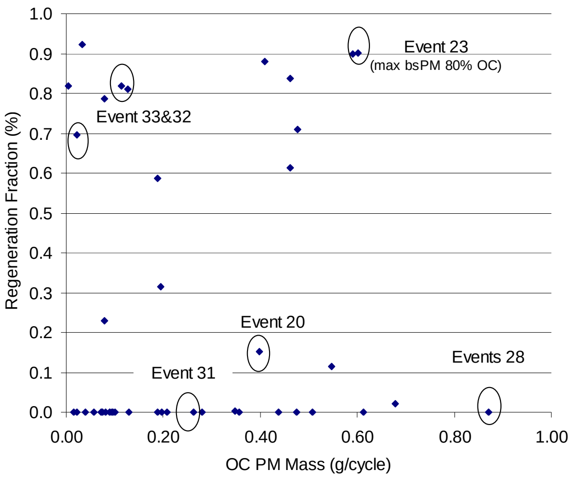


Figure A-G5 regeneration fraction as a function of OC PM mass (Volvo)

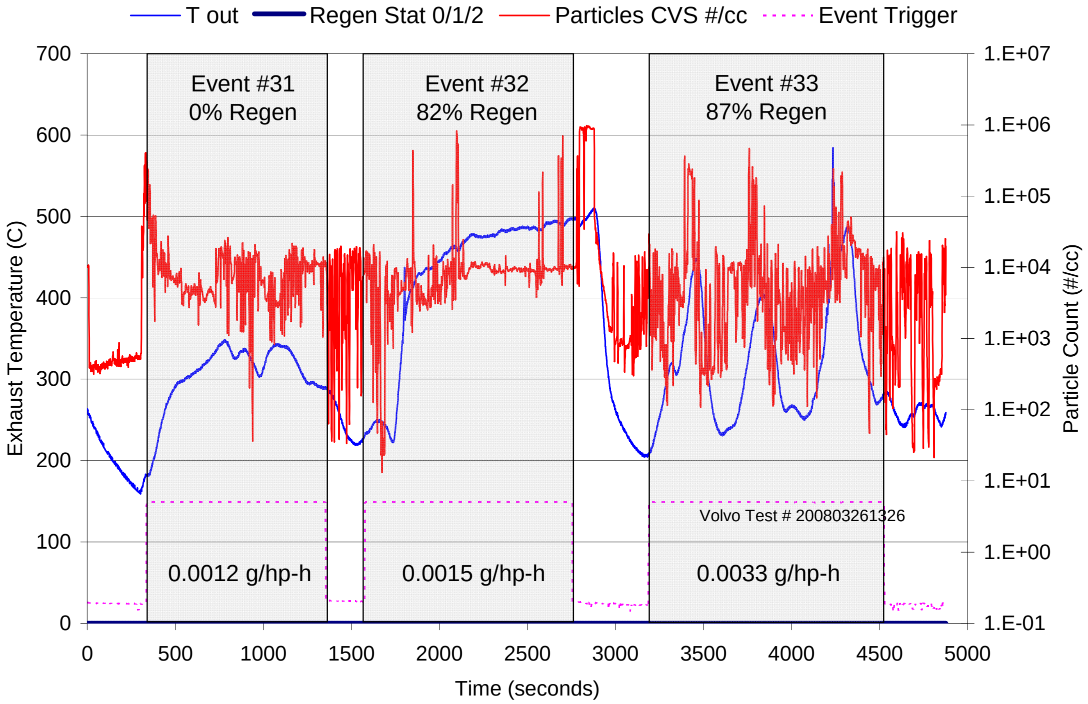


Figure A-G6 Exhaust temperatures, particle number for events #31, 32, and 33 (Volvo)

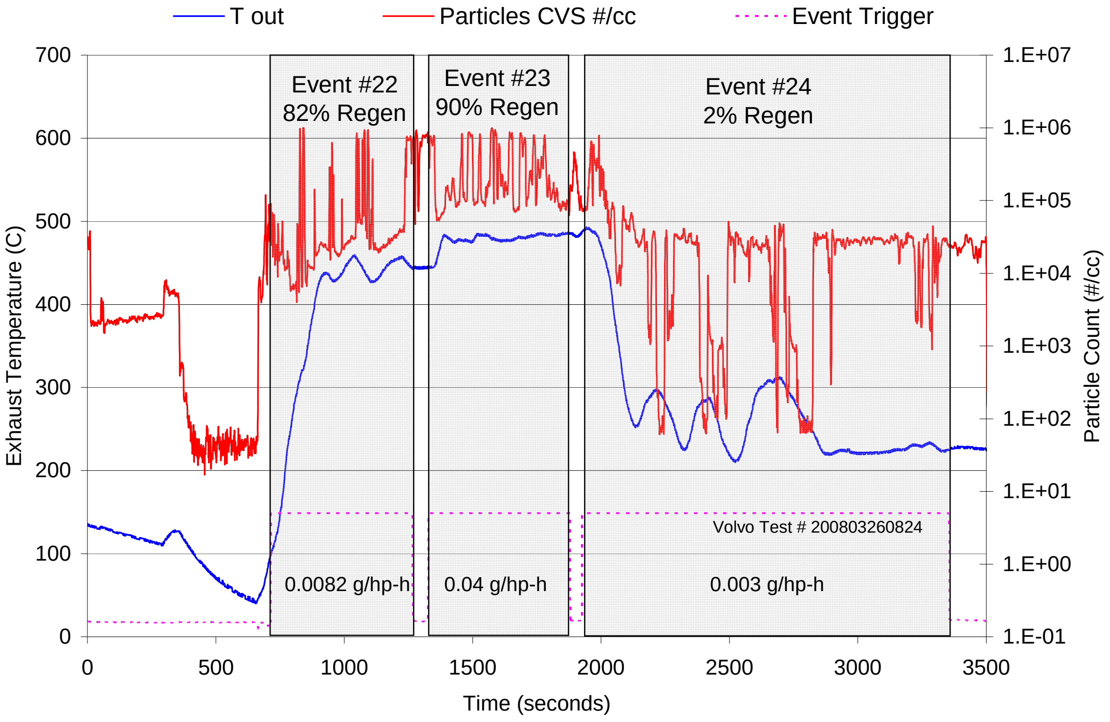


Figure A-G7 Exhaust temperatures, particle number for events #31, 32, and 33 (Volvo)

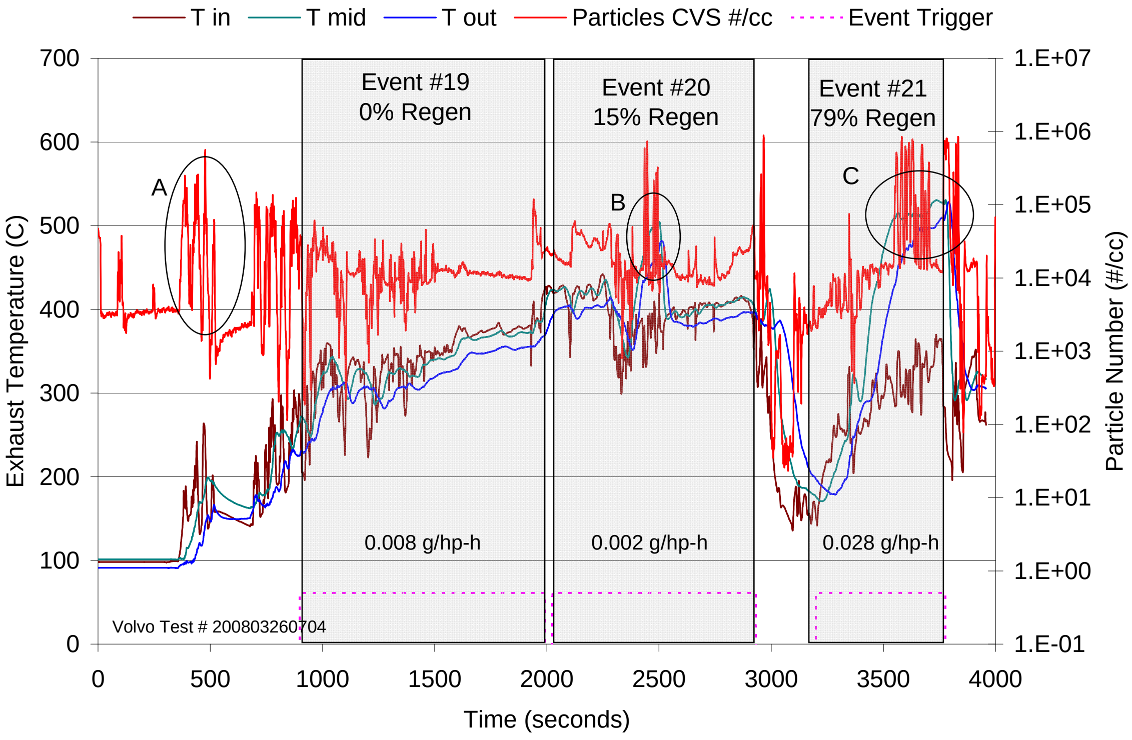


Figure A-G8 Exhaust temperatures, particle number for events #19, 20, and 21 (Volvo)

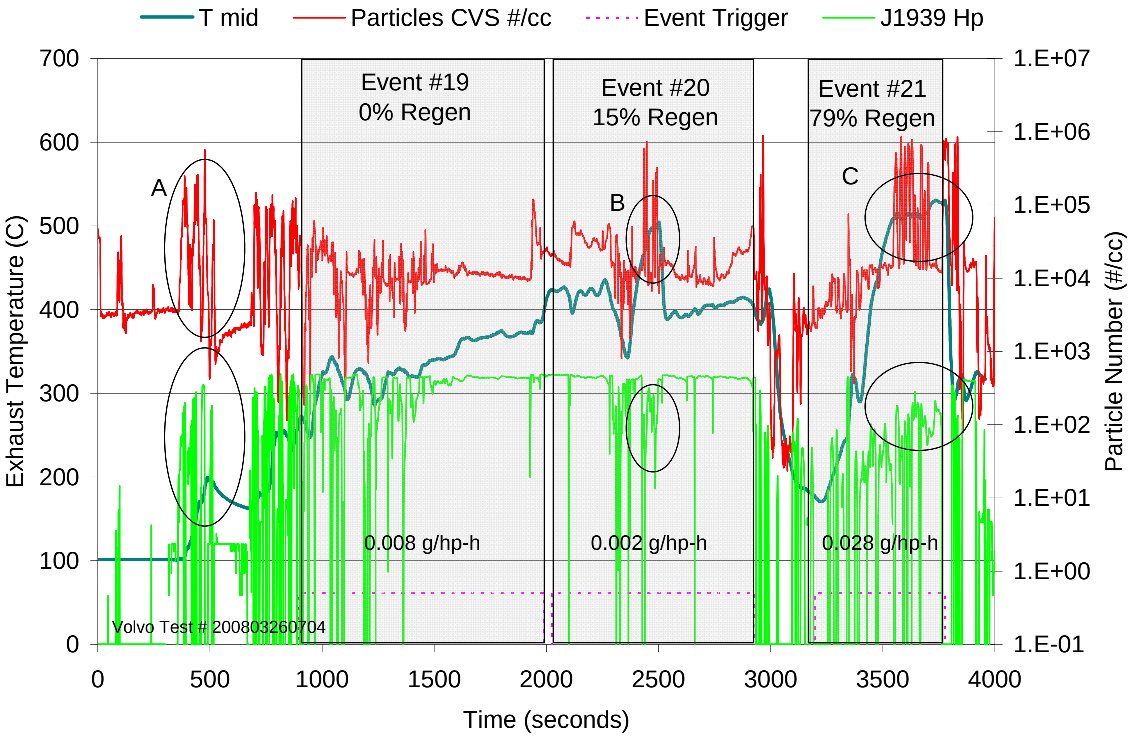


Figure A-G9 Exhaust temperature, ECM hp, particle number for events #19, 20, and 21 (Volvo)

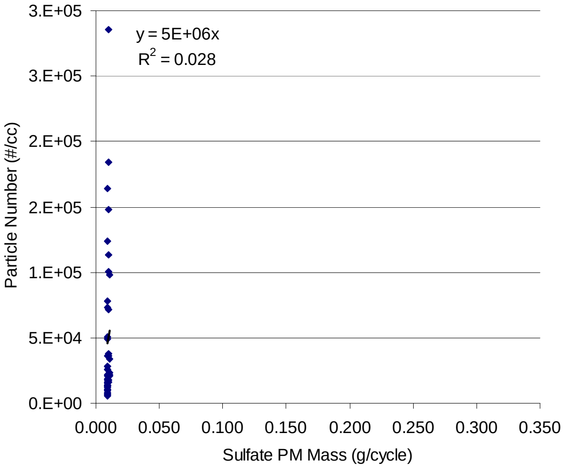


Figure A-G10 sulfate mass vs particle number during forced events (Volvo)

Cummins Light Off Temperatures

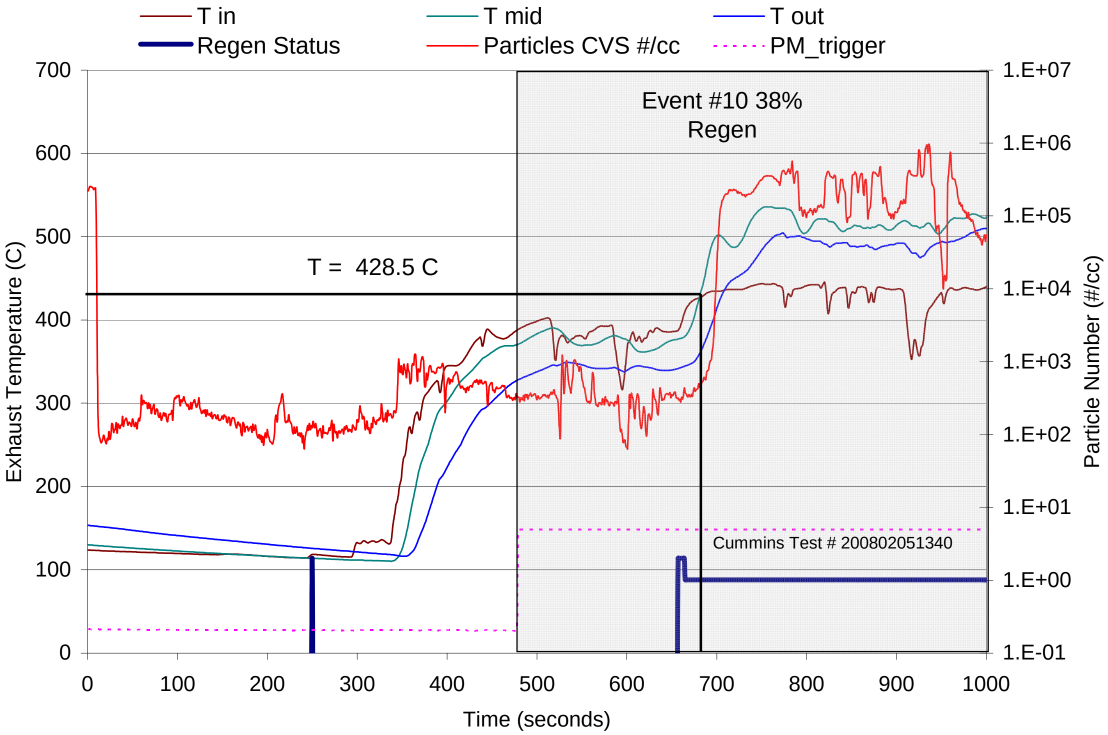


Figure A-G11 Cummins regeneration temperature activation on Event #10

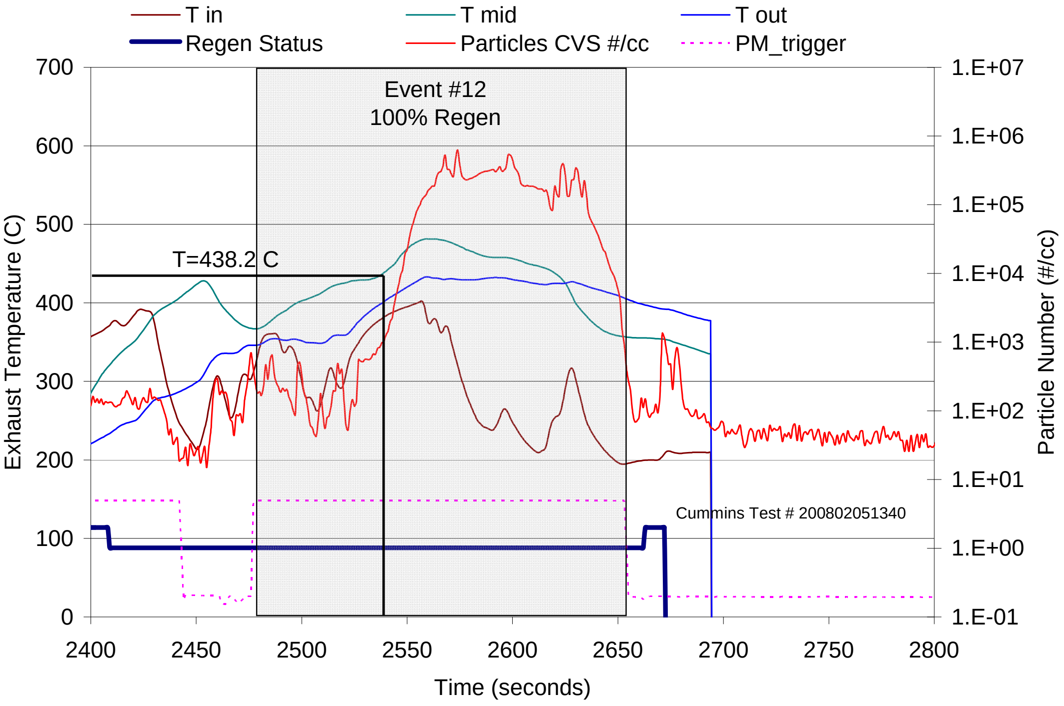


Figure A-G12 Cummins regeneration temperature activation on Event #12

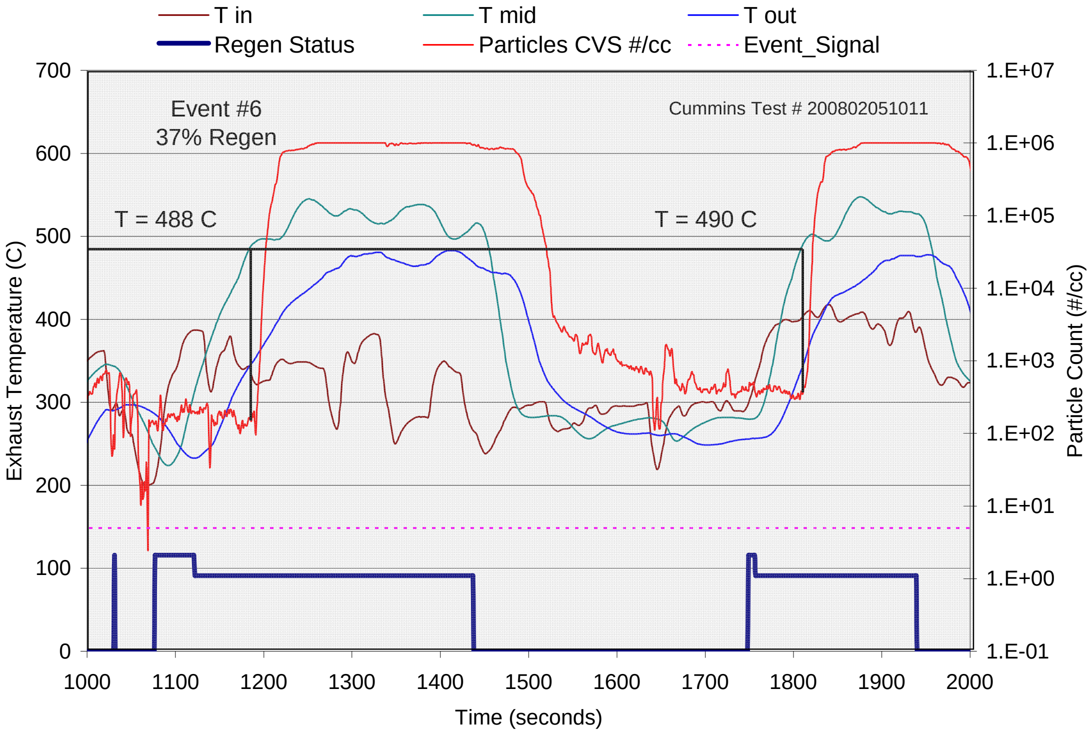


Figure A-G13 Cummins regeneration temperature activation on Event #6

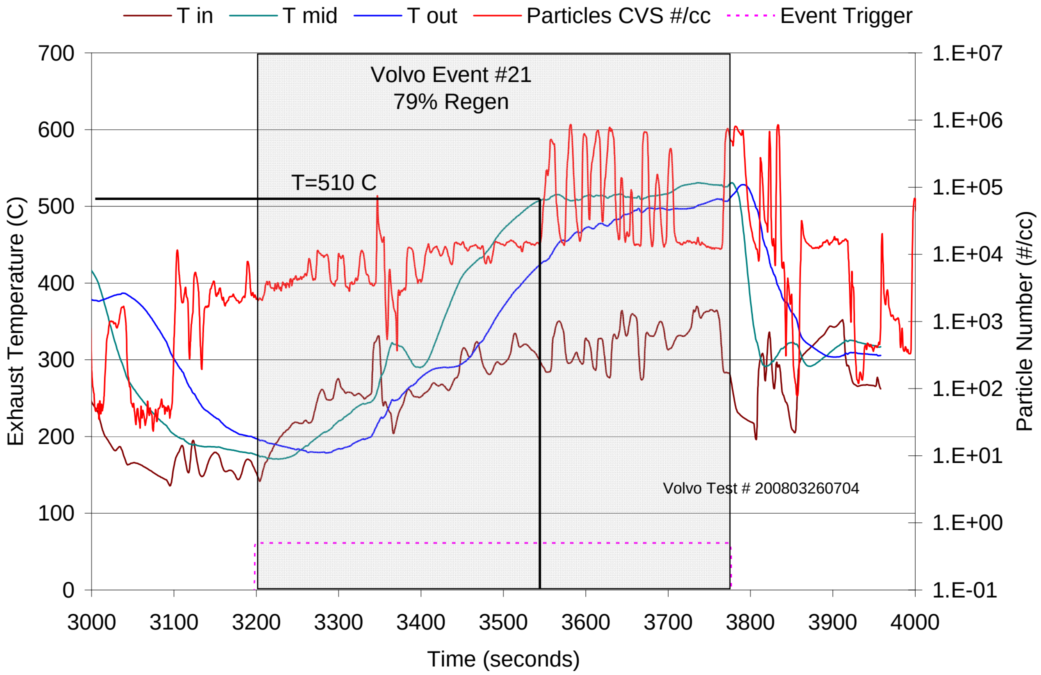


Figure A-G14 Volvo regeneration temperature activation on Event #21 (not very clear)

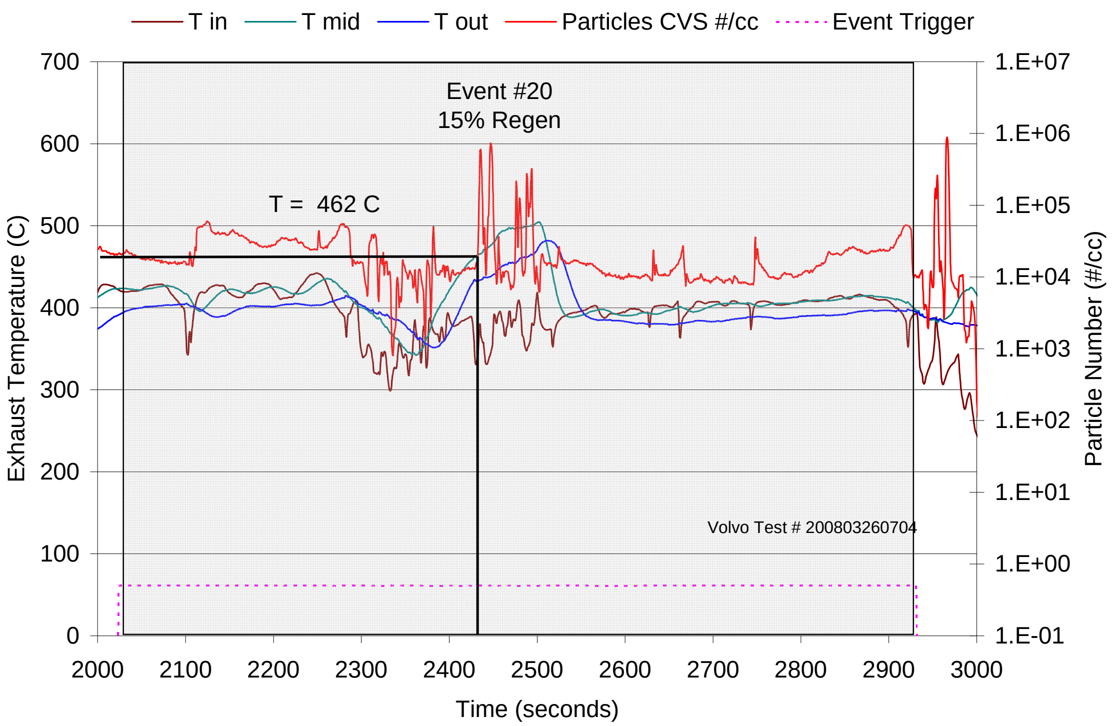


Figure A-G15 Volvo regeneration temperature activation on Event #21 (not very clear)

Selected Real-time PM Figures

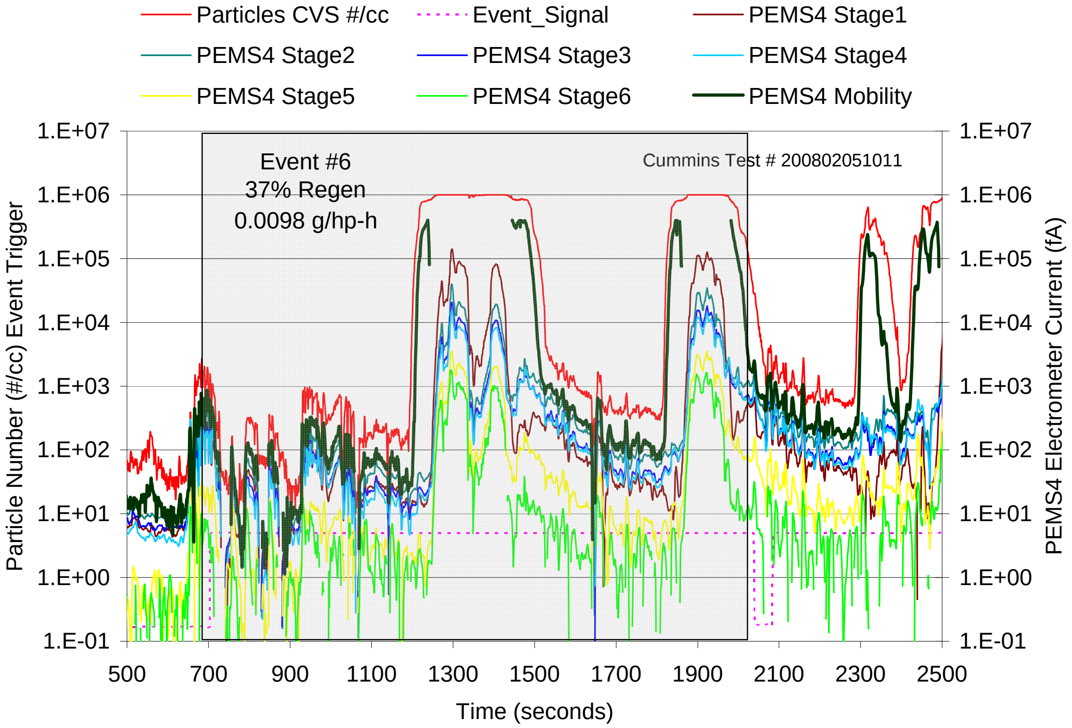


Figure A-G16 Cummins event #6 showing PEMS4 impaction and mobility currents

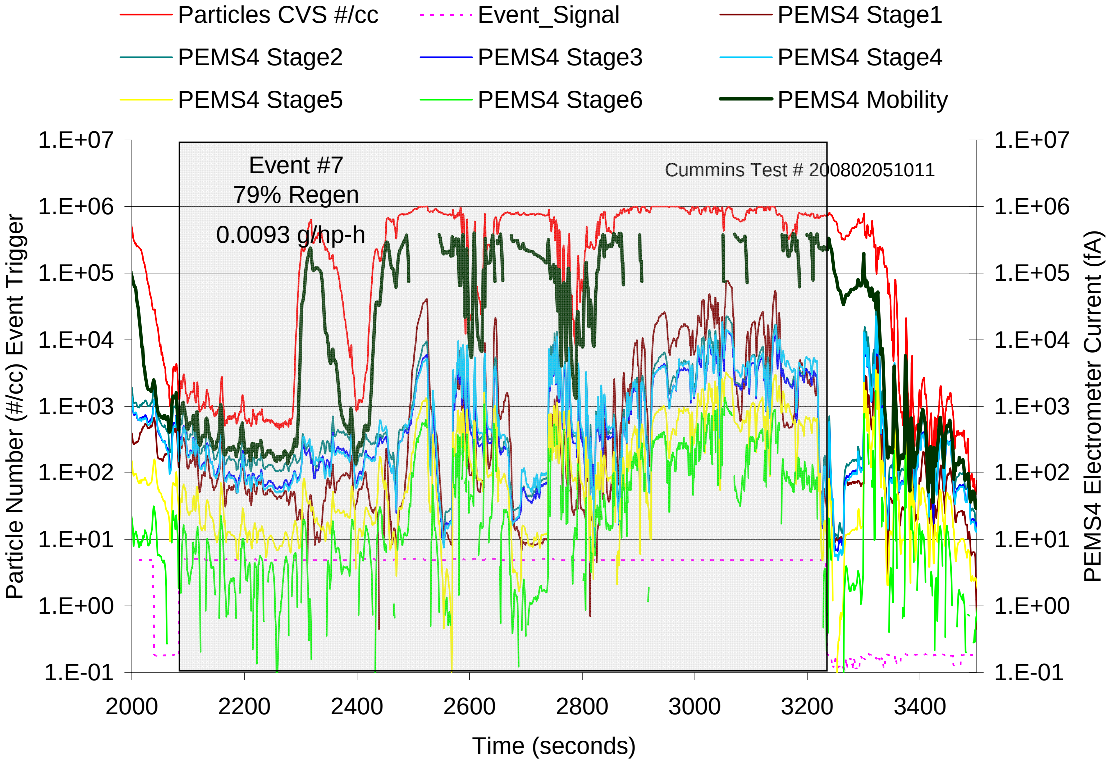


Figure A-G17 Cummins event #7 showing PEMS4 impaction and mobility currents

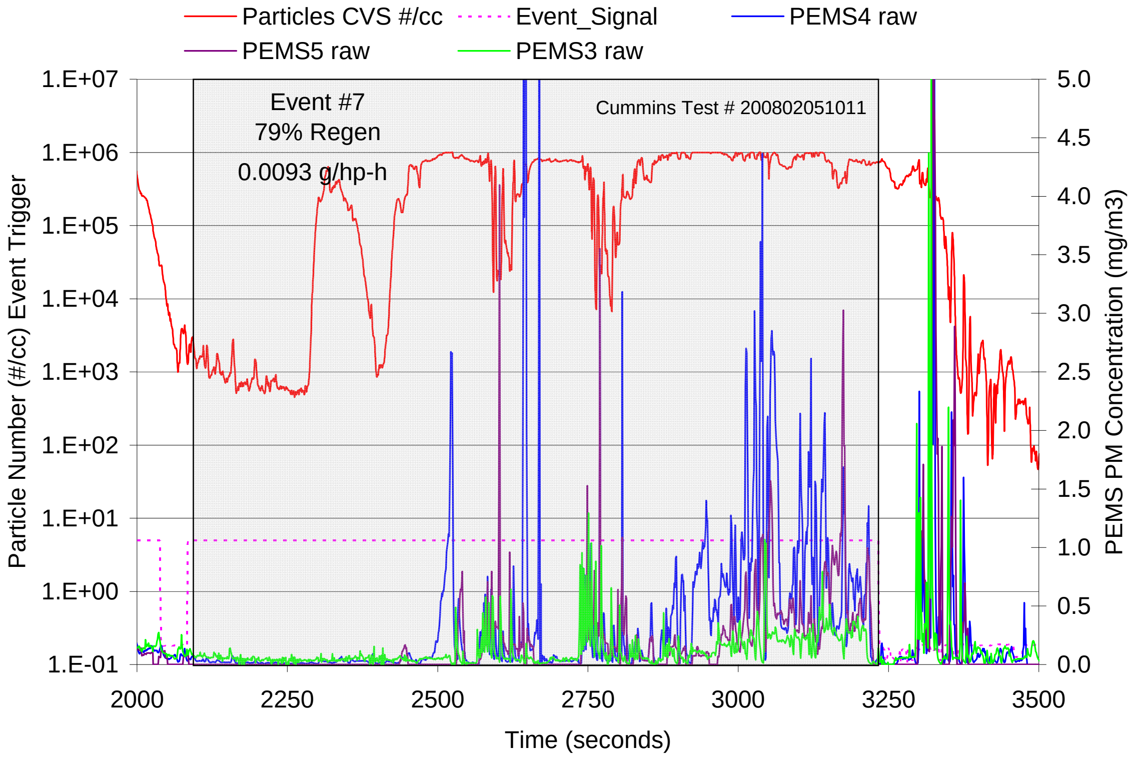


Figure A-G18 Cummins event #7 showing PEMS3,4, and 5 real-time signals

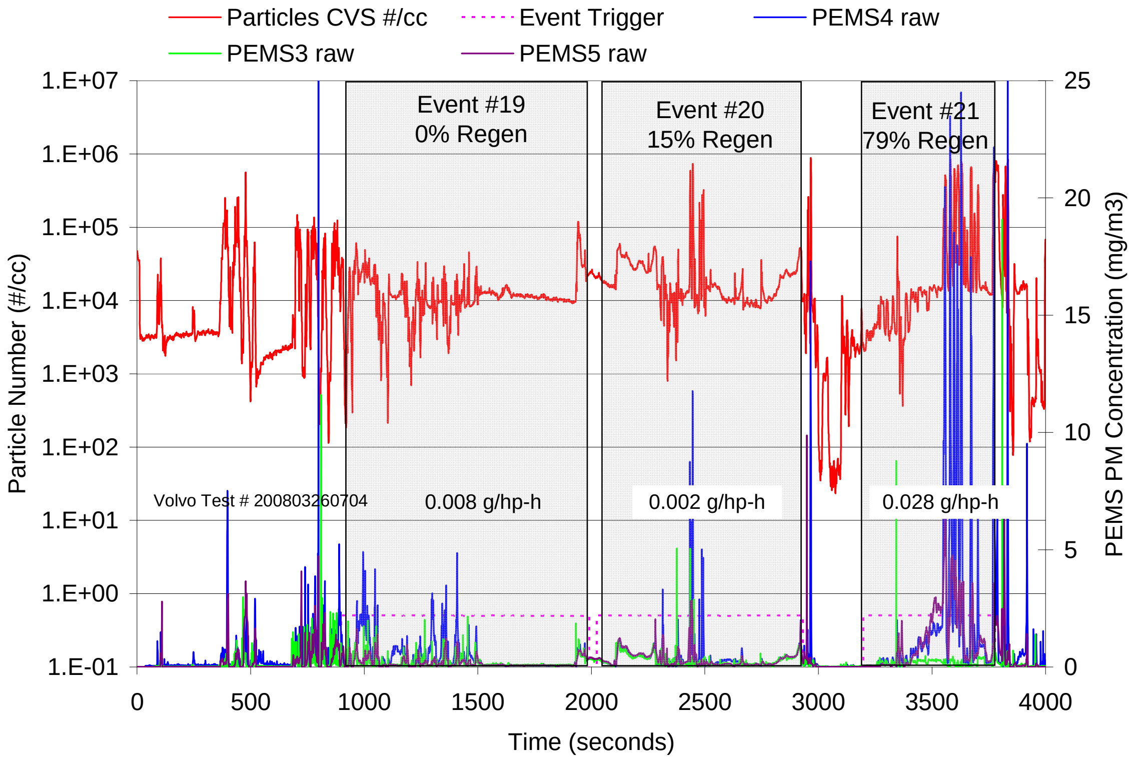


Figure A-G19 Volvo event #19, #20, and #21 showing PEMS3,4, and 5 real-time signals

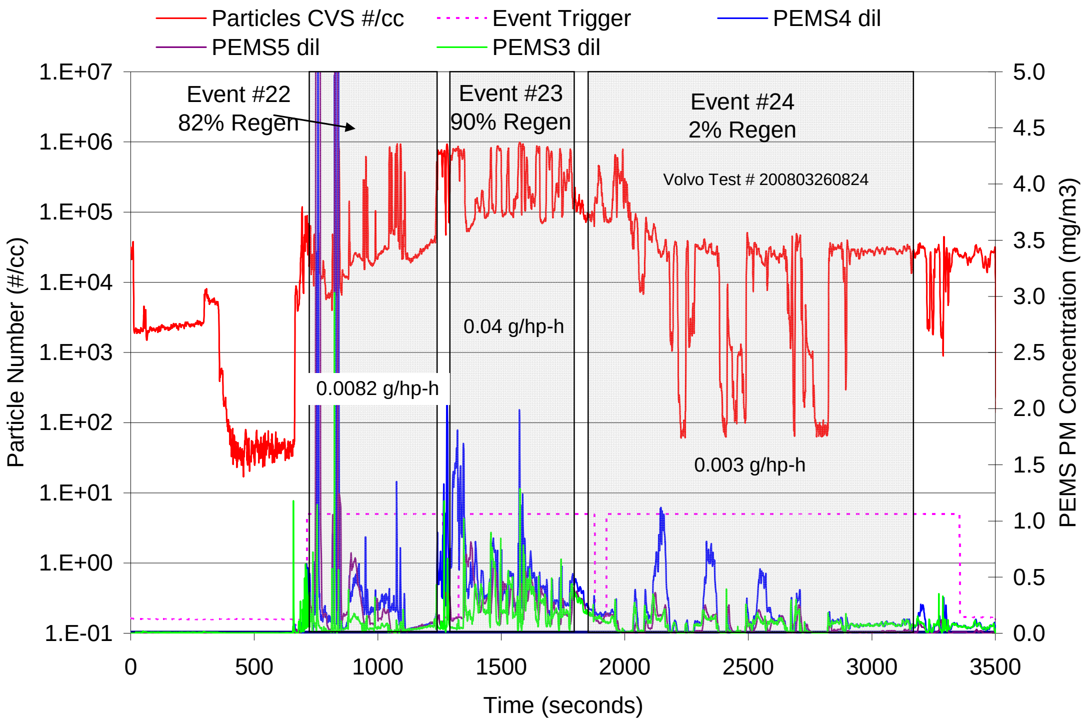


Figure A-G20 Volvo event #19, #20, and #21 showing PEMS3,4, and 5 real-time singals

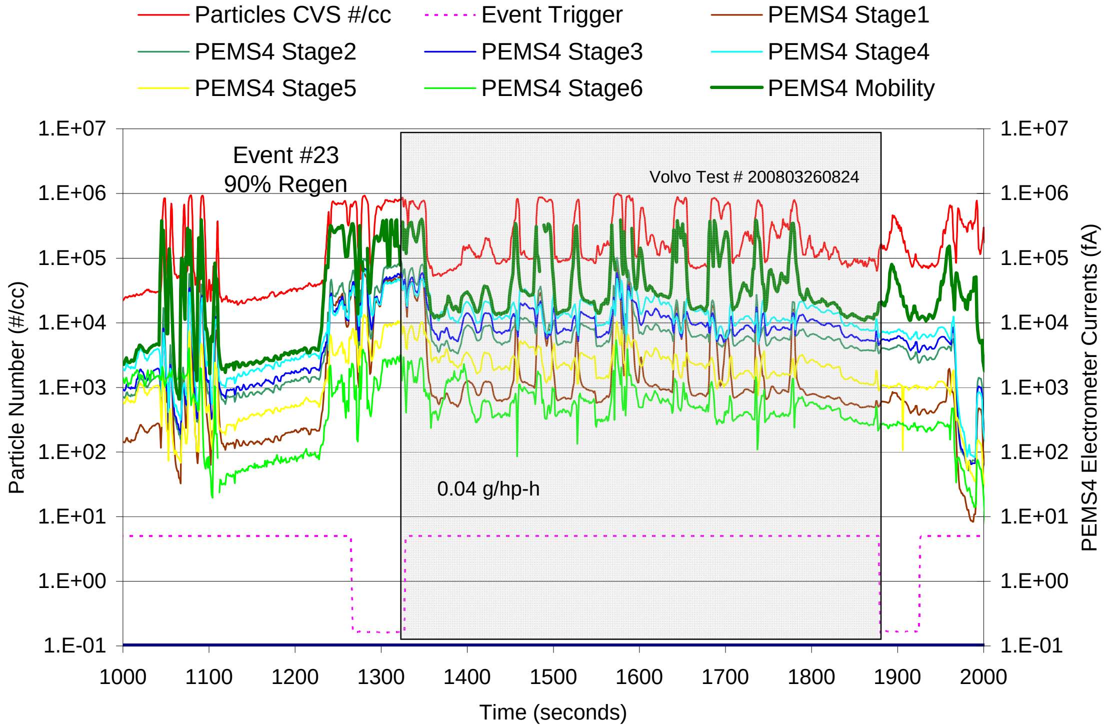


Figure A-G21 Volvo event #23 showing PEMS4 impaction and mobility currents

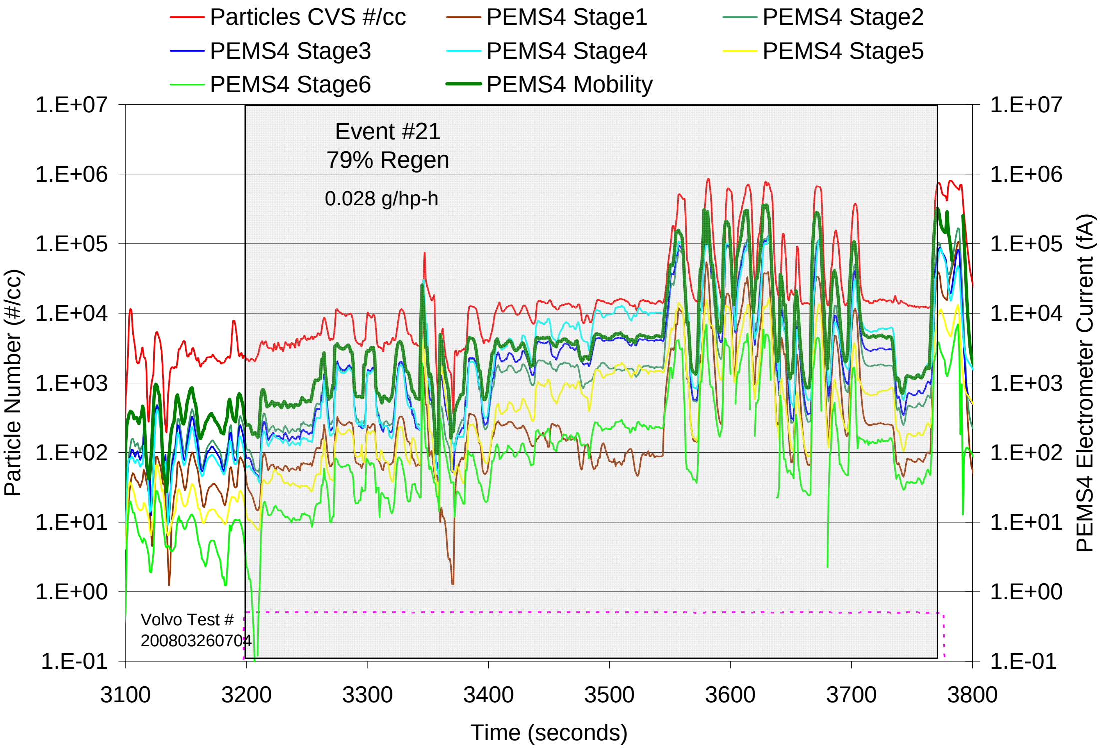


Figure A-G22 Volvo event #21 showing PEMS4 impaction and mobility currents

Appendix H –Field Notes

Test 01/31/2008 Cummins Engine Testing Notes:

Overview:
There were two NTEs forced by CE-CERT on local Riverside freeways. The first NTE was started on the 91 West to the 15 North to the 60 east back to the start of the 91 West. The Sessions was started at CE-CERT in the morning, but due to difficulties with the PPMD the tests did not get started until after lunch. The second of the NTEs was over the same course as the first NTE, but with a forced regen during the entire NTE route (same as before).

PPMD
NTE 1 – around 500 ng and data pre and post signal looked stable
NTE 2 – around 1000 ng and data pre and post looked noisy. David commented the corona currents were also noisy. NTE 2 did not have enough time after the test to complete the cycle. CE-CERT ended the test too soon (we needed to wait 10 minutes and we only waited about 5 minutes). David was able to take crystal info from the second test segment (driving back to CE-CERT) to get pre and post weights. CE-CERT needs to not do this in the future.

AVL
Serious problem with data. Large negative and positive numbers (+/- 2 mg/m3). All setup data looked good and met mfg specifications. A new instrument is being installed for the next set of testing. Caterpillars' AVL instrument will replace the MFG's instrument for the next week of testing. The CAT one should be installed on Monday 2/3/2008

Semtech DS
Semtech

MEL
No issues and filters looked light grey, but weights were from 90 to 300 μg (NTE 1 and NTE 2)

DMM
No issues and data used to set the MEL filter loadings.

Regens
Could not get data recorded to save (the laptop locked up). Set regens by setting the real-time pm loading parameter from 25 to 120. Also set parameters from 0 to 1 to override the real-time ECM calculator. The ECM connection was made not on the J1939 traffic buss, but at a lower level to prevent issues with MEL and Semtech PID traffic. This was at the advice of Cummins when we had Multiplexing errors.
NTE 1 – One 5 minute regen on the 15 N where DMM loadings spiked at the end of the regen up to levels around 2 mg/m3 indicated by the DMM.
NTE 2 – Full cycle regen with DMM levels highest at the end of the route at 10 μg/m3 in the beginning and 200 μg/m3 near the end of the test.

PPMD/Semtech DS/AVL Update, Date 2/10/2008

CE-CERT completed 4 days of testing with the PPMD/Semtech DS and AVL systems (1/31, 2/5, 2/6, 2/7). The MEL filters ranged from 30 µg to 200 µg over the various configurations of regens durations. Some of the filters were sampled with no regeneration events. The FEL emission levels for the test engine is 1.45 g/bhp-hr kNOx and 0.01 g/bhp-hr PM. The kNOx values appear to be much higher during regen events by around 2-3 times when watching the real-time concentration data in the MEL. More analysis is necessary to evaluate the in-use emissions levels during NTEs in terms of g/bhp-hr.

There were several problems that limited the amount of actual testing for each of the four days. Typical start up times took around 4 hours and the longest start up time was 6 hours on 1/31. Most of the problems were due to the PPMD, but there were some software issues with the Semtech DS and some vibration issues with the AVL Photo Acoustic (PA) instrument. The Semtech DS and AVL instruments did not delay test times due to the cooperation of Nate and Joel from Caterpillar. Below is a summary of some of the problems and details from each system:

PPMD:

1. **Communications Problem**- The PPMD had/has continuous communication issues when trying to perform the startup routines. These problems/delays caused start up times to exceed 6 hours on day 1/31 and averaged 4 hours each day. CE-CERT continued to shift start up time from 6:00 AM to 4:30 AM in order to get a reasonable amount of test time. CE-CERT also had to modify the start up procedures to prevent any additional delays such as eliminating some of the 1065 start up audits and crystal checks at the permission of sensors. The skipped procedures were performed at the end of the day when more time was available.

2. **Software Parameters Problem** - Another serious problem was a result of some invalid parameters in the software. This problem invalidated the data on 1/31. The bad parameters caused the proportional flow to not calculate the correct dilution rates and the sample flow and dilution flows were out of control and not proportional to exhaust flow thus all data was invalid on 1/31. These parameters may have been contaminated with the numerous attempts to communication and operate the start up audit software from 1/26 to 1/31.

3. **Water Contamination Problem** - There was another problem with some water in the differential pressure transducers preventing proper flow, proportionality, and valve look up table operations on day 4 (2/7). The start up procedure should remove this water with a purge cycle, but the purge cycle did not work. The water caused a bias in the transducer zero reading by 0.5 kpa. CE-CERT manually removed the water at the guidance of sensors before testing. Brief analysis of day 4 data suggests a problem on test run 2 and 3 that could be a result of water in the lines. More analysis is necessary to confirm.

4. **Compressor Valve Stuck Problem** - There was also a problem with the main compressor drain valve sticking and preventing any dilution flow on day 4. The PPMD

would not build pressure and prevented CE-CERT from building the lookup table necessary to run the first day of testing.

AVL:

1. **Noisy Signal Problem** - The AVL photo acoustic soot sampler seems to have a serious signal noise problem on this Prostar installation. It appears the problem is associated with road vibration and not acoustic pressure waves in the exhaust as suggested by AVL representatives. More details will be available as the data is analyzed. Several installations and vibration absorbing configurations were tried and will be presented later.

MEL:

The DMM and MEL appeared to operate with out any serious problems. The MEL collected filter data on about 40 filters. In addition to gas phase emissions, Dekati DMM, and gravimetric filters, the MEL sampled particle number with a 3776 CPC (3 nm cut), fast scan SMPS (8 sec scan time from 3 nm to 500 nm) and quartz filters for EC/OC analysis. Sulfate analysis could also be performed on the Teflon filters with ion chromatography analysis.

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Below is a quick summary of the testing completed:

01/26/2008 - 01/30/2008: Check Out

CE-CERT spent about 4 days getting to the point where we were able to get through the PPMD start up routines. The main problems appear to be in the communication between devices causing flow audits and look up tables to fail. These failures would prevent valid data from being collected. Daily logs are recorded for each failed event.

01/31/2008: Test Day 1

1. The PPMD was powered at 5:54 and the first test was started at 13:10 and ended testing around 15:00. Post test PPMD checks and QCM cleaning ended around 18:00.
2. The PPMD data was invalid because of some coefficients in the software were wrong causing the MPS calculations to be divided by 0 or NaN errors. The coefficients caused proportionality calculations to be outside of all possible bounds thus causing the PPMD data to be unusable.
3. The AVL instrument showed severe noise and may not be valid also. CAT shipped out a replacement.
4. The DMM/MEL/Semtech appears to be valid.

02/04/2008: PPMD and AVL Repairs

1. Spent day with David Booker and PPMD to fix coefficients. Got MPS and PPMD to sample proportional data. The PPMD seemed to be working. Eliminated start up of MPS 2 to accelerate PPMD startup procedures.
2. Caterpillar's AVL was installed same location as AVL PA instrument.
3. The DMM/MEL/Semtech appears to be valid.

02/05/2008: Test Day 2

1. The PPMD was powered on at 5:29 and first test started around 9:00
2. CATs PA instrument also noisy, added more vibration isolation.
3. The DMM/MEL/Semtech appears to be valid.

02/06/2008: Day 3

1. The PPMD was powered on at 5:15 and first test started at 9:00
2. Moved CAT PA instrument to MEL laboratory and sample probe also moved. Noise seemed to go away.
3. The DMM/MEL/Semtech appears to be valid.

02/07/2008: Day 4

1. The PPMD was powered on at 4:29 and first test started around 9:30. Problem with water in sample line. Did all flow audits and crystal checks after testing to prevent any more start up delays.
2. Added AVL PA instrument back to frame and left CAT PA instrument in MEL laboratory. AVL PA instrument sampled ambient, internal zero and filtered ambient. Only the internal zero was stable.
3. The DMM/MEL/Semtech appears to be valid.

1/31/2008 Startup and Setup Conditions

Semtech Log:
NO and NO2 zeros are deviating. Software version 10.09 is not stable with the vehicle interface software. Nate is working on these issues.

- Unable to zero NDUV without “red” indicator showing.
- After zeroing, Analyzer drifted positive to values around 1000ppm for NO and NO2.
- After stabilizing, attempted zeroing with success… analyzer zeroed with “green” indicator.

AVL Log:
Startup and verified zero voltage and found it was at 0.95 mv and the cleaning procedure is set for 1 mv. The AVL lens was cleaned and inlet sample and bypass filters were replaced. The post cleaning zero voltage was 0.065 mv. Residence test was performed as Joel about. After cleaning and zeroing instrument a calibration check was performed by placing the soot window on it and pressing cal. The calibration was 3.87 reference and measure dwas 4.027 or 4.06% high. Joel made the adjustment and spanned the AVL system. The final value was 3.87 reference measured was 3.866 which is a % deviation of -0.116%.

Ask for more cleaning swabs from AVL

PPMD Log:

- The PPMD initially did not communicate with the MPS1.
- Once problem was fixed there was a problem with the flow check on the Major dilution flow. Calibration of Major dilution flow was necessary, but software was not working (it

would cal, but not update the data table. Tried 4 times. even latest version of software). Had to use David's low level software to resolve
- Starting over in the morning (power surge and CB popped and battery to vehicle was dead. Located new circuit and charging up truck and PPMD. Started at 5:07

MEL Log:
Burn out, clean secondary, tunnel blank, reference blanks, 1065 audit on temps and flows

ECM Log:
Verified regens status with John from Cummins

2/4/2008 Test Notes
Proportionality was Davids concern not the QCM. Open PPMD Host ver 2.204. Zero MPS1 first, then looked at look up table by "read parameters". The setup was not good. Total flow is 8.00 set (blue) and actual is green.

Constant dilution mode (Misc Advanced – Constant Dilution)
- DR Set-Point = 10, Total at 8 then sample at 10 to 1 should be .8 and we are getting .69
- DR Set of 50
- Minor flow is not changing
-
-

Critical parameters to dictate the flow
- Throat diameter, secondary capillary diameter and discharge coef
- Throat diam (6_1.float.Model_Vt) in meters per second max is around 100
- Throat temp (6_1.float.Tthroat) still
- T2_factor (can not calc float)
- Venturi throat diam (set to 0.002 or 2 mm) and now we get the throat velocity
- Needle diameter set to 1.5 mm
- Slip correction using (M) variable set to 3
- Back to DR to see how the effect look. Now we are getting minor flows changing.

Save data at different constant DR set points
- 50, 40,30, …. Click File Saving On to save. Then look at data to make decisions.

MSP Advanced tab
- Multivariable fit
- Load in test one data saved. And it should fit equations to those flows
- This is necessary to use data to estimate the capillary diameter. It is raised to the power 4 and

Back to DR and verified flows, but the minor flow didn't work well
- Then we went to advanced MPS
- And did generate look up table (data logging must be off first)

Something wrong with minor flow go to MPS advanced stuff

- MPS Main Micro Processor
- Minor_Ratio
- Major Ratio
- Minor Ratio Adjusted (this is a correction for altitude and stuff) There is one for major and minor (data is saved as structures)
- Completed the look up table, but still wrong. Look at MPS micro parameters again
- Minor flow Offset Parameter was NAN and set to a number to get working.
- Looking at flows, velocities and other MPS related calculations.

David thinks something got corrupted in the audit software that made the parameters to be far off and not be sampling proportionally. David is showing me how to verify the parameters. He verified the sample flow total flow and minor flows moved as expected by setting different constant dilution ratios. Now he set different dilution ratios and is saving the data from 10 to 50 in steps of 5. Load in test 2 data and

Go to multivariable fit (don't need to close file to do this). Solved for the throat and needle diameter in order to fit the saved data. This should not need to be done each test time. He suggest doing all this evaluation using data with exhaust temp and moisture to remove these errors also. How much.

Now we are going to save a final test 3 (ending running) he is going to learn from this file.

Day 2 – 02/06/2008 05:15 Startup

Problems with communications… Look at file

Day 3 – 02/06/2008 05:00 Starup
Problems with communications reset PPMD several times. Problems with Crystal tares reset several times. First test ready by 8:30. Could not get flow audits to work well with communication problems. Perform audits after testing.

Arrive CE-CERT at 2:30. Started audits at 3:00 finished audits after several failures by 5:30 when the equipment was powered off.

Day 4 - 02/07/2008 04:30 Startup
I15 Baker Route

Lookup table failure and sample flow failure. Delta P sensors did not zero, but made it through the startup and did not allow you to start testing (look up table and audits not necessary for testing). Add some screen shots of failures modes

Completely failed look up table. This also caused a serious fault on the sample flow sensors. It turns out the problem was due to a delta p sensors zero offset of 2 kpa below 0 kpa. This offset wiped out all low flows. This problem may have been present yesterday

03/12/2008 Volvo Engine with Navistar International PPMD In-Use Testing Notes

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03/12/2008 – 03/17/2008 Installation

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This vehicle was a Volvo 13 liter DPF-equipped 2007 engine leased from a local dealer. The chassis had a passenger side fuel tank that was in the way of the PPMD installation thus it was decided that the fuel tank needed to be relocated to the driver side. The AVE, PPMD and Semtech were installed on the frame outside of vehicle chassis on the passenger side. A frame was constructed out of 2 in box tubing and was supported through the existing fuel tank mounting bolts. The AVL and Semtech DS were mounted to the frame using the standard vibration isolation systems provided during shipping. The PPMD did not have any vibration isolation since as per the manual. The exhaust was routed after the muffler by removing the exhaust stack and brining the exhaust back down to the PPMD. After the PPMD a small straight section is placed before the sample enters the MEL insulated 6” exhaust sample transfer line. The AVL problem is installed about 12 inches from the bend of the PPMD using their dilution probe sample conditioning system. The DR for the AVL for these runs was always 3 to 1.

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03/18/2008 Hookup and systems integration

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03/19/2008 Audits and Calibrations

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A full suite of audits and verifications were performed on all systems. The systems included the PPMD/Semtech/AVD/MEL/DMM and any other systems used for analysis in the study. All checks looked good. Systems ready for testing. See individual sections on instrument startup calibration procedures for more details.

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03/20/2008 ECU #1 Bypass #1

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Startup Instruments at 5:30. Semtech had a problem with the startup leak check. The leak was bad enough (15% leak in 5 min or 300 mbar loss out of 600) to try and trouble shoot a solution. CE-CERT was on the phone with Carl at Sensors for 1.5 hr and decided that a service technician would have to fix the problem. A technician came out the following day and repaired the problem. A day of testing was performed to evaluate the remaining instruments with the Semtech operating in this not ideal state. It is worth noting this Semtech DS can directly from sensors after passing a 1065 audit. The data from today should be an interesting benchmark for 1065 compliance, but with an inherent problem not caught by the procedures.

The PPMD passed startup checks

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03/24/2008 ECU #2 Bypass #1

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Startup Instruments at 5:00 am. Semtech not getting audit/span gas on CO/CO2/NO lines. PPMD issue with bypass flow. Bypass flow was only 0.8 when it should be 3.0. Abort testing and performed repairs to Semtech and PPMD. Semtech issue was related to misplacement of lines Used time to evaluate regens and bypass issue while sampling with Semtech.

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03/25/2008 ECU #2 Bypass #1

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Startup Instruments at 5:00 am.(AVL, PPMD, Semtech, DMM) MEL instruments left on as for normal practice, but pumps and gases started.

- PPMD startup consisted of Audit software [MPS1 communication/warm-up/zero/block pressure/look up table/diesel mode/proportional/EFM selection.
- The Semtech was started up as per manual where warm up time was around 1:00 when gas instruments were zeroed, spanned and audits. First test started at 7:00.
- AVL started and put in standby mode. All zeros and linearity's were valid and no issues for starting. AVL ready in 40 minutes from startup.

Test comments: Post test operations zero DMM, Semtech (ambient), and AVL. Verify and record as part of the file.

Test summary. 10 filters and 1 QC check were run today. One filter was sampled during a traffic jam. All the others should be during reasonable NTEs.

Test ID 200803250703.xls Forced filters logged below:

1. Forced event 10 minute regen in middle of test. THC climbed to about 200 ppm from regen condition and back down to 3 ppm when off.
2. No forced regen on this one.
3. Used as a dynamic blank (idle for 2 secs)

Test ID 200803250835.xls Forced filters logged below

1. Regen during test 15 minutes
2. 5 min Regen near beginning 5 minutes (good hill climb)
3. Full Regen in middle of hill

Test ID 200803250954.xls Forced filter logged below:

1. no Regen. Only one filter since a lot of this test is going down hill

Test ID 200803251120.xls Forced filters logged below: Before test started it was noticed that the power supply to the Semtech/PPMD was near 0 with the truck idling. It was then observed that he PPMD mode was (red led) in standby. Not sure what happened, but the system was restored by going into the audit software and forcing communications and putting the MPS 1 in proportional mode and verifying correct mode of operation. The QCM crystal head variables were verified that crystal 5 and 8 were disabled since these crystals are not oscillating. These problems were discovered after starting the next test sequence. Given the level of experience we have operating the PPMD the problem was fixed in a matter of minutes and did not delay test progress.

1. 10 minute Regen for 10 min cycle (QCM could be invalid because I tarred then started a test). There was not enough time for the QCM to evaluate the

2. 5 minute Regen (Check engine light came on and the vehicle said it was going into a de-rated condition during this cycle). The warning had to do with a regeneration need request. I forced a regen to help, but it didn't seem the clear the error. Stopped filter before getting to traffic jam on I10 (old fire on side of road that is being cleared away)
3. no Regen. The vehicle still has a check engine light.

Test ID 200803251322.xls Forced filter logged below:

1. first filter no regen (started test possibly too soon and maybe an issue to the PPMD) try to add data to make it happy. We got stuck in a traffic jam on this filter. So there may be a lot of idle conditions on this one.
2. 100% regen. Thought there was a problem with a valve because data from "Semtech Data Viewer" was showing valve 2 open and numbers were not frozen. I went into the low level software and everything was okay. Data is valid. During the regens on this test there was a very large nano particle peak as seen by the DMM. Look at sulfur analysis to see if there is any spikes on this one.

Shutdown and back at CE-CERT by 15:00 hr

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03/26/2008 ECU #3 Bypass #1

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Today's route is to Baker CA and back. Tried to install 1" bypass for return to Riverside trip. Pipe fitting frozen and was not successful.

Test ID 200803260704.xls

1. no regen (dmm around 30 μg)
2. 2 min regen (dmm around 12 μg) waited to start next cycle due to downhill section
3. final filter with full regen (noticed regen going on and off 2 wait 3 is on from proprietary system). Also set flag after about 1 minute into this event. AVL has a slight elevated PM level where the DMM is increasing very quickly.

Test ID 200803260824.xls

1. full regen (trying to clean out filter and % soot parameter) Try around 10 min then do another filter on the same regen. This engine soot parameter doesn't get reset unless the regen is for a full 20 minutes
2. full regen (seemed high on DMM and AVL)
3. only 60 seconds of regen at beginning and soot load % was reset and the active flag was turned off and regen was turned off since it no longer was in a regen mode. By end of test soot loading was 15% as a FYI.

Test ID 200803261xxx.xls

1. 8 min full regen by Craig
2. 12 min full regen by Craig
3. 25 min no regen or small part by Craig

Test ID 200803261148.xls By pass modified (lost ¾ line due to frozen fitting)

1. no regen. Major issue with the PPMD lost all communications and mass were zero. I called David Booker on phone and he had me go into the advanced QCM micro parameters and turn on and off the QCM. This did not work then we pulled over and tried to reset the QCM and clean the crystals. This worked, but then 3 or 4 of the crystals were locked out. I then had to go in and clean the crystals. Finally got it working, but the

reference crystal was out of whack so you can not use the reference crystal on this run. The qcm was valid because I forced the PPMD to sample on the #2 crystal first. This worked and bought me time to get the others disabled (5, 8, and 1 are now off for the rest of today).

2. no regen on filter #2. Used crystal # Added a part of a regen to this filter near the end.
3. Not sure what I did on this filter. I had a regen on for the full part, but the test went into a calibration so soon. End of test during cal was a forced idle regen

Test ID 200803261326.xls

1. No regen.
2. partial regen (almost full)
3. Full regen, but mostly down hill filter

Done for the day. Try to get bypass fixed

****
03/27/2008 – ECU #3 and 1" bypass with some ½ pipe restrictions (both sets)
****

Test ID # 200803270704 aborted and file deleted due to Semtech lug curve not installed

Test ID # 200803270806 PPMD setup for NTE modes. Appears to be a problem with the Semtech not providing the proper NTE for this vehicle. Sensors is still doing real-time (unfiltered 4Hz NTE broadcast). The problem with this is if there is traffic or drop out on the J1939 then the NTE will go in and out even thought the J1939 ave NTE value is still valid. For example there were no valid NTEs on this run, but I'm sure when the data is post processed there will be > 5 valid NTEs. This caused the PPMD to cycle crystals rapidly and then the crystals were always in a frozen state. When watching the live data the work would go to inf on the real-time emissions NTE g/hp-h window. This is common result when a sampled set of ECM data is used and not filtered as per 1065 (replaced dropped values with previous). Sensors is sending a software patch for the Semtech PPMD integration to fix this problem. It is a beta version that will be installed on Nate's computer..

1. Filter 1 no regen, no AVL and PPMD in NTE mode not working
2. Filter 2 no regen, no AVL and PPMD in NTE mode not working
3. Filter 3 no regen, no AVL and PPMD in NTE mode not working

Test ID #200803270909

1. Filter 1 no regen, AVL back on and PPMD on crystal 3 (200 ng)
2. Filter 2 no regen, AVL on, PPMD on crystal 6 (1000 ng)
3. Filter 3 no regen, AVL on (.3 mg ave * 3 = 1 .005 mg/hp-h)

Test ID #200803271110 (lunch to 29 Palm) back to true NTE's beta version

1. Filter 1 no regen
2. Filter 2 no regen
3. Filter 3 no regen

Test ID #200803271308 (29 Palm to CE-CERT) back to forced filter events and standard Semtech Operational version

1. Filter 1 no regen

2. Filter 2 no regen
3. Filter 3 no regen

Appendix I – PEMS Startup/Issues

PEMS3 Startup

03/18/2008
Performed startup and cold not get leak check to start. Found out the AVL needs to be in sleep or pause mode not standby or measurement.

Standard Start Up Practice (30 minutes or less and requires no supervision)

- Leak check passed at instrument inlet and at probe inlet, but failed at probe inlet. Need to look at sample line. Sample line at box entry checked and passed. Found leak near dilution air inlet. Fixed and passed from probe inlet to instrument. Leak check valid and done.
- Zero check. The pollution window is low around 0.1 mv thus the window was not cleaned (clean required at ~1mv).
- Linearity check microphone passed (no absorber window installed). Result = 1.000. Only takes a few seconds.
- Calibration Check (absorber window installed). This takes about 10 minutes. The reference was 3.650 mg/m3 and as found was 3.651 mg/m3 and no adjustment was made.
- Linearity check laser (absorber window installed). Result = 1.000. Only takes a few seconds.
- Resonance check (absorber window installed). Result = 4148 Hz. Only takes a few seconds.
- Removed absorber window and repeated leak check. Passed (.4 ml/100mbar*s and .39 ml/100mbar*s). System is ready for sampling (DR is set to 3 to 1).

03/20/2008
AVL Started up with out issues except for a temperature warning. The warning prevents you from going into measurement mode. Thus instrument takes about 20 minutes to warm up from 15 C ambient temps. Times may vary and I'm not sure if the AVL has active temp control or if repeated pressing of standby forces the laser to help warm things

PEMS4 Startup

03/19/2008

- DMM startup included cleaning (isopropyl alcohol), air dry and zeroing. The impactors, sample line (to CVS), mobility section and internals were cleaned. They looked fairly dirty thus it was necessary to clean. Zero looked good (0.1 µg) and voltages looked good (< 5kVa). DMM is clean and signals are valid.
- Leak check: Inlet closed, leak check enabled "Inst Status Tab", mbar reading is 30 mbar. Close outlet valve and in 30 seconds went up o 47 mbar and in 60 seconds went to 88 mbar. Did not pass as per DMM manual. Repeated leak test and same type of rate about 60 mbar/min. Need to replace o-rings next. Order. Leak is minimal thus continue testing and fix ASAP.
- Nominal flow verified with BIOS meter

MEL CVS Startup

03/19/2008

- PM Secondary Leak check flow < 1% and pressure fall 28 inHg to 26 inHg in 1 minute. Pass.
- CVS leak check (0.05% meets spec of <1%) CVS only and with exhaust PPMD, AVL, Catalyst Bypass we get (0.62% with 6 connections). pass
- Propane CVS verification pass, tunnel blank < 5 µg/m3 pass
-

PEMS2 Issues

UCR performed the audit checks and every thing was looking good. MPS 1, Communications, warm-up, zero transducers, block pressures, look-up table (slight jog in table), leak test, sample flow, dilution flow major, dilution flow minor, then TC check and Diesel mode select.

Sample flow comment. Looked like only three points were on plot. Pass verification so not sure what is going on. Will send file to Sensors for comment.

Dilution flow major problem. Failed first calibration check. Rerunning. Did not save data when the error looked like a communication problem. Second time through it passed (15 min each).

Started crystal startup, all went well, warm-up, tare crystals, clean/replace, then started self check at 20:20 at night (still running at 20:56).

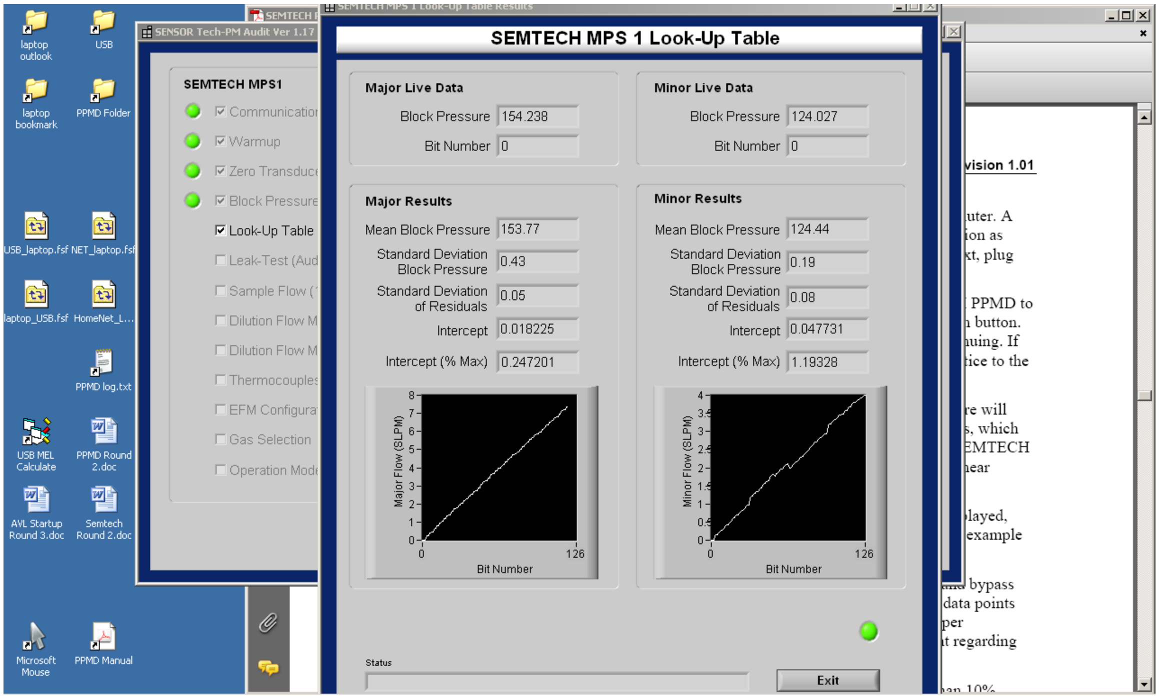
Greasing Crystals: I was instructed to grease the crystals they should be glued in. I found on that was loose and a post on the QCM head was bent (it still went in). Before I greased the crystals I made sure the masses were tarred (0.005 μg) reading. I tarred the crystals 4 times from the PPMD Audit software screen "Clean/Replace Crystals". Once the crystals were tarred all reading about 0.005 μg. After cleaning then greasing I got the following results. [3.5, 0.84, 19.3, 25.4, 0.8, 10.8, 0.6, 1.1]. The grease was applied by first cleaning with isopropyl alcohol. Then I cleaned an area with isopropyl alcohol on a metal surface. I put the grease on the clean metal surface and wiped it away. Then I took a swab and dabbed it in the grease and applied each crystal.

Sample flow check: Called Carl Ensfield about concern. Left message

Loose Crystal: Called Carl Ensfield to ask advice about loose crystal. Do I grease?

QCM Overnight Check: Left QCM on overnight to verify mass levels after 8 hr. The mass levels should be close to readings above since nothing changed [3.48,0.623, 19.7, 25.46, 0.875, 10.943, 33.714, 1.071]. Looks like crystal 7 drifted 33 μg all the others are less than 0.5 μg. I tarred the crystals this time so things should be relative to zero. (all mass are less than 0.01 (pos and neg)

Look-up Table comment



SEMTECH MPS 1 Look-Up Table

Major Live Data

Block Pressure 154.238

Bit Number 0

Minor Live Data

Block Pressure 124.027

Bit Number 0

Major Results

Mean Block Pressure 153.77

Standard Deviation Block Pressure 0.43

Standard Deviation of Residuals 0.05

Intercept 0.018225

Intercept (% Max) 0.247201

Minor Results

Mean Block Pressure 124.44

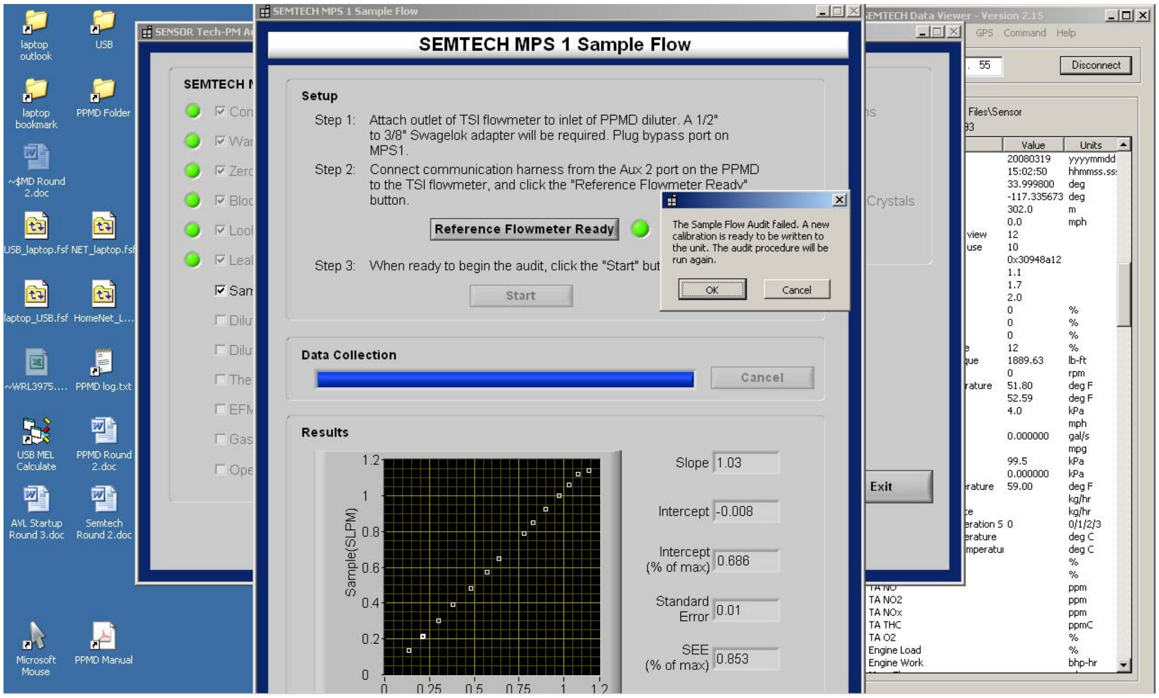
Standard Deviation Block Pressure 0.19

Standard Deviation of Residuals 0.08

Intercept 0.047731

Intercept (% Max) 1.19328

Zero Check, pass at 0.12 % On with n2 purge at pump and MPS1 inlet (return) and MPS1 outlet going to O2 analyzer and sample and bypass plugged



SEMTECH MPS 1 Sample Flow

Setup

Step 1: Attach outlet of TSI flowmeter to inlet of PPMD diluter. A 1/2" to 3/8" Swagelok adapter will be required. Plug bypass port on MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

Step 3: When ready to begin the audit, click the "Start" but

The Sample Flow Audit failed. A new calibration is ready to be written to the unit. The audit procedure will be run again.

Results

Slope 1.03

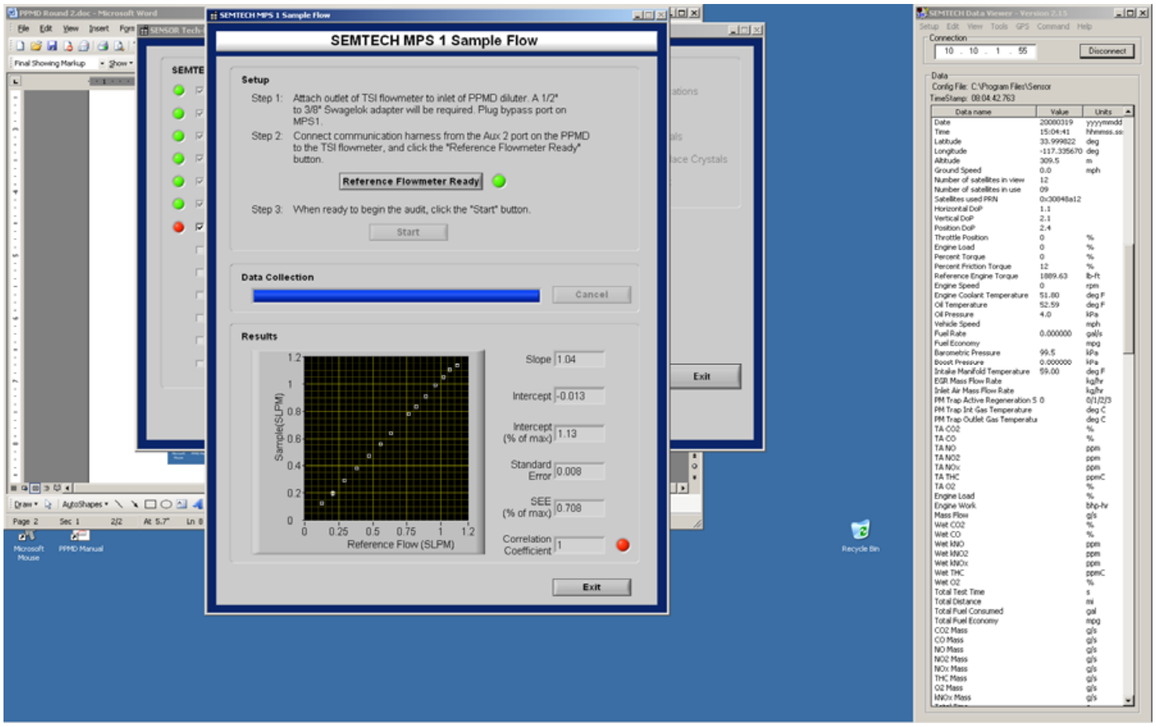
Intercept -0.008

Intercept (% of max) 0.686

Standard Error 0.01

SEE (% of max) 0.853

Sample Flow Audit: Repeat flow audit to see more than 3 data points. Much more this time. See below, but it failed. Looks like last point failed. Hit cancel and will repeat.



Setup

Step 1: Attach outlet of TSI flowmeter to inlet of PPMD diluter. A 1/2" to 3/8" Swagelok adapter will be required. Plug bypass port on MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

Results

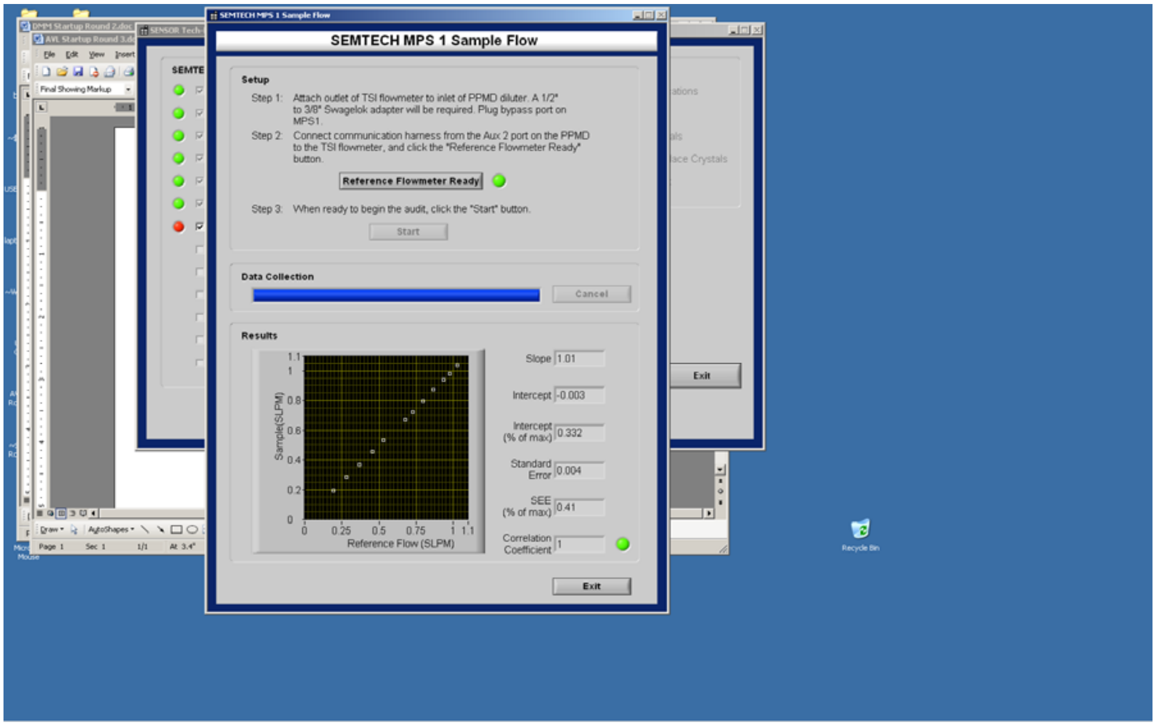
Slope 1.04
Intercept -0.013
Intercept (% of max) 1.13
Standard Error 0.008
SEE (% of max) 0.708
Correlation Coefficient 1

Connection 10 . 10 . 1 . 55

Data
Config File: C:\Program Files\Sensor
TimeStamp: 08:04:42.763

Data name	Value	Units
Date	20080319	yyyymmdd
Time	15:04:41	hhmmss.ss
Latitude	33.999822	deg
Longitude	-117.335670	deg
Altitude	309.5	m
Ground Speed	0.0	mph
Number of satellites in view	12	
Number of satellites in use	09	
Satellites used PRN	0x30848a12	
Horizontal DoP	1.1	
Vertical DoP	2.1	
Position DoP	2.4	
Throttle Position	0	%
Engine Load	0	%
Percent Torque	0	%
Percent Friction Torque	12	%
Reference Engine Torque	1889.63	lb-ft
Engine Speed	0	rpm
Engine Coolant Temperature	51.80	deg F
Oil Temperature	52.59	deg F
Oil Pressure	4.0	kPa
Vehicle Speed		mph
Fuel Rate	0.000000	gal/s
Fuel Economy		mpg
Barometric Pressure	99.5	kPa
Boost Pressure	0.000000	kPa
Intake Manifold Temperature	59.00	deg F
EGR Mass Flow Rate		kg/hr
Inlet Air Mass Flow Rate		kg/hr
PM Trap Active Regeneration S	0	0/1/2/3
PM Trap Int Gas Temperature		deg C
PM Trap Outlet Gas Temperatu		deg C
TA CO2		%
TA CO		%
TA NO		ppm
TA NO2		ppm
TA NOx		ppm
TA THC		ppmC
TA O2		%
Engine Load		%
Engine Work		bhp-hr
Mass Flow		g/s
Wet CO2		%
Wet CO		%
Wet kNO		ppm
Wet kNO2		ppm
Wet kNOx		ppm
Wet THC		ppmC
Wet O2		%
Total Test Time		s
Total Distance		mi
Total Fuel Consumed		gal
Total Fuel Economy		mpg
CO2 Mass		g/s
CO Mass		g/s
NO Mass		g/s
NO2 Mass		g/s
NOx Mass		g/s
THC Mass		g/s
O2 Mass		g/s
kNOx Mass		g/s

Passed now by using parameters from previous audit (not above ones. I did not save). They looked like the one below, but around 1.06 slope.



Setup

Step 1: Attach outlet of TSI flowmeter to inlet of PPMD diluter. A 1/2" to 3/8" Swagelok adapter will be required. Plug bypass port on MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

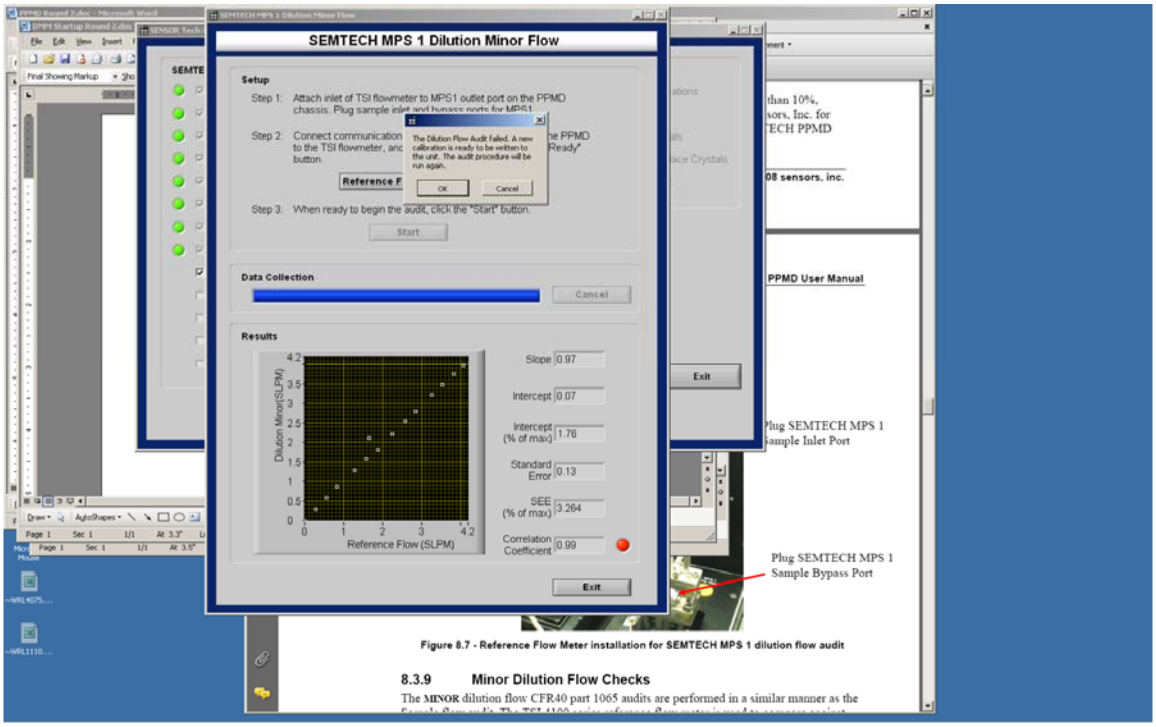
Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

Results

Slope 1.01
Intercept -0.003
Intercept (% of max) 0.332
Standard Error 0.004
SEE (% of max) 0.41
Correlation Coefficient 1

Recheck dilution flows. Major fine, but minor had an issue with one point. I will not save this even thought the software wants to write a new table. The bad point is not real.



SEMTECH MPS 1 Dilution Minor Flow

Setup

Step 1: Attach inlet of TSI flowmeter to MPS1 outlet port on the PPMD chassis. Plug sample inlet and bypass ports for MPS1.

Step 2: Connect communication … the PPMD to the TSI flowmeter, and … Ready" button.

Step 3: When ready to begin the audit, click the "Start" button.

The Dilution Flow Audit failed. A new calibration is ready to be written to the unit. The audit procedure will be run again.

Slope: 0.97
Intercept: 0.07
Intercept (% of max): 1.76
Standard Error: 0.13
SEE (% of max): 3.264
Correlation Coefficient: 0.99

Plug SEMTECH MPS 1 Sample Inlet Port

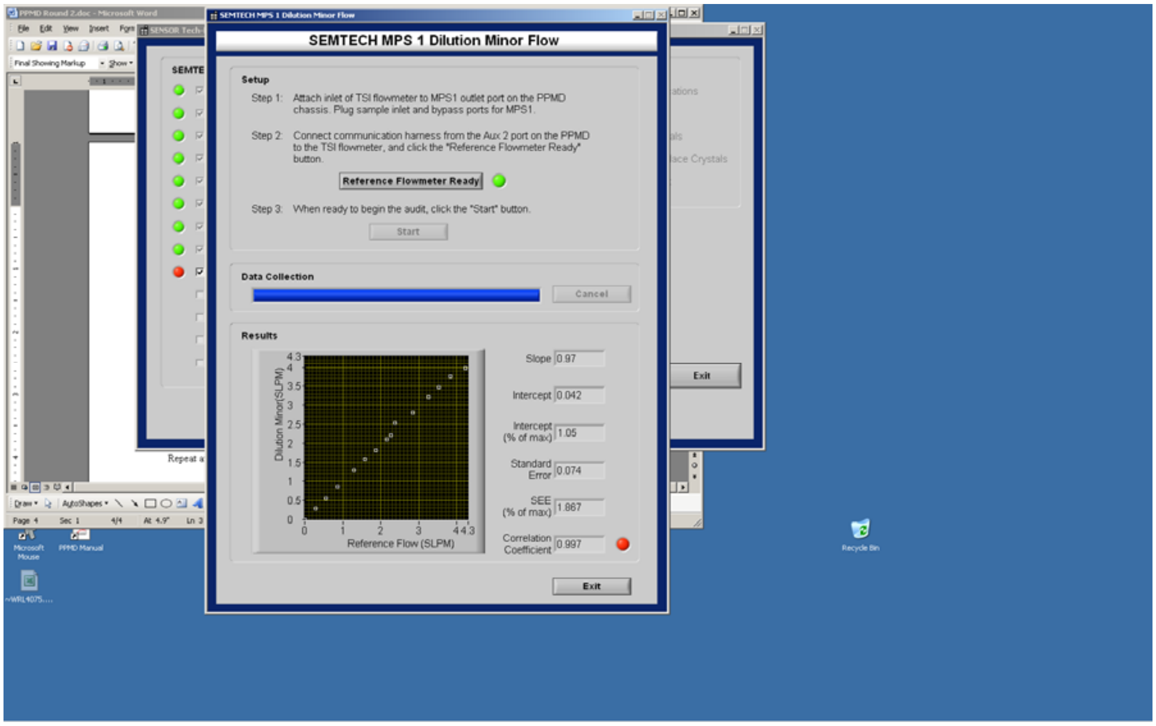
Plug SEMTECH MPS 1 Sample Bypass Port

Figure 8.7 - Reference Flow Meter installation for SEMTECH MPS 1 dilution flow audit

8.3.9 Minor Dilution Flow Checks

The MINOR dilution flow CFR40 part 1065 audits are performed in a similar manner as the

Repeat audit on dilution minor flow



SEMTECH MPS 1 Dilution Minor Flow

Setup

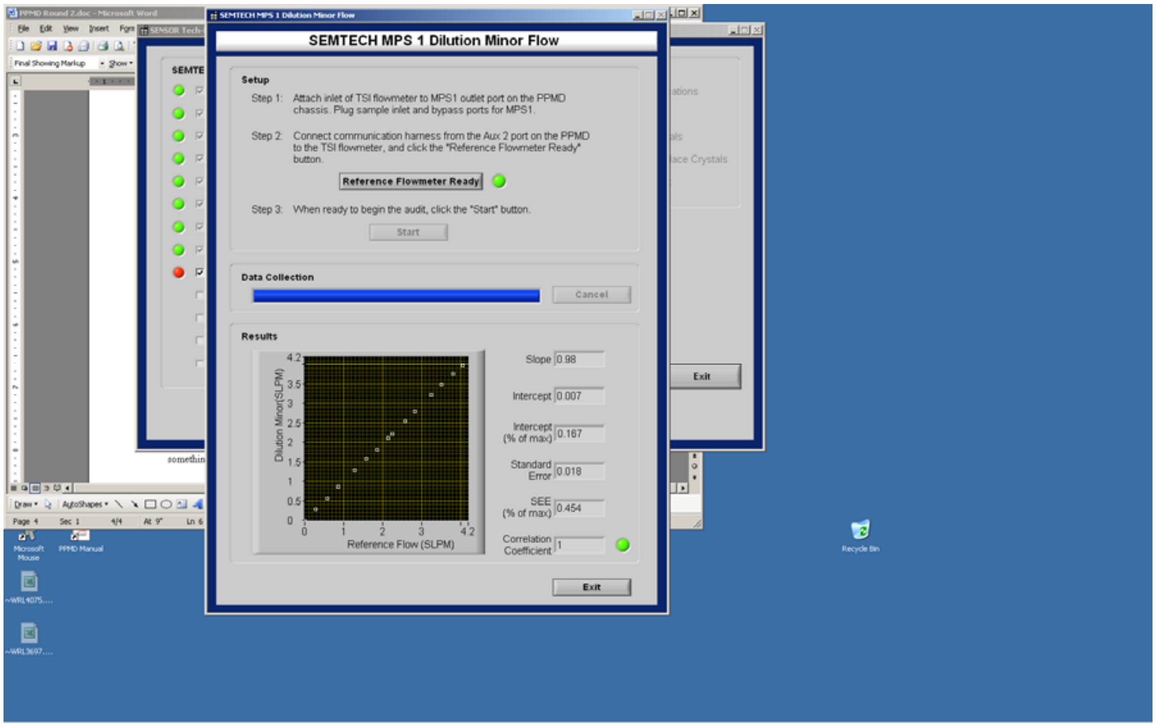
Step 1: Attach inlet of TSI flowmeter to MPS1 outlet port on the PPMD chassis. Plug sample inlet and bypass ports for MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

Step 3: When ready to begin the audit, click the "Start" button.

Slope: 0.97
Intercept: 0.042
Intercept (% of max): 1.05
Standard Error: 0.074
SEE (% of max): 1.867
Correlation Coefficient: 0.997

Repeat audit again (moved RS232 to aux 1). By visual inspection data looks fine, but something is wrong with one of the points. This is the last repeat. Moving on. Luckily it passed.


SEMTECH MPS 1 Dilution Minor Flow

Setup

Step 1: Attach inlet of TSI flowmeter to MPS1 outlet port on the PPMD chassis. Plug sample inlet and bypass ports for MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

Results

Slope 0.98

Intercept 0.007

Intercept (% of max) 0.167

Standard Error 0.018

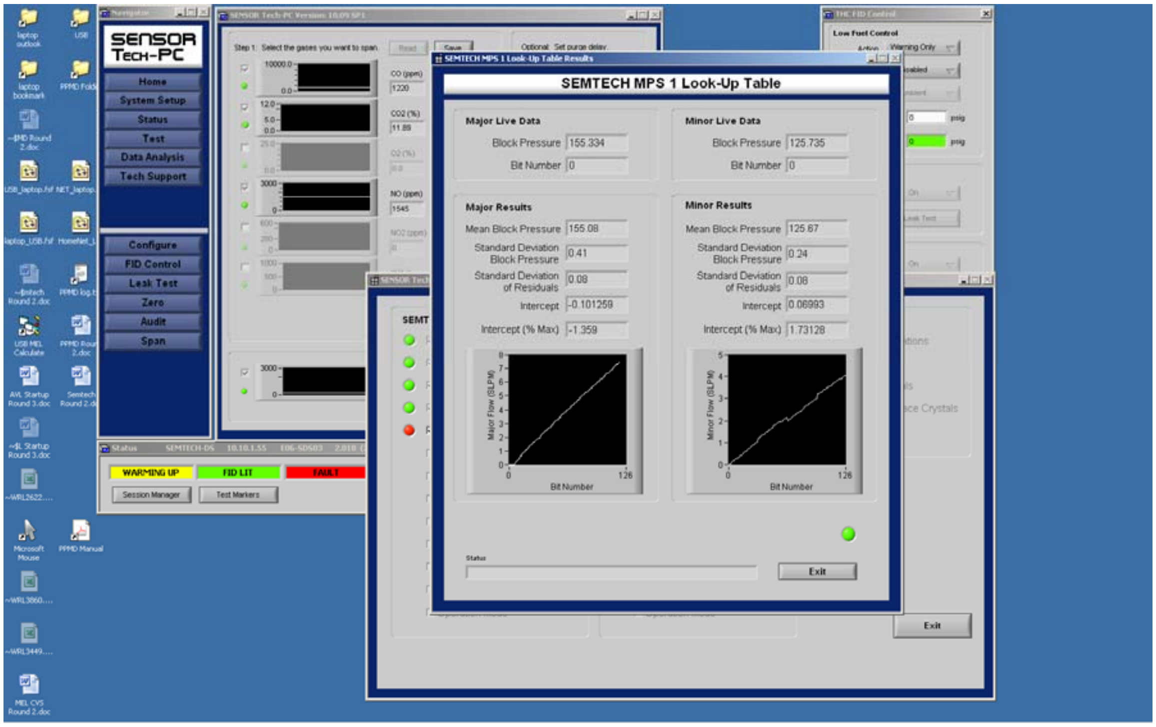
SEE (% of max) 0.454

Correlation Coefficient 1

Repeat audit on dilution minor flow

03/20/2008 Day One Testing

Start at 5:25 and completed communications for MPS1, 2, and QCM. Completed warm-up, zero MPS1, block pressures. Failed first look up table (did not do screen capture). Re ran look up table, but first repeat MPS1 zero, block pressure then look up table


SEMTECH MPS 1 Look-Up Table

Major Live Data

Block Pressure: 155.334

Bit Number: 0

Minor Live Data

Block Pressure: 125.735

Bit Number: 0

Major Results

Mean Block Pressure: 155.08

Standard Deviation Block Pressure: 0.41

Standard Deviation of Residuals: 0.08

Intercept: -0.101259

Intercept (% Max): -1.359

Minor Results

Mean Block Pressure: 125.67

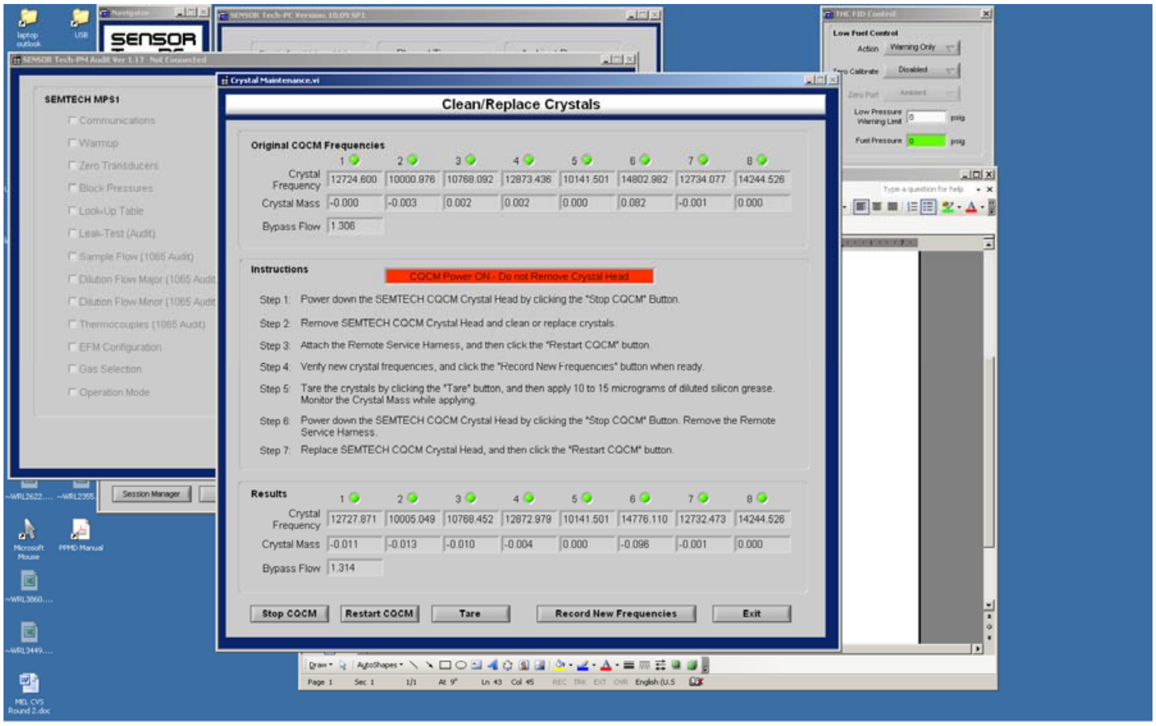
Standard Deviation Block Pressure: 0.24

Standard Deviation of Residuals: 0.08

Intercept: 0.06993

Intercept (% Max): 1.73128

Look up table screen shot passed on MPS1


Clean/Replace Crystals

Original CQCM Frequencies

	1 ●	2 ●	3 ●	4 ●	5 ●	6 ●	7 ●	8 ●
Crystal Frequency	12724.600	10000.976	10768.092	12873.436	10141.501	14802.982	12734.077	14244.526
Crystal Mass	-0.000	-0.003	0.002	0.002	0.000	0.082	-0.001	0.000
Bypass Flow	1.306							

Instructions

CQCM Power ON - Do not Remove Crystal Head

Step 1: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button.

Step 2: Remove SEMTECH CQCM Crystal Head and clean or replace crystals.

Step 3: Attach the Remote Service Harness, and then click the "Restart CQCM" button.

Step 4: Verify new crystal frequencies, and click the "Record New Frequencies" button when ready.

Step 5: Tare the crystals by clicking the "Tare" button, and then apply 10 to 15 micrograms of diluted silicon grease. Monitor the Crystal Mass while applying.

Step 6: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button. Remove the Remote Service Harness.

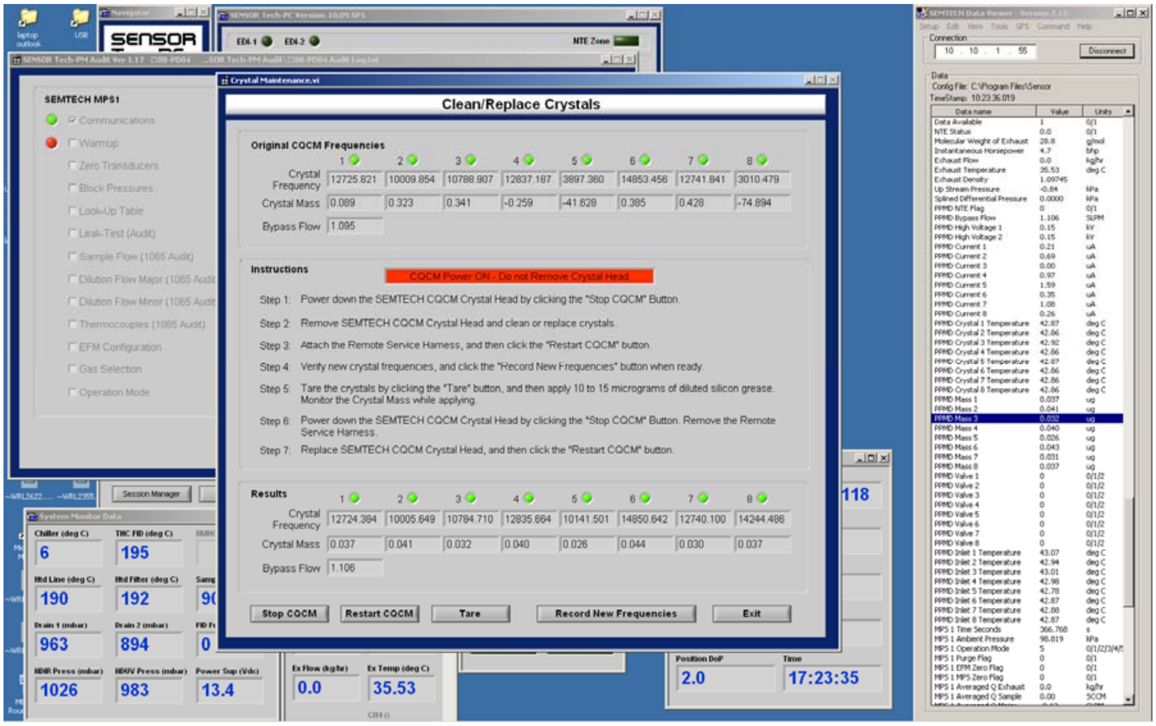
Step 7: Replace SEMTECH CQCM Crystal Head, and then click the "Restart CQCM" button.

Results

	1 ●	2 ●	3 ●	4 ●	5 ●	6 ●	7 ●	8 ●
Crystal Frequency	12727.871	10005.049	10768.452	12872.979	10141.501	14776.110	12732.473	14244.526
Crystal Mass	-0.011	-0.013	-0.010	-0.004	0.000	-0.096	-0.001	0.000
Bypass Flow	1.314							

Chrystal check all looks good. QCM and MPS ready for testing 6:47 without any audits or QCM check procedures (they were performed yesterday).

Problem with QCM. It was sampling the first crystal (#2) on MEL filter #1. All looked good then when I ended the first filter. The PPMD switched to crystal #3, but the MEL had not started the forced filter #2. MEL waited about 30 seconds and crystal #3 stayed on (current was high valve open and mass increasing and sample flowing). MEL triggered forced filter #2 and then the PPMD went to crystal #4. I had two valves open, two corona currents on and two masses increasing. Next thing I noticed is the valve started to index to crystal #5, THEN #6, THEN #7…. It kept doing this until the MEL pulled over (10 minutes). Carl at Sensors instructed me to cycle the power. After cycling power and resetting Semtech to PPMD, Carl and I went through two crystals to verify proper forced filter operation. It worked as expected. Starting another test ASAP.



Crystal Maintenance.vi

Clean/Replace Crystals

Original CQCM Frequencies

	1 ●	2 ●	3 ●	4 ●	5 ●	6 ●	7 ●	8 ●
Crystal Frequency	12725.821	10009.854	10788.907	12837.187	3897.380	14853.456	12741.841	3010.479
Crystal Mass	0.089	0.323	0.341	-0.259	-41.628	0.385	0.428	-74.894
Bypass Flow	1.095							

Instructions

CQCM Power ON - Do not Remove Crystal Head

Step 1: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button.

Step 2: Remove SEMTECH CQCM Crystal Head and clean or replace crystals.

Step 3: Attach the Remote Service Harness, and then click the "Restart CQCM" button.

Step 4: Verify new crystal frequencies, and click the "Record New Frequencies" button when ready.

Step 5: Tare the crystals by clicking the "Tare" button, and then apply 10 to 15 micrograms of diluted silicon grease. Monitor the Crystal Mass while applying.

Step 6: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button. Remove the Remote Service Harness.

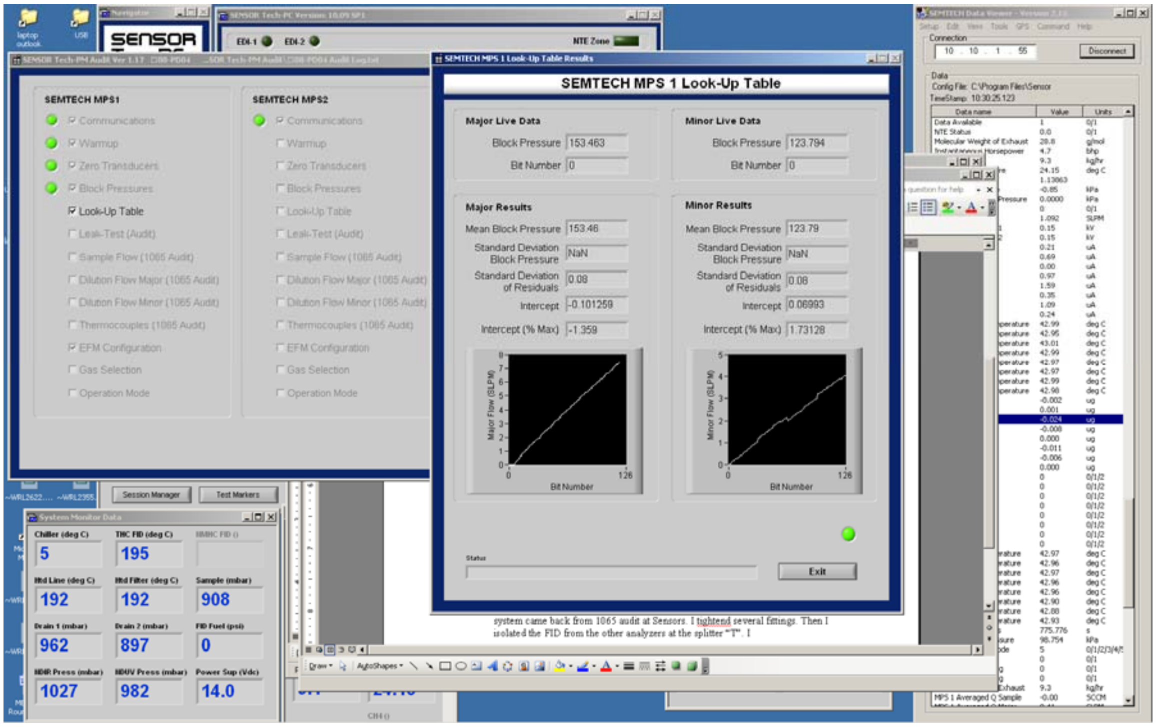
Step 7: Replace SEMTECH CQCM Crystal Head, and then click the "Restart CQCM" button.

Results

	1 ●	2 ●	3 ●	4 ●	5 ●	6 ●	7 ●	8 ●
Crystal Frequency	12724.384	10005.649	10784.710	12835.664	10141.501	14850.642	12740.100	14244.486
Crystal Mass	0.037	0.041	0.032	0.040	0.026	0.044	0.030	0.037
Bypass Flow	1.106							

Chiller (deg C): 6
THC FID (deg C): 195
Htd Line (deg C): 190
Htd Filter (deg C): 192
Drain 1 (mbar): 963
Drain 2 (mbar): 894
HDIR Press (mbar): 1026
HDUV Press (mbar): 983
Power Sup (Vdc): 13.4
Ex Flow (kg/hr): 0.0
Ex Temp (deg C): 35.53
Position DoP: 2.0
Time: 17:23:35

Restart PPMD showing currents after tarring before starting after reset



SEMTECH MPS1

- ● ☑ Communications
- ● ☑ Warmup
- ● ☑ Zero Transducers
- ● ☑ Block Pressures
- ☑ Look-Up Table
- ☐ Leak-Test (Audit)
- ☐ Sample Flow (1065 Audit)
- ☐ Dilution Flow Major (1065 Audit)
- ☐ Dilution Flow Minor (1065 Audit)
- ☐ Thermocouples (1065 Audit)
- ☑ EFM Configuration
- ☐ Gas Selection
- ☐ Operation Mode

SEMTECH MPS2

- ● ☑ Communications
- ☐ Warmup
- ☐ Zero Transducers
- ☐ Block Pressures
- ☐ Look-Up Table
- ☐ Leak-Test (Audit)
- ☐ Sample Flow (1065 Audit)
- ☐ Dilution Flow Major (1065 Audit)
- ☐ Dilution Flow Minor (1065 Audit)
- ☐ Thermocouples (1065 Audit)
- ☐ EFM Configuration
- ☐ Gas Selection
- ☐ Operation Mode

SEMTECH MPS 1 Look-Up Table

Major Live Data

Block Pressure: 153.463

Bit Number: 0

Minor Live Data

Block Pressure: 123.794

Bit Number: 0

Major Results

Mean Block Pressure: 153.46

Standard Deviation Block Pressure: NaN

Standard Deviation of Residuals: 0.08

Intercept: -0.101259

Intercept (% Max): -1.359

Minor Results

Mean Block Pressure: 123.79

Standard Deviation Block Pressure: NaN

Standard Deviation of Residuals: 0.08

Intercept: 0.06993

Intercept (% Max): 1.73128

System Monitor Data

Chiller (deg C) 5	THC FID (deg C) 195	NMHC FID ()
Htd Line (deg C) 192	Htd Filter (deg C) 192	Sample (mbar) 908
Drain 1 (mbar) 962	Drain 2 (mbar) 897	FID Fuel (psi) 0
NDIR Press (mbar) 1027	NDUV Press (mbar) 982	Power Sup (Vdc) 14.0

system came back from 1065 audit at Sensors. I tightend several fittings. Then I isolated the FID from the other analyzers at the splitter "T". I

Performed MPS1 Communication, warm-up, zero, block pres, and lookup table above results.

Run 2 Filters (3,4,5)

During test I noticed that the PPMD was cycling between crystals (1 is reference) every 1 minute. This is different from the previous testing on the Cummins. Also crystal 4 was skipped (not sure why since reference is 1 also skipped) Crystal #4 is oscillating and looks good. Turns out crystal 1 did get sampled thus crystal 4 must be the reference. I'll verify this on the next rotation. Each crystal is getting 1 minute that is 7 minutes around for each. Crystal 5 and 8 appear to be frozen at 0 µg and they are still being sampled on when the PPMD cycles through the masses.

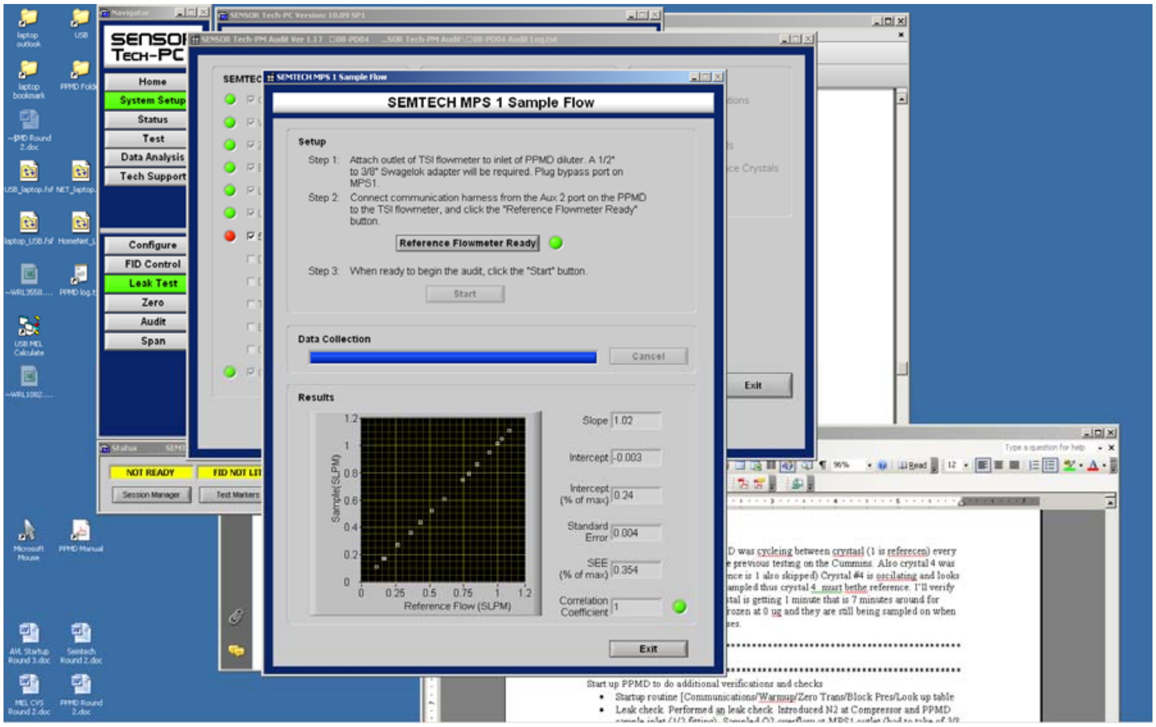
****

03/21/2008

****

Start up PPMD to do additional verifications and checks

- Startup routine [Communications/Warm-up/Zero Trans/Block Pres/Look up table
- Leak check. Performed an leak check. Introduced N2 at Compressor and PPMD sample inlet (1/2 fitting). Sampled O2 overflow at MPS1 outlet (had to take of 3/8 180 bend). Used MEL 02 analyzer (zero span first to get good zero). Pass is when leak is less than 0.2%. Flow is around 4 lpm so I had to bypass my manifold to prevent under sampling (manifold is 15 lpm). Ambient measurement was 20.9% zero was 0.00%, leak sample through PPMD was 0.02%. Passed leak check.
- Next performed flow audits again as a repeat since there is time today and not next week. Sample



SEMTECH MPS 1 Sample Flow

Setup

Step 1: Attach outlet of TSI flowmeter to inlet of PPMD diluter. A 1/2" to 3/8" Swagelok adapter will be required. Plug bypass port on MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

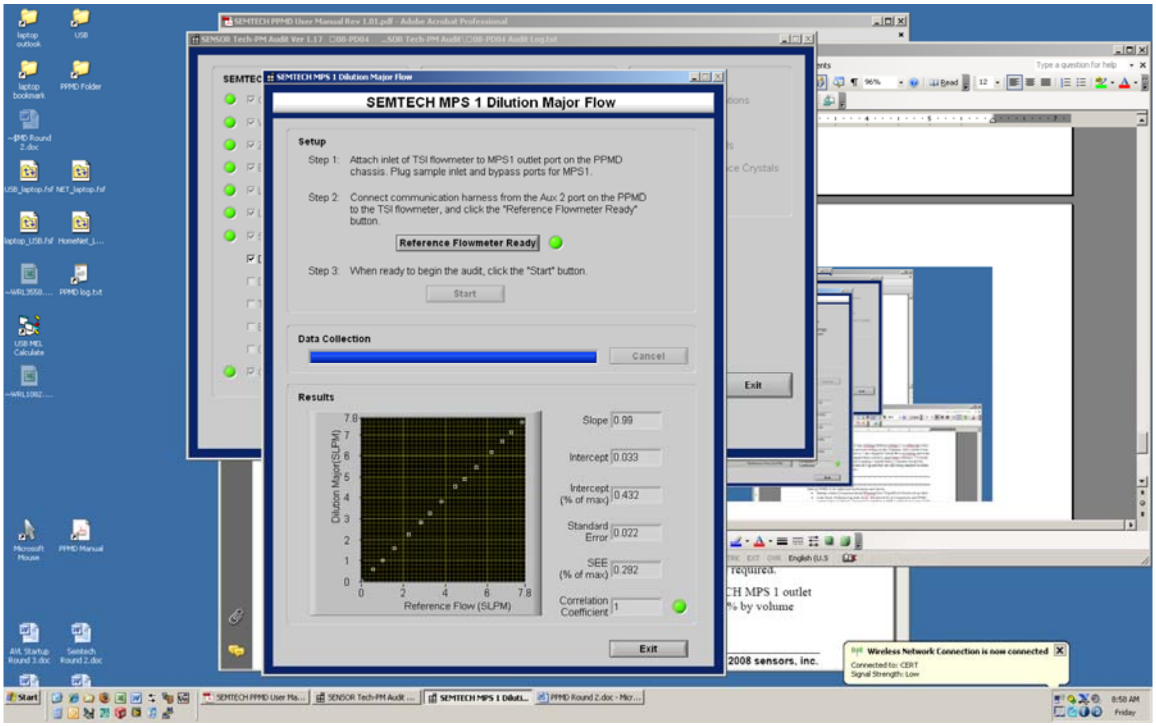
Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

Results

Slope 1.02
Intercept -0.003
Intercept (% of max) 0.24
Standard Error 0.004
SEE (% of max) 0.354
Correlation Coefficient 1

Sample flow 1065 verification



SEMTECH MPS 1 Dilution Major Flow

Setup

Step 1: Attach inlet of TSI flowmeter to MPS1 outlet port on the PPMD chassis. Plug sample inlet and bypass ports for MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

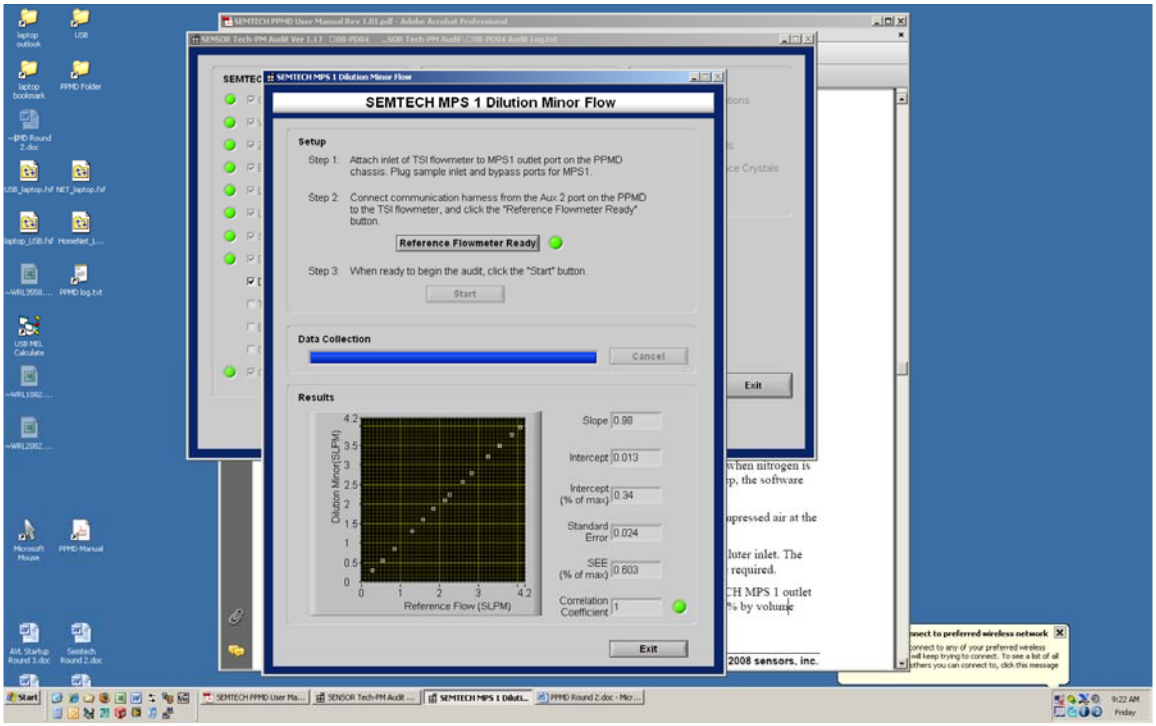
Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

Results

Slope 0.99
Intercept 0.033
Intercept (% of max) 0.432
Standard Error 0.022
SEE (% of max) 0.292
Correlation Coefficient 1

Dilution flow (major) 1065 verification


SEMTECH MPS 1 Dilution Minor Flow

Setup

Step 1: Attach inlet of TSI flowmeter to MPS1 outlet port on the PPMD chassis. Plug sample inlet and bypass ports for MPS1.

Step 2: Connect communication harness from the Aux 2 port on the PPMD to the TSI flowmeter, and click the "Reference Flowmeter Ready" button.

Step 3: When ready to begin the audit, click the "Start" button.

Data Collection

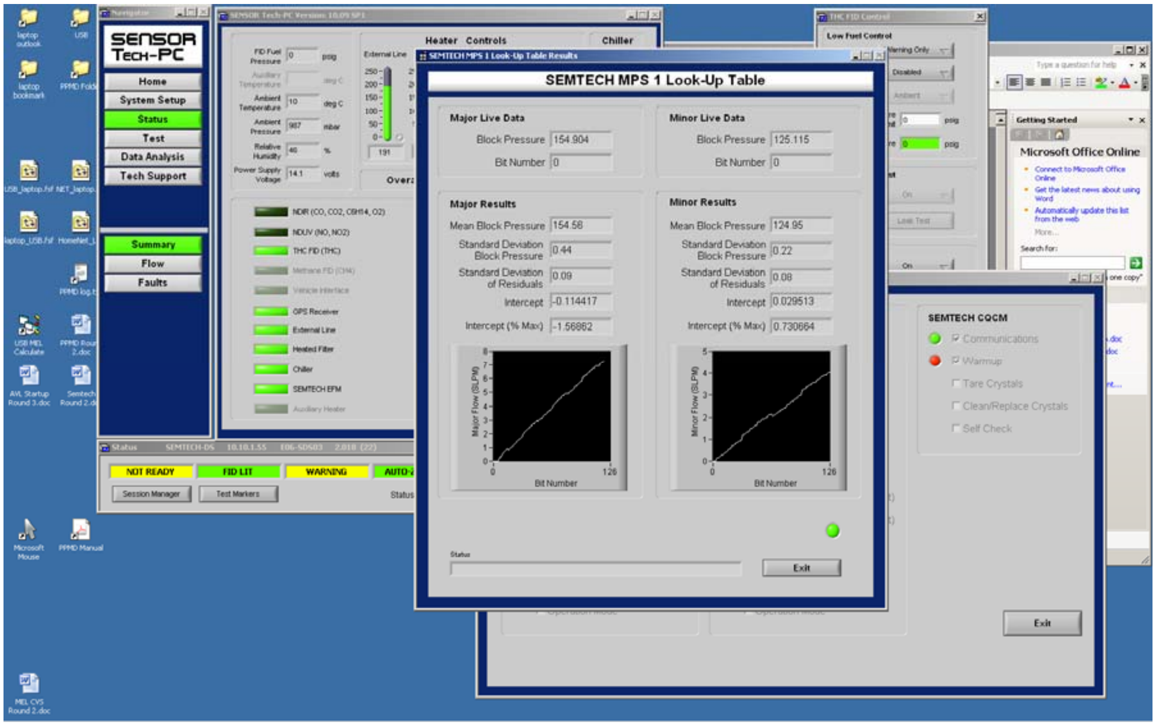
Results

Slope	0.98
Intercept	0.013
Intercept (% of max)	0.34
Standard Error	0.024
SEE (% of max)	0.603
Correlation Coefficient	1

Dilution flow (minor) 1065 verification

03/24/2008 Startup

Performed routine startup [communications, zero, pumps lookup table]


SEMTECH MPS 1 Look-Up Table

Major Live Data

Block Pressure	154.904
Bit Number	0

Minor Live Data

Block Pressure	125.115
Bit Number	0

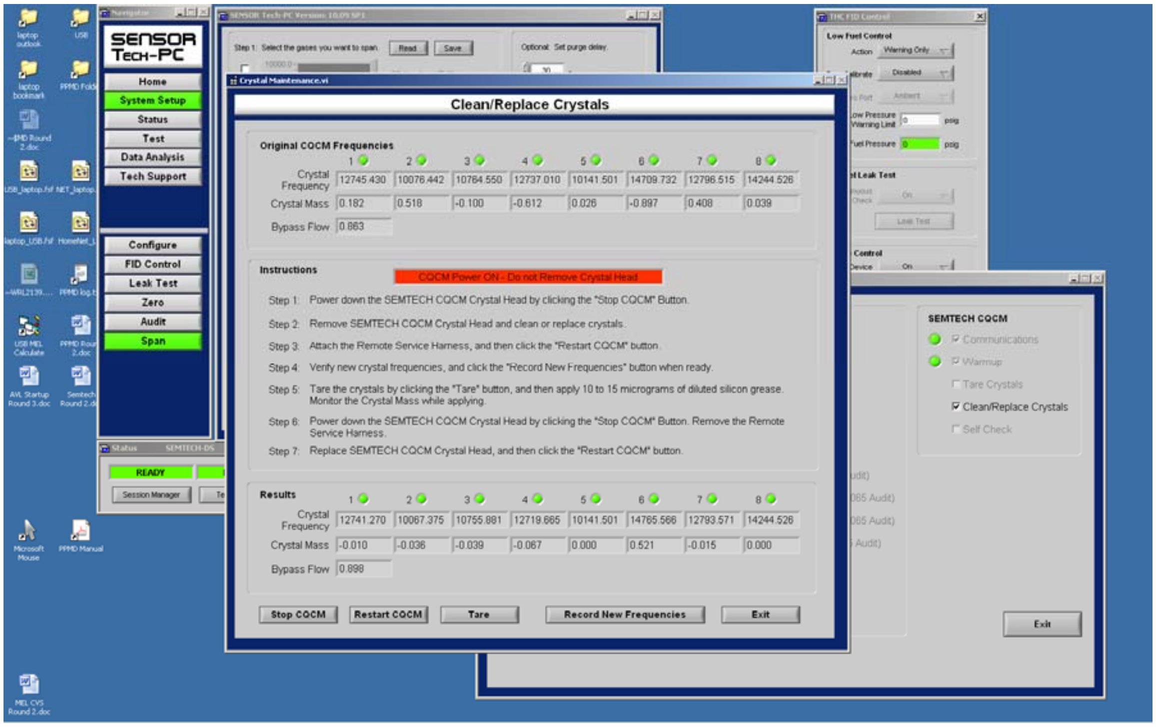
Major Results

Mean Block Pressure	154.58
Standard Deviation Block Pressure	0.44
Standard Deviation of Residuals	0.09
Intercept	-0.114417
Intercept (% Max)	-1.56862

Minor Results

Mean Block Pressure	124.95
Standard Deviation Block Pressure	0.22
Standard Deviation of Residuals	0.08
Intercept	0.029513
Intercept (% Max)	0.730664

Results from today's lookup table



Crystal Maintenance.vi

Clean/Replace Crystals

Original CQCM Frequencies

	1	2	3	4	5	6	7	8
Crystal Frequency	12745.430	10076.442	10764.550	12737.010	10141.501	14709.732	12796.515	14244.526
Crystal Mass	0.182	0.518	-0.100	-0.612	0.026	-0.897	0.408	0.039
Bypass Flow	0.863							

Instructions

CQCM Power ON - Do not Remove Crystal Head

Step 1: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button.

Step 2: Remove SEMTECH CQCM Crystal Head and clean or replace crystals.

Step 3: Attach the Remote Service Harness, and then click the "Restart CQCM" button.

Step 4: Verify new crystal frequencies, and click the "Record New Frequencies" button when ready.

Step 5: Tare the crystals by clicking the "Tare" button, and then apply 10 to 15 micrograms of diluted silicon grease. Monitor the Crystal Mass while applying.

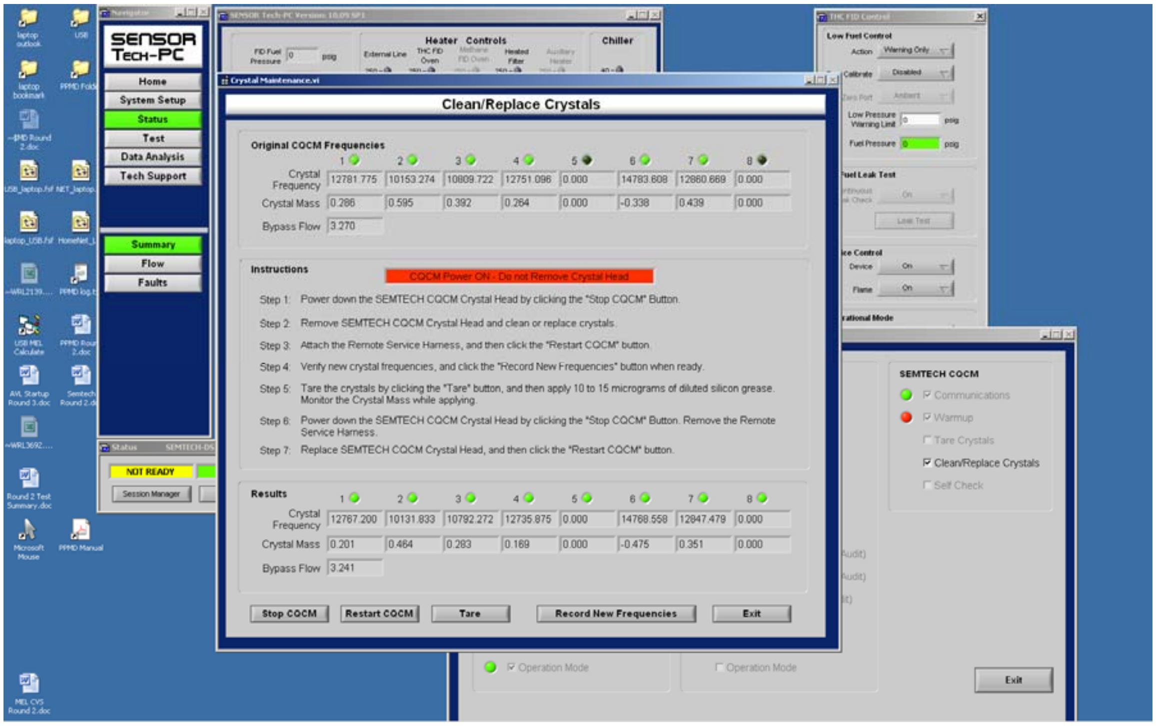
Step 6: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button. Remove the Remote Service Harness.

Step 7: Replace SEMTECH CQCM Crystal Head, and then click the "Restart CQCM" button.

Results

	1	2	3	4	5	6	7	8
Crystal Frequency	12741.270	10067.375	10755.881	12719.665	10141.501	14765.566	12793.571	14244.526
Crystal Mass	-0.010	-0.036	-0.039	-0.067	0.000	0.521	-0.015	0.000
Bypass Flow	0.898							

Startup tarred crystals for PPMD



Crystal Maintenance.vi

Clean/Replace Crystals

Original CQCM Frequencies

	1	2	3	4	5	6	7	8
Crystal Frequency	12781.775	10153.274	10809.722	12751.096	0.000	14783.608	12860.669	0.000
Crystal Mass	0.286	0.595	0.392	0.264	0.000	-0.338	0.439	0.000
Bypass Flow	3.270							

Instructions

CQCM Power ON - Do not Remove Crystal Head

Step 1: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button.

Step 2: Remove SEMTECH CQCM Crystal Head and clean or replace crystals.

Step 3: Attach the Remote Service Harness, and then click the "Restart CQCM" button.

Step 4: Verify new crystal frequencies, and click the "Record New Frequencies" button when ready.

Step 5: Tare the crystals by clicking the "Tare" button, and then apply 10 to 15 micrograms of diluted silicon grease. Monitor the Crystal Mass while applying.

Step 6: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button. Remove the Remote Service Harness.

Step 7: Replace SEMTECH CQCM Crystal Head, and then click the "Restart CQCM" button.

Results

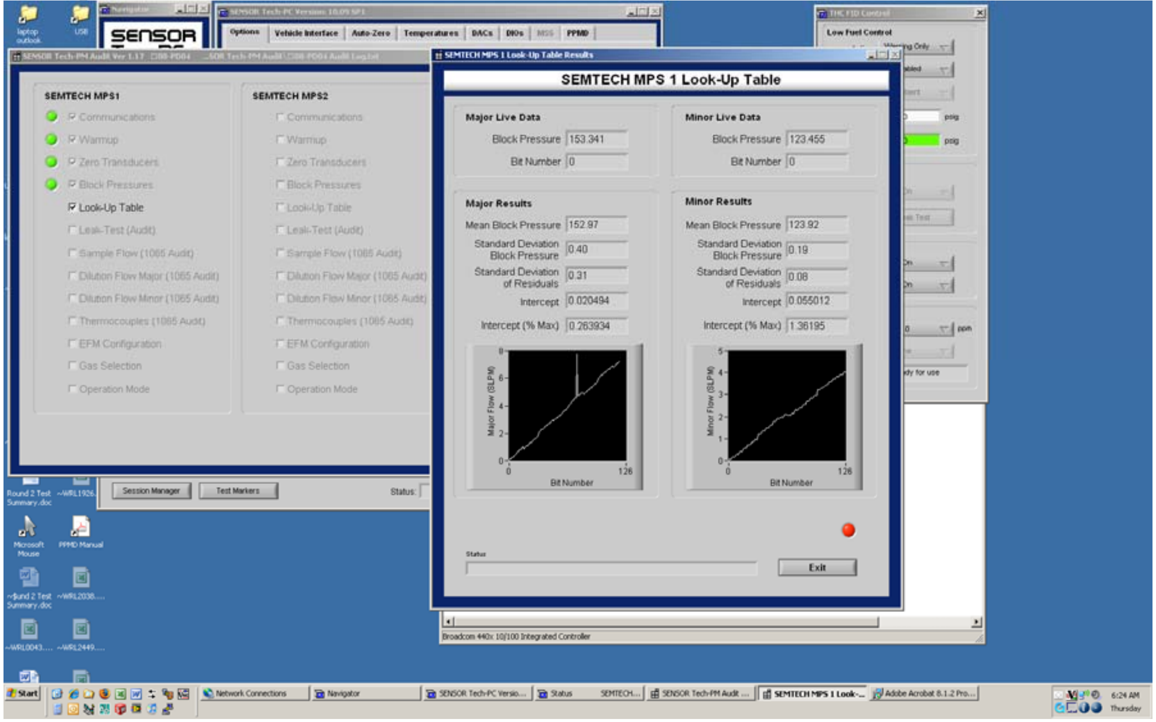
	1	2	3	4	5	6	7	8
Crystal Frequency	12767.200	10131.833	10792.272	12735.875	0.000	14768.558	12847.479	0.000
Crystal Mass	0.201	0.464	0.283	0.169	0.000	-0.475	0.351	0.000
Bypass Flow	3.241							

Startup 3/25/2008 for PPMD crystals. Look up table was similar to previous days.

Startup 3/26/2008

Went fine no startup problems. Cleaned crystals and recovered #8 thus re enabled in software since not automatic

Startup 3/27/2008



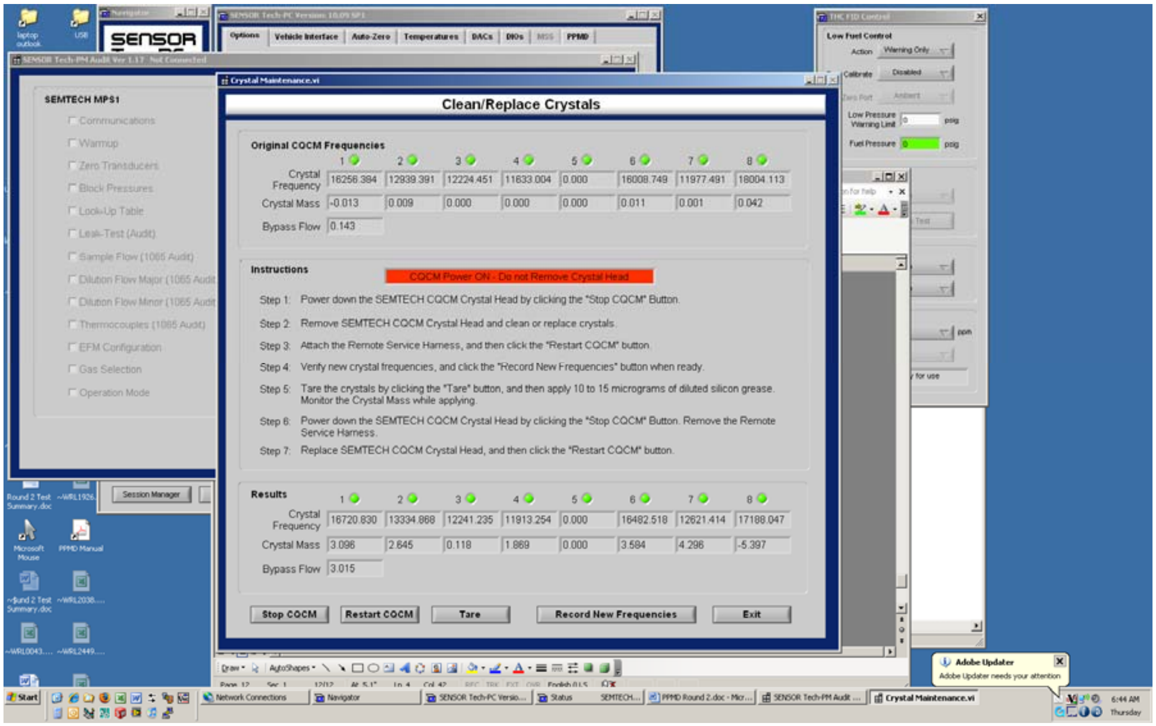
Major Live Data
Block Pressure 153.341
Bit Number 0

Minor Live Data
Block Pressure 123.455
Bit Number 0

Major Results
Mean Block Pressure 152.97
Standard Deviation Block Pressure 0.40
Standard Deviation of Residuals 0.31
Intercept 0.020494
Intercept (% Max) 0.263934

Minor Results
Mean Block Pressure 123.92
Standard Deviation Block Pressure 0.19
Standard Deviation of Residuals 0.08
Intercept 0.055012
Intercept (% Max) 1.36195

Startup problem with look up table repeat



Original CQCM Frequencies

	1	2	3	4	5	6	7	8
Crystal Frequency	16256.384	12939.391	12224.451	11633.004	0.000	16008.749	11977.491	18004.113
Crystal Mass	-0.013	0.009	0.000	0.000	0.000	0.011	0.001	0.042
Bypass Flow	0.143							

Instructions

CQCM Power ON - Do not Remove Crystal Head

Step 1: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button.

Step 2: Remove SEMTECH CQCM Crystal Head and clean or replace crystals.

Step 3: Attach the Remote Service Harness, and then click the "Restart CQCM" button.

Step 4: Verify new crystal frequencies, and click the "Record New Frequencies" button when ready.

Step 5: Tare the crystals by clicking the "Tare" button, and then apply 10 to 15 micrograms of diluted silicon grease. Monitor the Crystal Mass while applying.

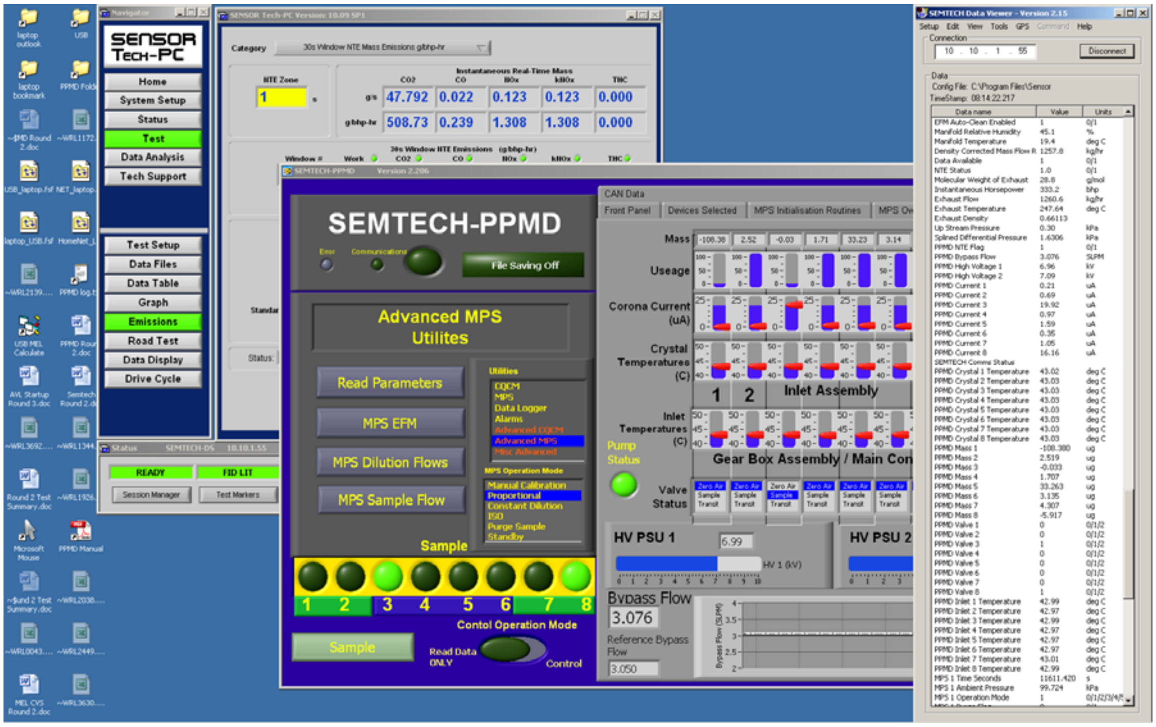
Step 6: Power down the SEMTECH CQCM Crystal Head by clicking the "Stop CQCM" Button. Remove the Remote Service Harness.

Step 7: Replace SEMTECH CQCM Crystal Head, and then click the "Restart CQCM" button.

Results

	1	2	3	4	5	6	7	8
Crystal Frequency	16720.830	13334.868	12241.235	11913.254	0.000	16482.518	12621.414	17188.047
Crystal Mass	3.096	2.645	0.118	1.869	0.000	3.584	4.296	-5.397
Bypass Flow	3.015							

Crystal greasing results show 2 µg of grease



Category: 30s Window NTE Mass Emissions g/bhp-hr

NTE Zone: 1

Instantaneous Real-Time Mass

	CO2	CO	NOx	kNOx	THC
g/s	47.792	0.022	0.123	0.123	0.000
g/bhp-hr	508.73	0.239	1.308	1.308	0.000

Mass: -100.38, 2.52, -0.03, 1.71, 33.23, 3.14

HV PSU 1: 6.99

Bypass Flow: 3.076

Reference Bypass Flow: 3.050

SEMTECH Data Viewer - Version 2.15

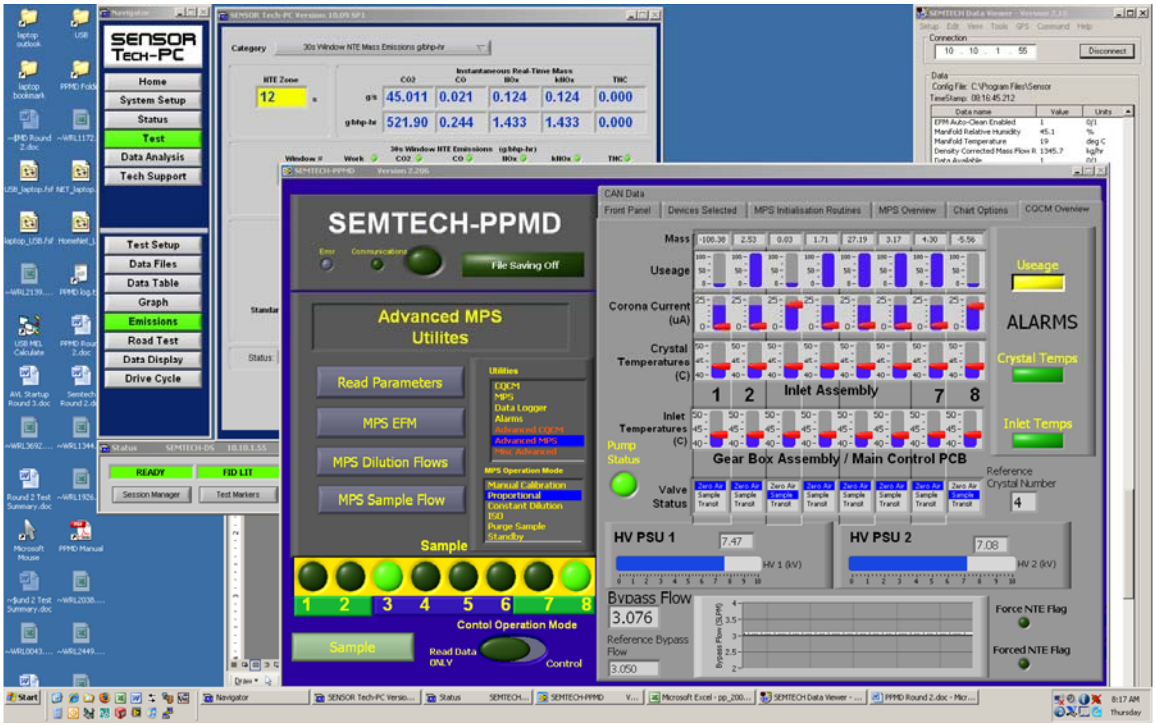
Connection: 10 . 10 . 1 . 55

Config File: C:\Program Files\Sensor

TimeStamp: 08:14:22.217

Data name	Value	Units
EFM Auto-Clean Enabled	1	0/1
Manifold Relative Humidity	45.1	%
Manifold Temperature	19.4	deg C
Density Corrected Mass Flow R	1257.8	kg/hr
Data Available	1	0/1
NTE Status	1.0	0/1
Molecular Weight of Exhaust	28.8	g/mol
Instantaneous Horsepower	333.2	bhp
Exhaust Flow	1260.6	kg/hr
Exhaust Temperature	247.64	deg C
Exhaust Density	0.66113	
Up Stream Pressure	0.30	kPa
Splined Differential Pressure	1.6306	kPa
PPMD NTE Flag	1	0/1
PPMD Bypass Flow	3.076	SLPM
PPMD High Voltage 1	6.96	kV
PPMD High Voltage 2	7.09	kV
PPMD Current 1	0.21	uA
PPMD Current 2	0.69	uA
PPMD Current 3	19.92	uA
PPMD Current 4	0.97	uA
PPMD Current 5	1.59	uA
PPMD Current 6	0.35	uA
PPMD Current 7	1.05	uA
PPMD Current 8	16.16	uA
SEMTECH Comms Status		
PPMD Crystal 1 Temperature	43.02	deg C
PPMD Crystal 2 Temperature	43.03	deg C
PPMD Crystal 3 Temperature	43.03	deg C
PPMD Crystal 4 Temperature	43.03	deg C
PPMD Crystal 5 Temperature	43.03	deg C
PPMD Crystal 6 Temperature	43.03	deg C
PPMD Crystal 7 Temperature	43.03	deg C
PPMD Crystal 8 Temperature	43.03	deg C
PPMD Mass 1	-100.380	ug
PPMD Mass 2	2.519	ug
PPMD Mass 3	-0.033	ug
PPMD Mass 4	1.707	ug
PPMD Mass 5	33.263	ug
PPMD Mass 6	3.135	ug
PPMD Mass 7	4.307	ug
PPMD Mass 8	-5.917	ug
PPMD Valve 1	0	0/1/2
PPMD Valve 2	0	0/1/2
PPMD Valve 3	1	0/1/2
PPMD Valve 4	0	0/1/2
PPMD Valve 5	0	0/1/2
PPMD Valve 6	0	0/1/2
PPMD Valve 7	0	0/1/2
PPMD Valve 8	1	0/1/2
PPMD Inlet 1 Temperature	42.99	deg C
PPMD Inlet 2 Temperature	42.97	deg C
PPMD Inlet 3 Temperature	42.99	deg C
PPMD Inlet 4 Temperature	42.97	deg C
PPMD Inlet 5 Temperature	42.97	deg C
PPMD Inlet 6 Temperature	42.97	deg C
PPMD Inlet 7 Temperature	43.01	deg C
PPMD Inlet 8 Temperature	42.99	deg C
MPS 1 Time Seconds	11611.420	s
MPS 1 Ambient Pressure	99.724	kPa
MPS 1 Operation Mode	1	0/1/2/3/4/5

This figure shows that two crystals are on during a real NTE. This seems like a problem.



Category: 30s Window NTE Mass Emissions g/bhp-hr

NTE Zone: 12

Instantaneous Real-Time Mass

	CO2	CO	NOx	kNOx	THC
g/s	45.011	0.021	0.124	0.124	0.000
g/bhp-hr	521.90	0.244	1.433	1.433	0.000

Mass: -100.38, 2.53, 0.03, 1.71, 27.19, 3.17, 4.30, -5.56

Reference Crystal Number: 4

HV PSU 1: 7.47

HV PSU 2: 7.08

Bypass Flow: 3.076

Reference Bypass Flow: 3.050

SEMTECH Data Viewer - Version 2.15

Connection: 10 . 10 . 1 . 55

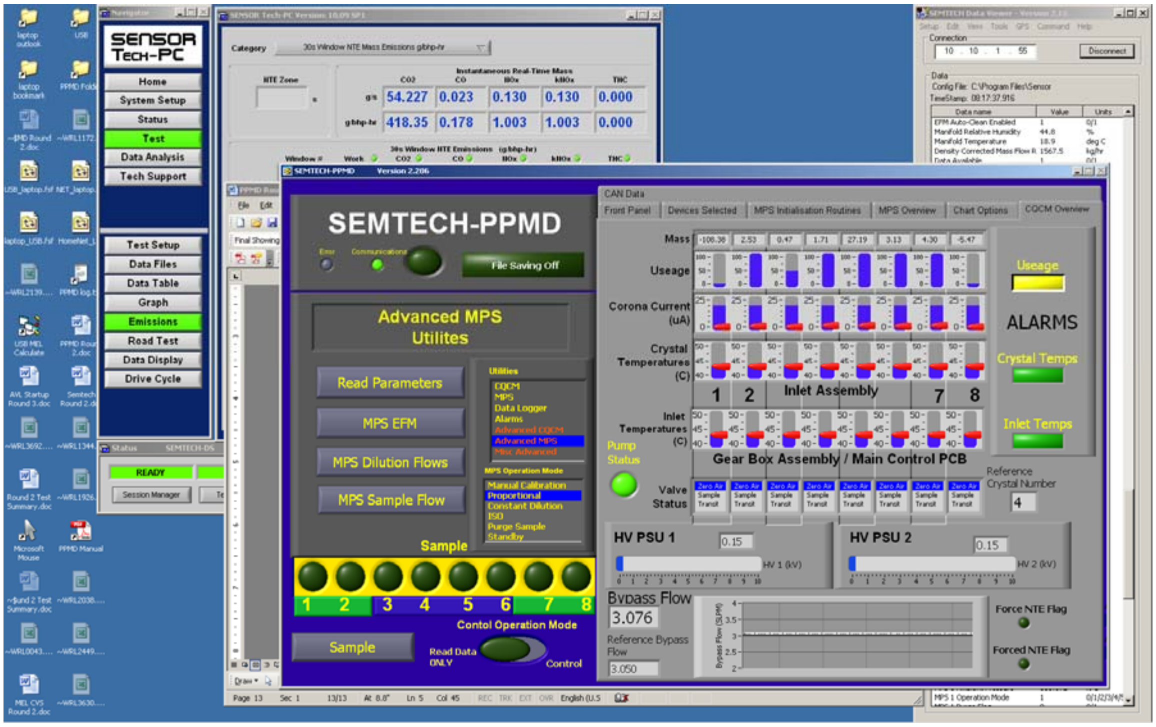
Config File: C:\Program Files\Sensor

TimeStamp: 08:16:45.212

Data name	Value	Units
EFM Auto-Clean Enabled	1	0/1
Manifold Relative Humidity	45.1	%
Manifold Temperature	19	deg C
Density Corrected Mass Flow R	1345.7	kg/hr

8:17 AM Thursday

Two Crystals are sampling as seen by corona currents on 3 and 8 during in-use testing



Category: 30s Window NTE Mass Emissions g/bhp-hr

Instantaneous Real-Time Mass

	CO2	CO	NOx	kNOx	THC
g/s	54.227	0.023	0.130	0.130	0.000
g/bhp-hr	418.35	0.178	1.003	1.003	0.000

Connection: 10 . 10 . 1 . 55

Config File: C:\Program Files\Sensor

TimeStamp: 08:17:37.916

Data name	Value	Units
EFM Auto-Clean Enabled	1	0/1
Manifold Relative Humidity	44.8	%
Manifold Temperature	18.9	deg C
Density Corrected Mass Flow R	1567.5	kg/hr

Mass: -100.38 2.53 0.47 1.71 27.19 3.13 4.30 -5.47

HV PSU 1: 0.15

HV PSU 2: 0.15

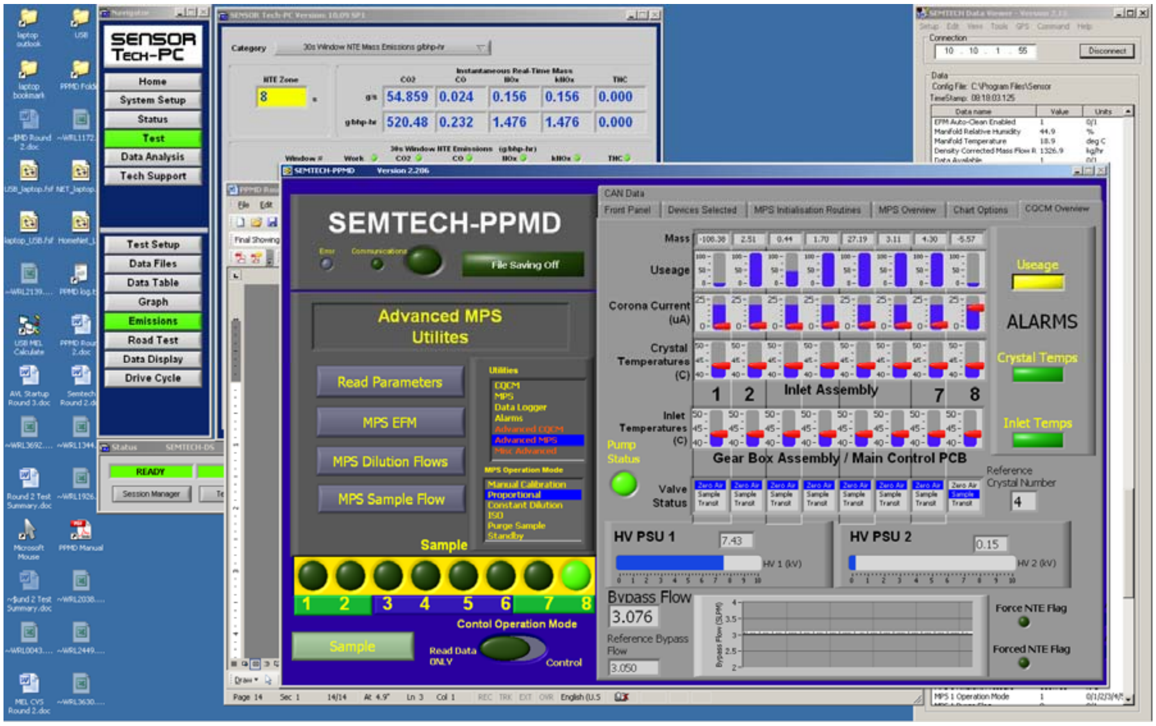
Bypass Flow: 3.076

Reference Bypass Flow: 3.050

Reference Crystal Number: 4

MPS 1 Operation Mode: 1 0/1/2/3/4/5

Now it seems to be off and not sure why it went off



Category: 30s Window NTE Mass Emissions g/bhp-hr

NTE Zone: 8

Instantaneous Real-Time Mass

	CO2	CO	NOx	kNOx	THC
g/s	54.859	0.024	0.156	0.156	0.000
g/bhp-hr	520.48	0.232	1.476	1.476	0.000

Connection: 10 . 10 . 1 . 55

Config File: C:\Program Files\Sensor

TimeStamp: 08:18:03.125

Data name	Value	Units
EFM Auto-Clean Enabled	1	0/1
Manifold Relative Humidity	44.9	%
Manifold Temperature	18.9	deg C
Density Corrected Mass Flow R	1326.9	kg/hr

Mass: -100.38 2.51 0.44 1.70 27.19 3.11 4.30 -5.57

HV PSU 1: 7.43

HV PSU 2: 0.15

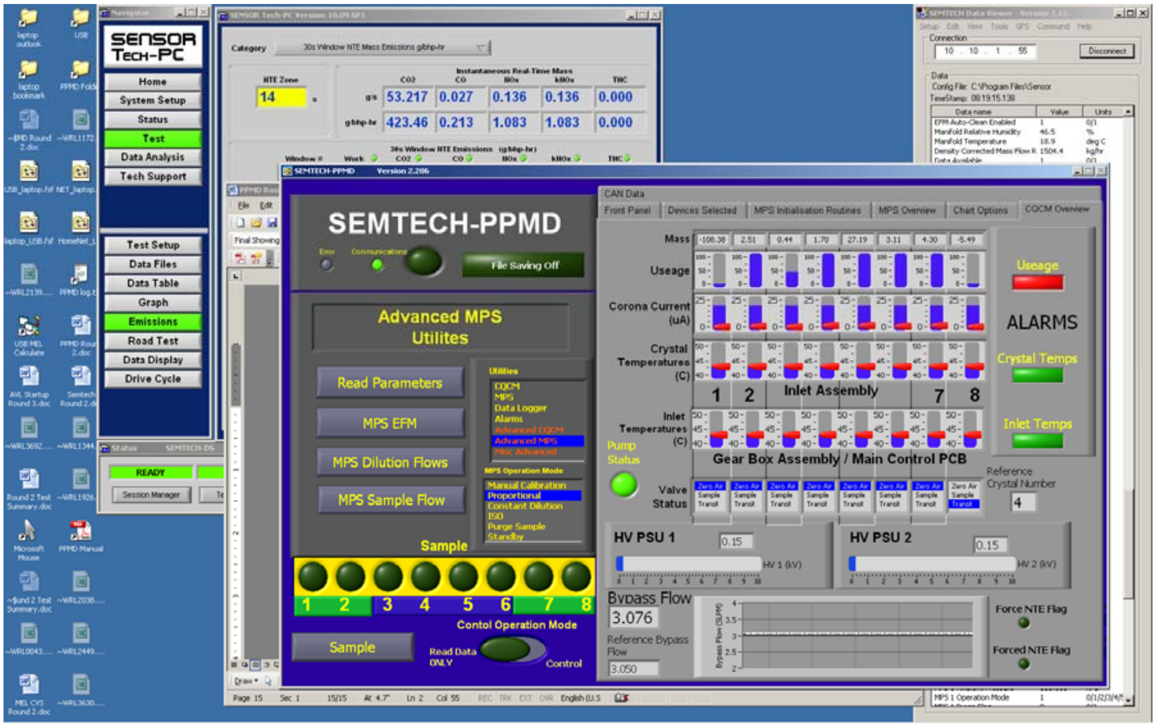
Bypass Flow: 3.076

Reference Bypass Flow: 3.050

Reference Crystal Number: 4

MPS 1 Operation Mode: 1 0/1/2/3/4/5

This is how long it takes to go into an NTE it was 8 seconds when crystal 8 came on. No other crystals have been engaged. Not sure what is happening.



During in-use testing where the engine is in an NTE, but still no crystals are on after waiting 14 seconds. Test aborted.

Appendix J – PEMS Supplemental Issues and Comments

PEMS2

Valve Timing Additional Information

Volvo

Start Delta	Stop Delta
2.3	2.0
2.7	3.2
2.6	0.7
0.6	1.2
0.8	0.9
2.7	3.7
0.9	0.7
1.7	0.5
1.1	1.7
2.8	9.5
2.5	2.2
2.7	2.3
2.2	0.3
2.3	1.5
3.5	2.0
2.8	5.6
3.2	1.8
3.3	2.1
2.3	2.7
2.1	3.3
1.8	2.8

ave	2.234	2.418
stdev	0.806	2.049

Cummins

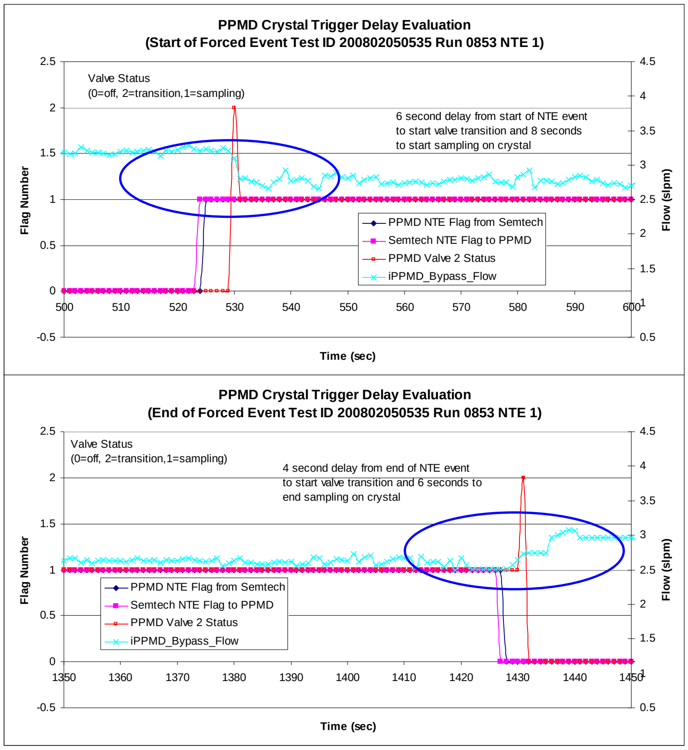
Delta Start	Delta Stop
3.7	3.3
2.9	4.0
4.5	2.8
3.2	2.8
1.9	111.0 *
2.7	-1.4
3.0	6.8
3.6	3.8
3.2	0.4
1.2	5.4
4.6	1.9
2.1	2.8
2.0	4.0
2.5	6.3
5.6	3.4
3.3	1.9
5.2	2.9
3.8	4.6
2.7	4.1
2.0	2.7
1.8	2.2
2.6	2.6
1.2	1.4
1.3	4.5

* Post processor filter caused duration to go long (actual 1sec)

Start ~3.5 sec longer

End ~ 3.2 sec longer

Cummins



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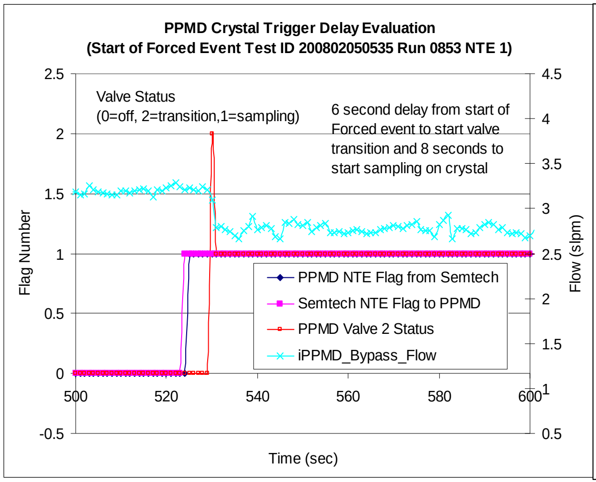
Semtech Processed *.csv (1Hz) file vs PPMD extracted data file (2Hz)

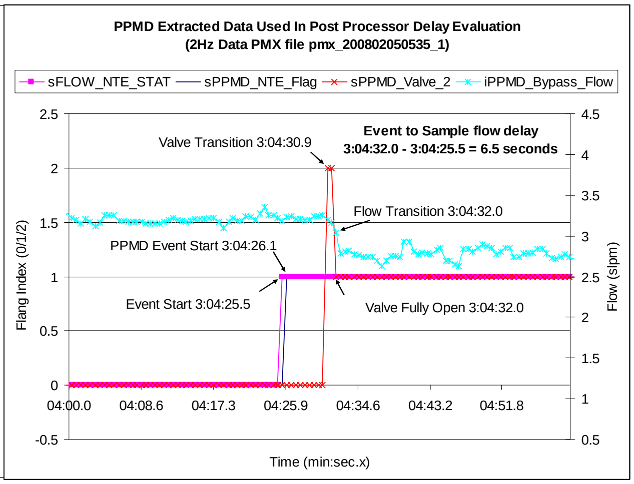


PPMD Crystal Trigger Delay Evaluation
(Start of Forced Event Test ID 200802050535 Run 0853 NTE 1)

Valve Status
(0=off, 2=transition,1=sampling)

6 second delay from start of Forced event to start valve transition and 8 seconds to start sampling on crystal

Semtech Processed *.csv (1Hz)



PPMD Extracted Data Used In Post Processor Delay Evaluation
(2Hz Data PMX file pmx_200802050535_1)

Valve Transition 3:04:30.9

Event to Sample flow delay
3:04:32.0 - 3:04:25.5 = 6.5 seconds

Flow Transition 3:04:32.0

PPMD Event Start 3:04:26.1

Event Start 3:04:25.5

Valve Fully Open 3:04:32.0

PPMD pmx*.csv (~2Hz)

PPMD extracted file shows 1.5 sec less delay. Possible time truncation with Semtech *.csv file compared to PPMD “pmx*.csv” file

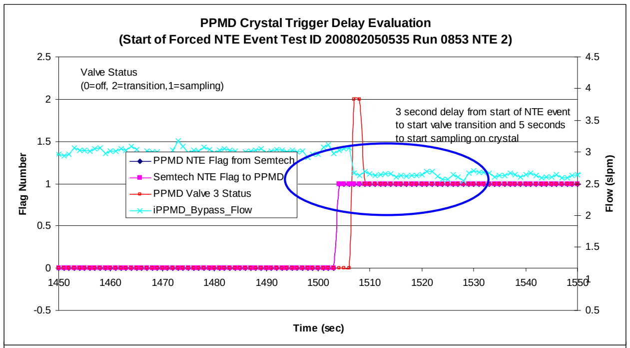
Volvo

	Start Delta	Stop Delta
	2.3	2.0
	2.7	3.2
	2.6	0.7
	0.6	1.2
	0.8	0.9
	2.7	3.7
	0.9	0.7
	1.7	0.5
	1.1	1.7
	2.8	9.5
	2.5	2.2
	2.7	2.3
	2.2	0.3
	2.3	1.5
	3.5	2.0
	2.8	5.6
	3.2	1.8
	3.3	2.1
	2.3	2.7
	2.1	3.3
	1.8	2.8
ave	2.234	2.418
stdev	0.806	2.049

Cummins

Delta Start	Delta Stop
3.7	3.3
2.9	4.0
4.5	2.8
3.2	2.8
1.9	111.0
2.7	-1.4
3.0	6.8
3.6	3.8
3.2	0.4
1.2	5.4
4.6	1.9
2.1	2.8
2.0	4.0
2.5	6.3
5.6	3.4
3.3	1.9
5.2	2.9
3.8	4.6
2.7	4.1
2.0	2.7
1.8	2.2
2.6	2.6
1.2	1.4
1.3	4.5

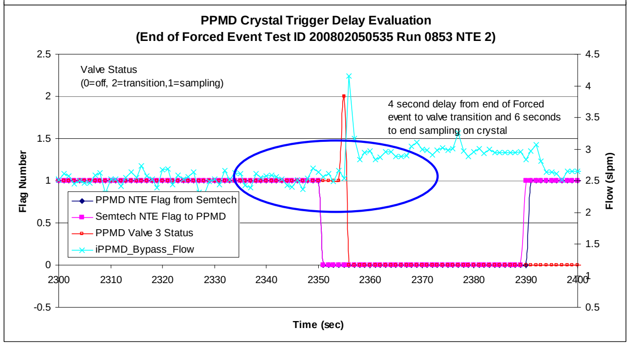
Cummins



PPMD Crystal Trigger Delay Evaluation
(Start of Forced NTE Event Test ID 200802050535 Run 0853 NTE 2)

Valve Status
(0=off, 2=transition,1=sampling)

3 second delay from start of NTE event to start valve transition and 5 seconds to start sampling on crystal



PPMD Crystal Trigger Delay Evaluation
(End of Forced Event Test ID 200802050535 Run 0853 NTE 2)

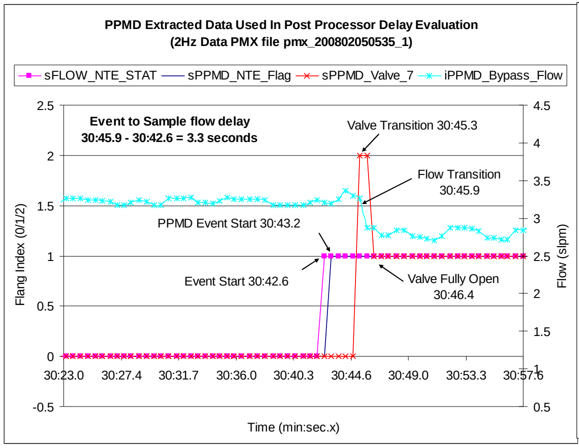
Valve Status
(0=off, 2=transition,1=sampling)

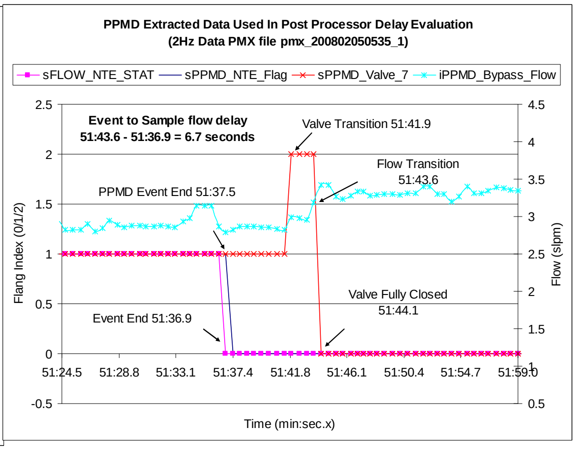
4 second delay from end of Forced event to valve transition and 6 seconds to end sampling on crystal

Start ~ Same

End ~1 sec longer

PPMD extracted data delay evaluation


PPMD Extracted Data Used In Post Processor Delay Evaluation
(2Hz Data PMX file pmx_200802050535_1)


PPMD Extracted Data Used In Post Processor Delay Evaluation
(2Hz Data PMX file pmx_200802050535_1)

Summary data agrees with PPMD extracted data to within 1 second (gold circled data from previous slide)