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Validation Testing for the PM-PEMS Measurement Allowance Program

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Final Report

Validation Testing for the PM-PEMS Measurement Allowance Program

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Abstract

The United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) agencies are implementing a series of regulations that will control emissions, including oxides of nitrogen (NO_x) and particulate matter (PM), from diesel engines during "in-use" conditions. The purpose is to ensure the emission standards can be maintained throughout the course of the engine's useful lifetime. One of the most important regulations with respect to controlling in-use emissions is the Not-To-Exceed (NTE) regulation. This regulation sets limits for pollutants that are emitted during operation in a defined portion of the engine map and specifies the protocols required to make those measurements.

Portable Emissions Measurement Systems (PEMS) are critical for the implementation of these in-use regulations. The EPA, CARB, and the Engine Manufacturers Association (EMA) formed a measurement allowance steering committee (MASC) to develop a "measurement allowance" to account for measurement error associated with the use of PEMS for in-use measurements. A comprehensive program was completed for the gas-phase measurement allowance (Miller et al., 2008; Buckingham et al. 2007; Fiest et al. 2007). This report presents the results of the in-use validation portion of the PM measurement allowance program. The MASC approach pursued an experimental program to try to use laboratory measurements and modeling to characterize errors that might be observed with in-use, and then validate those errors with in-use testing. The development of the MA involved a sophisticated Monte Carlo model that considered laboratory measurement errors associated with engine broadcast information, emissions measurements, affects due to ambient conditions, and affects that might be observed due to on-vehicle operating conditions. The in-use validation effort used the same PEMS systems used for the laboratory testing, but under real-world conditions. The idea was that the errors found in-use should be within the bounds of the proposed MA.

For this program, comparisons were made between the PM PEMS and UCR's Mobile Emissions Laboratory (MEL) reference laboratory under in-use 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. Two PEMS manufacturers were selected for the in-use validation testing, and multiple serial numbers of each of the selected PEMS were included in the in-use testing. Measurements were made from one class 8 heavy-duty diesel vehicle equipped with a original equipment manufacturer (OEM) diesel particulate filter (DPF). A bypass system was designed to simulate a failed DPF while maintaining the functionality of the diesel oxidation catalyst (DOC). The bypass was designed to target an in-use bsPM emission level of 25 mg/hp-h. In-use routes were designed and utilized to exercise the PM PEMS equipment over a range of environmental conditions, and included segments near sea level, in coastal regions, in desert regions, and longer uphill incline segments and segments at elevations up to 4500 ft. Prior to validation testing, the MEL underwent a series of 1065 audits and a cross laboratory correlation with SwRI.

All PM PEMS and PM instruments tested showed a negative bias compared to the reference system. The PEMS2 non-regeneration mean bias at the 20 mg/hp-h bsPM emissions was -10 mg/hp-h, and at 30 mg/hp-h the mean bias was -18 mg/hp-h. When the intercept was forced through zero, the mean bias at 20 mg/hp-h went to -15 mg/hp-h. The PEMS3 non-regeneration

mean bias at the 20 mg/hp-h bsPM emissions was -1.7 mg/hp-h, and at 30 mg/hp-h the mean bias was -2.2 mg/hp-h. When the intercept was forced through zero, the PEMS3 mean bias went to -1 mg/hp-h at the 20 mg/hp-h level. The other instruments used showed a higher mean bias than PEMS3 and lower mean bias than PEMS2. The proposed bsPM MA is 6 mg/hp-h at the 20 mg/hp-h in-use standard. For these results, the PEMS3 system was within the proposed MA, while the PEMS2 values exceeded the proposed MA.

Several issues were discovered during testing, including problems related to testing under in-use conditions, operational issues, and post processing issues. The in-use issues ranged from electrical and mechanical connections, crystal usage from short NTE's, valve switching, measurement signals, and crystal behaviors. Operational problems occurred during startup, commissioning, and with the systems prior to testing in-use. Typical issues include incorrect system configurations, procedures that don't work, and issues with the startup software and other recommended practices that didn't function according to the manual. The post processing issues ranged from data filtering, bsPM differences between processor versions, data identification, and method calculations not being available. In general, PEMS2 had more issues than PEMS3 for each of these categories.

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
CO_2...carbon dioxide
CVS..constant volume sampling
CPC..condensation particle counter
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
efuel...ECM fuel consumption rate
EMA...Engine Manufacturers Association
EPA ....United States Environmental Protection Agency
FID ....flame ionization detector
FTP...Federal Test Procedure
GFM...gravimetric filter module
g/hp-h ....grams per brake horsepower hour
HDIUT ....heavy-duty in-use testing
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
OEM...original equipment manufacturer
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
fSMPS...fast scanning mobility particle sizer
SOF ....soluble organic fraction
SwRI ....Southwest Research Institute
THC..total hydrocarbons
UCR ....University of California at Riverside
ULSD ....ultralow sulfur diesel

Executive Summary

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" (MA). 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 MA. This report presents the results of the in-use validation portion of the PM measurement allowance program.

The MA program was divided into two main parts, where the Southwest Research Institute (SwRI) developed the MA through a series of laboratory tests and Monte Carlo simulations and UCR's role was to validate the proposed MA with in-use measurements. This report presents UCR's in-use measurements and the corresponding comparison differences between the PM PEMS and UCR Mobile Emissions Laboratory (MEL) reference laboratory under on-the-road driving conditions. The MEL is a full 1065 compliant constant volume sampling system (CVS) with gravimetric PM measurements. Given the nature of in-use measurements and PM PEMS commercial availability, UCR was tasked with five major responsibilities including bsPM measurements:

- PM and gaseous emission audits and a laboratory comparison with SwRI were used to assess UCR's ability to provide accurate reliable results from its mobile reference laboratory and to show its comparison at the 25 mg/hp-h bsPM with SwRI emissions laboratory.

- The testing was designed to provide a wide range of environmental conditions while controlling the emissions system targeting 25 mg/hp-h target utilizing a bypass system designed at UCR. The elements of the test planning included the test matrix, the test article and route design.

- PM PEMS commissioning, installation, and operation of the PEMS according to manufacturer's recommendations was the responsibility of UCR. Two manufacturers were selected for the in-use testing; AVL and Sensors. Horiba was not tested due to budgetary constraints

- PM emissions were the main part of the program, and the PM PEMS were directly compared with the MEL under on-the-road driving conditions. The PEMS-MEL deltas were used to validate the SwRI model.

- Characterizing the issues and lessons learned with using the PEMS in-use was an important element of the program, as requested by the steering committee, and represents a significant part of the presented work. In-use conditions may have a contribution to

some special sources of error that are still being investigated for their impact on the overall bsPM comparisons.

Audits and comparisons
UCR's MEL underwent a 40CFR Part 1065 self-audit for PM criteria selected by the MASC. All checks were found to pass and the system to comply with 40CFR Part 1065. Other audits such as NO_x converter efficiency, analyzer quench checks, and gaseous analyzer linearity's were also performed and found to comply with regulations. The MEL's in-use carbon balance showed an R^2 that ranged from 0.98 to 0.99 with a slope of 0.98 to 1.00 between units. The PEMS carbon balance comparisons (after exhaust flow correction) showed a similar R^2 with a slightly wider slope with an R^2 from 0.87 to 0.99 and a slope of 1.0 to 1.08 between units.

UCR's MEL was cross-compared against the SwRI emissions laboratory in San Antonio, TX. This interlaboratory comparison exercise verified UCR's PM system relative to SwRI and challenged UCR's ability to travel 1500 miles and produce accurate bsPM results promptly. Both primary and secondary dilution tunnel propane recover tests were successfully performed prior to engine testing. The average SwRI bsPM was 28.7 mg/hp-h with a COV of 5.2% based on 16 repeats. The average UCR bsPM was 26.5 g/hp-h with a COV of 3.5% based on 15 tests. The overall bsPM emissions for UCR were about 7.7% lower than those for SwRI. Some of the low bias may be a result of additional heat loss from the longer MEL transfer line needed for the testing configuration.

Test matrix, test article and route design
Three PM PEMS were utilized for the MA determination at SwRI. PEMS1 and 2 were considered complete PEMS and PEMS3 was considered an alternate. The MASC chose the PEMS with the lowest positive MA from PEMS1 or 2 for validation testing, with PEMS2 being selected. The proposed MA was 6 mg/hp-h at 20 mg/hp-h bsPM emission level. PEMS3 was "piggy-backed" on PEMS2 due to its small size and ability to test concurrently with PEMS2. Three different serial number PEMS, gaseous Semtech DS's, and exhaust flow meters were tested and denoted unit a, b, and c in Table ES-1. PEMS3 included a prototype gravimetric filter module (GFM) option for the validation testing which was not available for the model development. Due to issues with the GFM system on unit1, PEMS3 added a fourth unit at the PEMS3 manufacturer's cost. Additional measurements were also made with two PM instruments that are already integrated into the MEL. These instruments are denoted differently as INST4 and 5, since they do not measure PM mass directly and hence do not meet the criteria defined for PEMS for in-use compliance testing under CFR40 Part 1065 regulations.

Measurements were made from a 2009 class 8 truck equipped with a 2008 Cummins 15 liter heavy duty diesel engine. The engine was certified to meet the 0.01 g/hp-h PM standard and used a DPF to meet this standard. The vehicle was selected to represent a heavy-duty diesel vehicle with DPF-out brake specific PM (bsPM) emissions of approximately 0.001 g/hp-h. The MEL provided the test weight load for the testing, with the combined weight of the tractor and trailer being 65,000 lbs. The vehicle had 64,000 miles at the beginning of the program. A bypass system was set-up for the DPF and regeneration controls were provided from Cummins engineering support.

Table ES-1 PM PEMS considered for MA test program and in-use validation

PM Systems	Manufacture	Product Name	Principle of Detection	In-Use Testing
PEMS 1	Horiba	TRPM	EAD + filter	no
PEMS 2a,b,c	Sensors Inc	PPMD	QCM	yes
PEMS 3a,b,c,d	AVL	MSS 483	photo acoustic	yes
PEMS 3F	AVL	MSS 483+GFM	photo acoustic + filter	yes[1]
INST 4	TSI	DustTrak 8530	90˚ light scattering	yes
INST 5	Dekati	DMM	electrical mobility + aero dynamic impaction	yes

[1]Although the AVL's MSS483 GFM was tested where only one serial number conditioning unit and filter module were evaluated, but three different serial number MSS483's were tested

The bypass system was designed to simulate a cracked DPF and a properly functioning DOC and was successfully designed at meeting the targeted bsPM emissions level of 25 mg/hp-h. The non-regeneration 50th percentile bsPM emissions for the DPF and bypass were 24 mg/hp-h, with a 5th and 95th percentile of 11 and 43 mg/hp-h, respectively. The bsPM emissions increased from Unit1 to Unit2 and 3 where the 50th percentiles were 18, 26, and 25 mg/hp-h respectively. A small fraction of regeneration events were required as part of the validation work. The regeneration 50th percentile bsPM emissions were 9.1 mg/hp-h, with a 5th and 95th percentile of 1.5 and 29 mg/hp-h, respectively.

In-use routes were designed and utilized to exercise the PM PEMS equipment over a range of environmental conditions, and included segments near sea level, in coastal regions, in desert regions, and longer uphill incline segments and segments at elevations up to 4500 ft. Measurements were made utilizing forced events that were as close as possible to real NTE events. The events were allowed to start at the beginning of an NTE (naturally), but the length of the event (forced) was controlled. Since the event length was controlled, the forced events could have transitions in and out of an NTE within the forced event. This method of operation allowed measurement issues associated with the beginning of real NTE's to be captured, while ensuring MEL filter loadings were sufficiently high. In addition, the PEMS were allowed to operate under true in-use NTE operational modes while the MEL did not sample. This event operation may be one of the reasons contributing to the negative bias between the PEMS and the MEL, as discussed below.

The bsPM results were calculated by three methods similar to those used during the gaseous MA program, but with some slight differences due to batch measurement methods, flow weighted measurements, and due to in-use testing. The methods used are listed below:

- Method 1 ($\overline{PM}$, torque$_i$, speed$_i$)
- Method 2 ($\overline{PM}$, torque$_i$, speed$_i$, carbon-balance$_i$, efuel$_i$)
- Method 3 (PM_i, torque$_i$, speed$_i$, efuel$_i$, carbon-balance$_i$)

Where the $\overline{PM}$ is the mass flow weighted PM measurement, and torque$_i$ and speed$_i$ are the instantaneous ECM measurements, and PMi is the instantaneous PM mass measurement. The carbon balance method incorporates the gaseous carbon concentrations and exhaust flow rate in its calculation. Methods 2 and 3 differ from Method 1 by using a dimensionless ratio of carbon-

balance$_i$ divided by efuel$_i$. Method2 uses this ratio in the denominator, and Method 3 uses it in the numerator. The ratio was frozen for Method2 for cases where the efuel$_i$ went to zero, since this would cause the calculation to go to infinity. Method 3 was only performed by PEMS3 due to its real-time measurement signal. Methods2 and 3 essentially normalize out the effects of the exhaust flow measurements, and hence remove error associated with these measurements.

The results presented in this report are based on a subset of the actual data sampled due to data yield from issues found during testing and post processing. The data yield from previous testing with these PEMS was low and was thus an important metric for this testing program. The PEMS2 average data yield was 61% where the units varied from 53% to 87%, see Table ES-2. The PEMS3 data yield averaged 70% and varied from 15% to 98%. PEMS3 unit1 data was significantly lower due to its prototype GFM system and the lower priority PEMS3 initially had in the validation testing objectives. The PEMS3 unit2, 3, and 4 data yield was more than 90% and ranged from 88% to 98%.

Table ES-2 PEMS data yield for non-regeneration events

Unit #	MEL Events [a]	PEMS2 [c]	PEMS3 + GFM	PEMS2 Final Yield	PEMS3 Final Yield
1	97	51	15 [d]	53%	15%
2	153	76	134	50%	88%
3	97	84	95	87%	98%
Totals	347	211	143	61%	70% [d]

[a] Non regeneration good MEL events are only included in this column
[c] Officially final data set filtered and reduced using best available version of post processor versions 3.40 build 25
[d] PEMS 3 Unit#1 was not given time for diagnosis and repairs due to guides of the MA program and as such data yield was very low for unit 1. The MA committee agreed to allow PEMS 3 manufacturer to submit Unit #4 self sponsored data which had a yield of 91% and a total of 42 submitted data points. Excluding Unit#1 PEMS3 yield is > 90% for Units#2, 3, and 4.

Data issues
Several issues were found during post processing that affected the bsPM results for both PEMS2 and 3. The issues ranged from incorrect parameters, exhaust flow measurement errors, incorrect operational settings, and possible in-use testing issues, as listed in Table ES-3. The impact of these errors on the results was a factor of approximately 1.3 to 1.5, depending on the PEMS and the unit number. The mass sensitivity and exhaust flow errors were corrected and found to be in good agreement with the MEL. The other issues were not corrected for and are part of the results presented. Additional PEMS2 testing is being conducted under a separate research program at UCR. The goal of the new program is to quantify the effectiveness of the solutions the PEMS2 manufacturer has developed to address the issues identified with their system in this program. The results of this new program will be available as an amendment to this report.

Table ES-3 PEMS issues and correction factors applied

Issue	PEMS Affected	Approximate Factor [2]	Units Affected	Corrected
Mass sensitivity: Wrong value	2	1.5	1	Yes
Exhaust flow: Internal plumbing	2 and 3	1.5 & 1.52	2 and 3	Yes
Exhaust flow: Pressure measure	2 and 3	0.85<x<1.15	1, 2, 3[1]	Yes
Sample Flow: Temperature ratio	2	1.00<x<1.10	1, 2, 3	No
Crystal Loading: Reduce limit	2	n/a	1, 2, 3	No
Crystal burn-in: Modify procedure	2	n/a	1, 2, 3	No

[1] Unit 4 PEMS3 was not affected by the pressure measurements because the external flow meter was used on Unit 4.
[2] The factor is a multiplier to the PEMS bsPM results to correct for associated issue

PEMS2 bsPM results

The PEMS2 bsPM results showed a similar low bias for all three units. The PEMS2 non-regeneration mean bias at the 20 mg/hp-h bsPM emissions was -10 mg/hp-h, and at 30 mg/hp-h the mean bias was -18 mg/hp-h. The overall correlation showed an R^2=0.37, a slope of 0.24, and a positive intercept of 4.2 mg/hp-h, see Figure ES-3 and Table ES-5. When the intercept was forced through zero, the mean bias at 20 mg/hp-h went to -15 mg/hp-h. The slope and R^2 decreased from unit1 to unit3, with the slope changing from 0.3 to 0.14 and the R^2 decreasing from 0.52 to 0.20, see Figure ES-1 and Table ES-4. The PM concentration was increased for the testing from unit1 to unit3 in an effort to reduce sample times, which may be one of the reasons for the lower correlation from unit1 to unit3. Unit3 also had a large zero intercept at 8 mg/hp-h, which may be a result of changing its crystal usage logic. The PEMS2 regeneration results also showed a low overall correlation with an R^2=0.4 and a slope of +0.11. The combined zero intercept was also fairly high at 3.2 mg/hp-h, suggesting PEMS2 has a positive bias at zero measurements.

The standard error estimate (SEE) between the PEMS2 and the MEL was relatively high at 5.4 mg/hp-h and 48 µg/mol. The two-tailed, paired t-test between the PEMS and MEL bsPM correlation results suggests the mean differences were statistically significant at a greater than 99% confidence level, even though the SEE was relatively high. PEMS2 manufacturer suggested the high variability may be from differences in the individual crystal sensitivity. Characterizing any improvements in variability is part of the evaluation planed at UCR with the follow-on work.
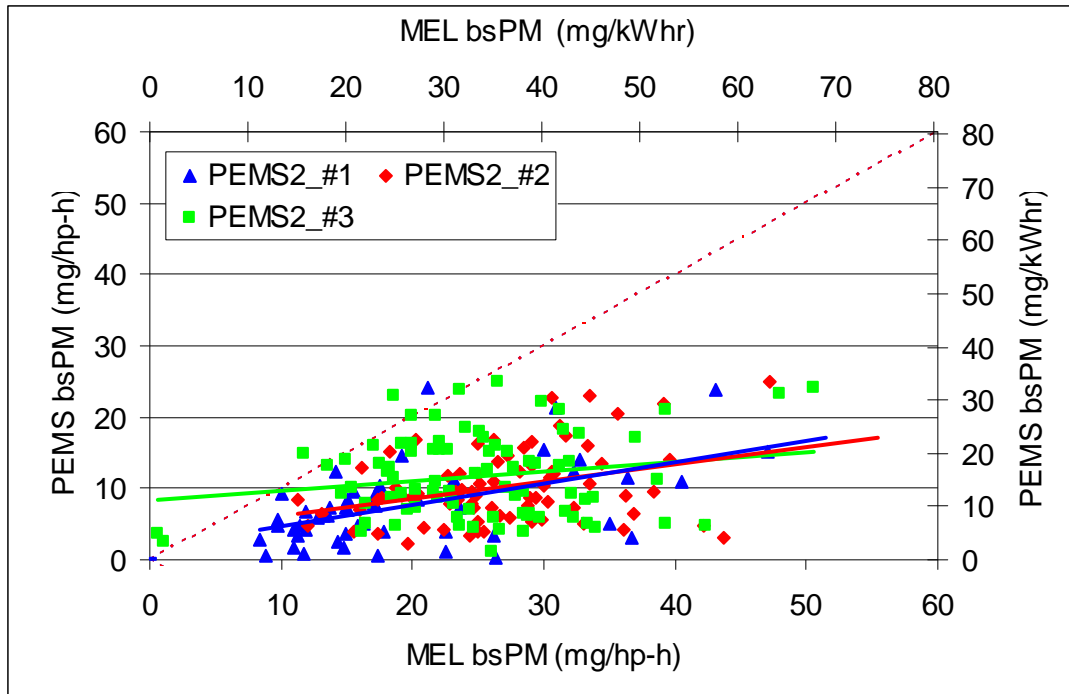
Figure ES-1 PEMS2 non-regeneration bsPM correlation unit by unit

PEMS3 bsPM results

The PEMS3 non-regeneration mean bias at the 20 mg/hp-h bsPM emissions was -1.7 mg/hp-h, and at 30 mg/hp-h the mean bias was -2.2 mg/hp-h. The overall correlation showed an R^2=0.94, a slope of 0.95, and a negative intercept of -0.7, see Figure ES-3 and Table ES-5. When the intercept was forced through zero, this PEMS mean bias went to -1 mg/hp-h at the 20 mg/hp-h level. The slope and R^2 were relatively consistent between units2 through unit4, where the slope varied from 0.98 to 0.87 and the R^2 varied from 0.98 to 0.93, see Figure ES-2 and Table ES-4. The slope for unit2 may have been biased high by exhaust flow measurements because the Method 2 bsPM results showed a lower slope of 0.9 for this unit which agrees better with units 3 and 4. The PM concentration increase from the unit1 to unit3 testing did not have an effect on the PEMS2 measurement system, as seen by the relatively similar slope and R^2 between units for Method 2. The PEMS3 MSS regeneration results showed a low overall correlation, with an R^2=-0.4 and a slope of -0.01. The negative correlation suggests there was no correlation between the reference measurement and the PEMS3 measurement.

The SEE between the PEMS3 and the MEL was relatively low at 3.0 mg/hp-h and 20 µg/mol. The two-tailed, paired t-test between the PEMS and MEL bsPM correlation results suggests the mean differences were statistically significant at a greater than 99% confidence level.
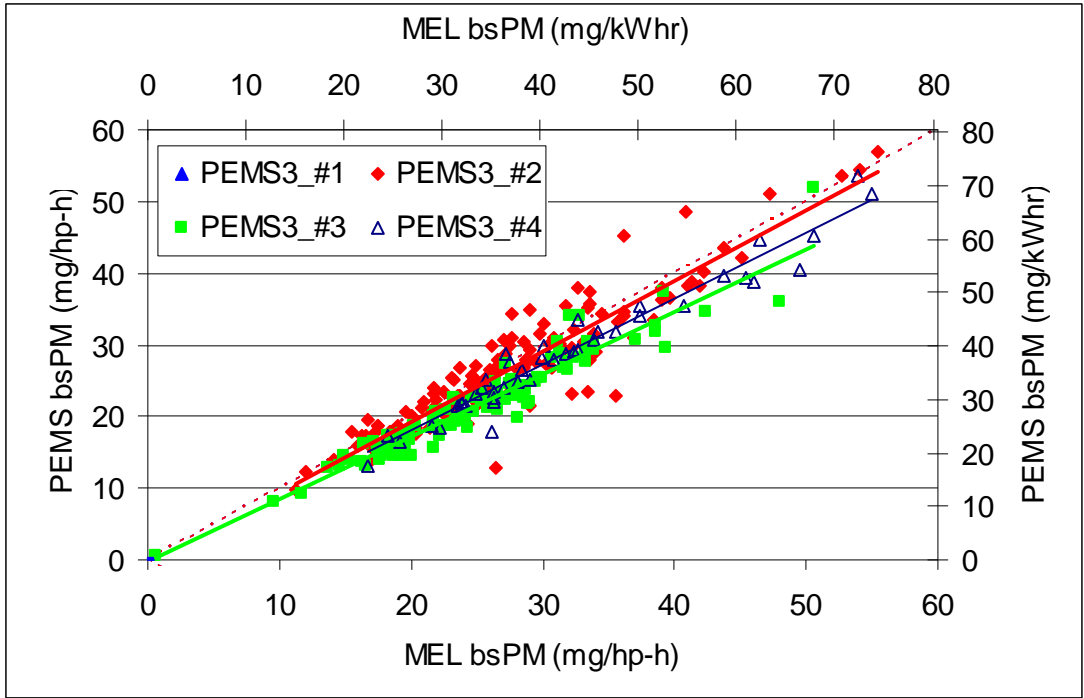
Figure ES-2 PEMS3 non-regeneration bsPM correlation unit by unit

Table ES-4 Non Regeneration PEMS bsPM Method 1 correlation by unit (mg/hp-h)

	Slope				Intercept				R^2			
PEMS	1	2	3	4	1	2	3	4	1	2	3	4
PEMS 2	0.30	0.24	0.14		1.5	3.9	8.2		0.52	0.34	0.20	
PEMS 3		0.98	0.87	0.92		-0.5	-0.3	-0.4		0.93	0.96	0.98
INST 4	1.00	0.70	0.74	0.76	-3.4	-0.7	-1.2	-0.7	0.89	0.87	0.89	0.89
INST 5	1.33	0.39	0.36	0.81	-9.4	0.4	3.2	-5.2	0.75	0.76	0.67	0.85

Summary Results for all PEMS and INSTs

Results for the combined data sets for all PEMS and INSTs are presented in Figure ES-3 and Table ES-5. All PEMS and INST showed a negative bsPM bias relative to the MEL reference method for both the non-regeneration bypass and regeneration cases. PEMS3 showed the best overall correlation and PEMS2 the lowest overall correlation, with the correlations for INST4 and INST5 in-between those units. PEMS2 also showed the highest positive zero intercept, while the other PEMS showed slightly negative zero intercepts.
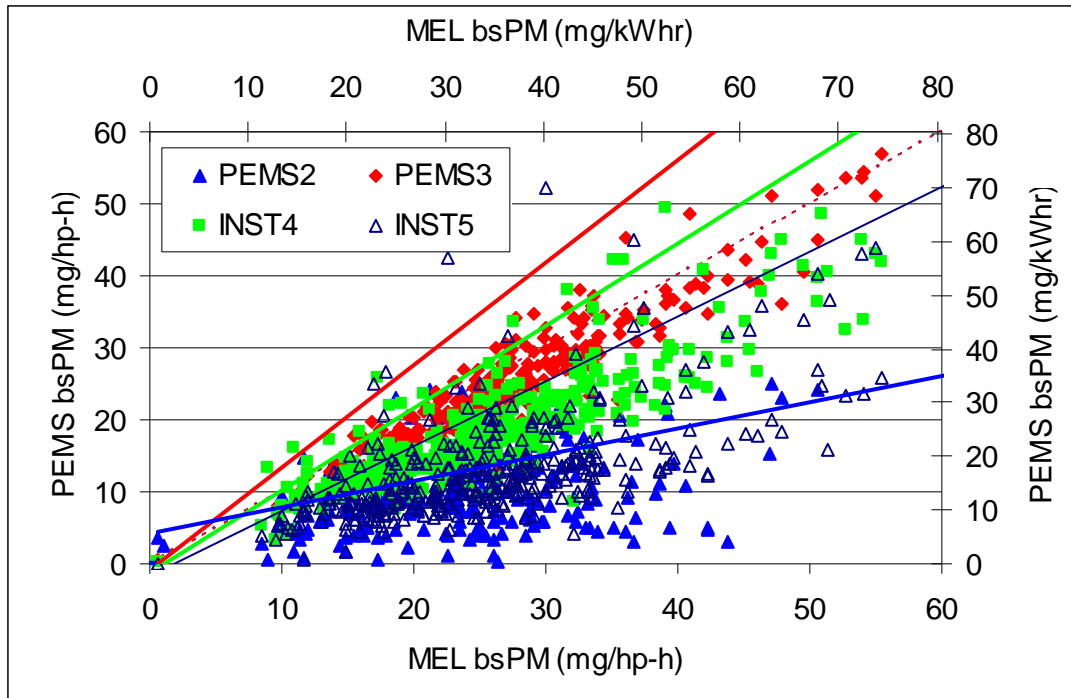
Figure ES-3 PEMS and INST non-regeneration bsPM correlation combined

Table ES-5 PEMS PM bsPM correlation results combined (mg/hp-h)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	0.24	4.2	0.37	5.4	2E-63
PEMS 3	0.95	-0.7	0.94	3.0	2E-25
INST 4	0.76	-1.0	0.86	4.3	1E-96
INST 5	0.59	-1.3	0.56	8.3	1E-78
PEMS 3_M2	0.90	-0.8	0.94	2.9	4E-54

Issues and lessons learned

PM PEMS are still evolving and, as such, their issues are important to document to provide a metric for tracking improvements in the instruments as they continue to develop. The issues included problems related to testing under in-use conditions, operational issues, and post processing issues. The in-use issues ranged from electrical and mechanical connections, crystal usage from short NTE's, valve switching, measurement signals, and crystal behaviors. Operational problems occurred during startup, commissioning, and with the systems prior to testing in-use. Typical issues include incorrect system configurations, procedures that don't work, and issues with the startup software and other recommended practices that didn't function according to the manual. The post processing issues ranged from data filtering, bsPM differences between processor versions, data identification, and method calculations not being available. In general, PEMS2 had more issues than PEMS3 for each of these categories.

1 Background

The United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) agencies are implementing a series of regulations that will control emissions, including oxides of nitrogen (NO_x) and particulate matter (PM), from diesel engines during "in-use" conditions. The purpose is to ensure the emission standards can be maintained throughout the course of the engine's useful lifetime. One of the most important regulations with respect to controlling in-use emissions is the Not-To Exceed (NTE) regulation. This regulation sets limits for pollutants that are emitted during operation in a defined portion of the engine map and specifies the protocols required to make those measurements.

Portable Emissions Measurement Systems (PEMS) are critical for the implementation of these in-use regulations. Regulators agreed PEMS measurement uncertainty could be larger than that for laboratory measurements, and thus should be accounted for with a "measurement allowance" (MA). The allowance is in essence would add to the in-use standard for a Not-To-Exceed combined standard. There are other aspects, such as deterioration, that will affect the total in-use standard, as described in 40CFR Part 1065. The EPA, CARB, and the Engine Manufacturers Association (EMA) formed a measurement allowance steering committee (MASC) to develop these MA values. A comprehensive program was completed for the gas-phase measurement allowance (Miller et al., 2008; Buckingham et al. 2007; Fiest et al. 2007). This report presents the results of the in-use validation portion of the PM measurement allowance program.

The MASC approach for the PM measurement allowance was similar to that for the gas phase program. The experimental program included laboratory measurements to formulate a MA error, then the validation those errors with in-use testing. Southwest Research Institute (SwRI) developed the MA and UCR validated the MA with in-use measurements. The development of the MA involved a sophisticated Monte Carlo model that considered laboratory measurement errors associated with engine broadcast information, emissions measurements, affects due to ambient conditions, and affects due to on-vehicle conditions (Khalek et al, 2010). The in-use validation effort used the same PEMS systems used for the laboratory testing, but under real-world conditions. The idea was that the errors found in-use should be within the bounds of the proposed MA developed at SwRI.

This report presents the results UCR's in-use validation effort. Measurements were made between the PM PEMS and UCR's Mobile Emissions Laboratory (MEL) reference laboratory under in-use 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. Two PEMS manufacturers were selected for the in-use validation testing, and multiple serial numbers of each of the selected PEMS were included in the in-use testing.

Measurements were made from one class 8 heavy duty diesel vehicle equipped with a original equipment manufacturer (OEM) diesel particulate filter (DPF). A bypass system was designed to simulate a failed DPF while maintaining the functionality of the diesel oxidation catalyst (DOC). The bypass was designed to target an in-use bsPM emission level of 25 mg/hp-h. In-use routes were designed and utilized to exercise the PM PEMS equipment over a range of environmental conditions, and included segments near sea level, in coastal regions, in desert regions, and longer uphill incline segments and segments at elevations up to 4500 ft. Measurements were made

utilizing forced events that were similar to real NTE events. The events were allowed to start at the beginning of an NTE (naturally), but the time of the event (forced) was typically lengthened to provide for higher gravimetric filter loadings.

Other commercially available PM instruments, such as a Dekati Mass Monitor (DMM) and DustTrak, were also considered as part of the MA program. The main goal of this work was to quantify the differences between PM PEMS and the MEL to validate the proposed measurement allowance of 6 mg/hp-h at the 20 mg/hp-h standard. UCR was tasked with five major responsibilities:

- Prior to in-use testing, complete a 1065 audit focused on PM and a correlation exercise with SwRI and UCR's MEL.

- Design the test matrix, procure the test article, and develop the test routes.

- Install, operate, and post process the data for the PM PEMS following manufactures recommendations.

- Report PEMS – MEL bsPM delta validation results.

- Document and report on issues and lessons learned with the operation of the PEMS in-use.

2   Quality Control

2.1   PM and gaseous laboratory audits

The MEL underwent a 40CFR Part 1065 self-audit for PM-related criteria selected by the Measurement Allowance Steering Committee (MASC). The results are provided here to document the MEL reference system. 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 described in Section 3.8. This includes, for example, the upgrading of the PM sampling system to provide higher face velocities.

The 1065 self-audit of the MEL 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 MASC. At the end of this section, some other relevant audits and checks performed to provide more confidence in the MEL results are also described.

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

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

1065.307 Linearity
Linearity verification was performed for the total hydrocarbon (THC) instrument, the PM balance, and the filter face temperature. In addition, UCR performed linearity checks on all its mass flow controllers (MFC) and system filter temperatures. A comprehensive list of these linearity checks is provided in Table 2-2. UCR also performed linearity on all its analyzers since these procedures are routinely performed, and these data are included in the table. During the course of the in-use testing program, several gaseous analyzer linearity checks were performed for the MEL and they all passed with results similar to those listed in Table 2-2. In general, all instruments and sensors meet the slope, intercept, standard error estimates (SEE), and coefficient of determination (R^2) requirements specified in the CFR40 1065.307.

Linearity Checks

Table 2-2 Linearity checks were performed on selected analyzers and systems

Sensor Name	Units	Date	Slope Value	Slope Criteria	Slope Pass/Fail	Intercept Value	Intercept Criteria	Intercept Pass/Fail	SEE Value	SEE Criteria	SEE Pass/Fail	r² Value	r² Criteria	r² Pass/Fail	Overall Pass/Fail
Dilute gaseous bench															
CO	ppm	10/01/09	1.00971	0.99 / 1.01	Pass	-0.693	1.854	Pass	0.597	1.854	Pass	0.9999587	0.998	Pass	Pass
CO2	%	10/01/09	1.00236	0.99 / 1.01	Pass	-0.002	0.049	Pass	0.007	0.049	Pass	0.9999929	0.998	Pass	Pass
NOx	ppm	10/01/09	1.00243	0.99 / 1.01	Pass	-0.438	3.627	Pass	0.275	3.627	Pass	0.9999977	0.998	Pass	Pass
THC	ppm	10/01/09	0.99938	0.99 / 1.01	Pass	0.130	1.490	Pass	0.097	1.490	Pass	0.9999979	0.998	Pass	Pass
CH4	ppm	10/01/09	1.00326	0.99 / 1.01	Pass	-0.097	1.119	Pass	0.108	1.119	Pass	0.9999962	0.998	Pass	Pass
PM dilution and sample flow systems															
MFC61	slpm	03/11/09	0.99999	0.99 / 1.01	Pass	0.312	1.073	Pass	0.599	1.073	Pass	0.9997778	0.998	Pass	Pass
MFC63	slpm	03/11/09	0.99902	0.99 / 1.01	Pass	-0.021	0.279	Pass	0.084	0.279	Pass	0.9999483	0.998	Pass	Pass
MFC65	slpm	03/11/09	0.99988	0.99 / 1.01	Pass	0.085	0.750	Pass	0.134	0.750	Pass	0.9999923	0.998	Pass	Pass
MFC68	slpm	03/11/09	1.00560	0.99 / 1.01	Pass	-0.036	0.537	Pass	0.379	0.537	Pass	0.9996336	0.998	Pass	Pass
MFC69	slpm	03/11/09	1.00075	0.99 / 1.01	Pass	-0.007	0.537	Pass	0.082	0.537	Pass	0.9999826	0.998	Pass	Pass
TC_Hxout	C	01/14/09	1.00799	0.99 / 1.01	Pass	-0.004	0.600	Pass	0.217	0.600	Pass	0.9999770	0.998	Pass	Pass
TC_Hxin	C	01/14/09	0.99300	0.99 / 1.01	Pass	0.165	0.600	Pass	0.120	0.600	Pass	0.9999928	0.998	Pass	Pass
TC_cont	C	01/14/09	0.99138	0.99 / 1.01	Pass	-0.100	0.600	Pass	0.208	0.600	Pass	0.9999782	0.998	Pass	Pass
TC_oven	C	01/14/09	1.00509	0.99 / 1.01	Pass	-0.093	0.600	Pass	0.385	0.600	Pass	0.9999271	0.998	Pass	Pass
TC_split	C	01/14/09	1.00856	0.99 / 1.01	Pass	-0.219	0.600	Pass	0.201	0.600	Pass	0.9999802	0.998	Pass	Pass
TC_filter	C	01/14/09	0.99488	0.99 / 1.01	Pass	0.148	0.600	Pass	0.342	0.600	Pass	0.9999414	0.998	Pass	Pass
Filter room and weighing chamber															
PM_balance	mg	08/20/09	0.99992	0.99 / 1.01	Pass	0.005	2.000	Pass	0.012	2.000	Pass	1.0000000	0.998	Pass	Pass
RH_chamber	%	01/14/09	1.00671	0.99 / 1.01	Pass	0.033	0.682	Pass	0.277	0.682	Pass	0.9996384	0.998	Pass	Pass
T_chamber	C	01/14/09	1.00026	0.99 / 1.01	Pass	0.126	0.371	Pass	0.286	0.371	Pass	0.9995815	0.998	Pass	Pass
MEL calibration titration system															
MFC41	sccm	03/11/09	1.00091	0.99 / 1.01	Pass	0.007	1.000	Pass	0.118	1.000	Pass	0.9999921	0.998	Pass	Pass
MFC42	slpm	03/11/09	1.00023	0.99 / 1.01	Pass	-0.001	0.010	Pass	0.002	0.010	Pass	0.9999773	0.998	Pass	Pass
MFC43	slpm	03/11/09	1.00484	0.99 / 1.01	Pass	-0.008	0.100	Pass	0.037	0.100	Pass	0.9999230	0.998	Pass	Pass
MFC44	slpm	03/11/09	0.99897	0.99 / 1.01	Pass	0.001	0.015	Pass	0.005	0.015	Pass	0.9999367	0.998	Pass	Pass
MFC45	slpm	03/11/09	0.99890	0.99 / 1.01	Pass	-0.006	0.290	Pass	0.042	0.290	Pass	0.9999879	0.998	Pass	Pass
MFC46	slpm	03/11/09	1.00001	0.99 / 1.01	Pass	0.001	0.050	Pass	0.001	0.050	Pass	0.9999996	0.998	Pass	Pass
MFC47	slpm	03/11/09	0.99961	0.99 / 1.01	Pass	-0.052	0.278	Pass	0.107	0.278	Pass	0.9999070	0.998	Pass	Pass

Standard conditions at 20C, 1 atm

1065.341 Propane Verification
Primary and secondary propane verifications are required to verify PM measurements under 1065. The provisions for a propane mass balance through the secondary dilution tunnel are similar to the procedures for the primary tunnel using the same critical flow orifice (CFO) kit used on the primary tunnel. The primary dilution tunnel propane verification was verified several times during the in-use testing program and averaged +0.5% high with a range from +0.8% to +0.2%. The secondary dilution tunnel recovery was slightly low at around -1.0%. During the correlation at SwRI, a similar comparison was found using SwRI's CFO system where the primary was high by +0.1% and the secondary was low by -0.5%. These results meet the 1065 requirements for both the primary (±2%) and secondary (±5%) tunnels. Although the MEL secondary tunnel CFO was slightly low, it is clear any bias with the secondary PM system was minor.

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 120 standard cubic centimeters per minute (sccm) of the minimum nominal flow of 30,000 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 8/20/2009. A copy of this certification is provided in Appendix B. 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 are provided in Table 2-2. 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, and zero and span calibrations. The net gain of the reference filter mass during this project was +0.0008 mg, which is less than the 0.010 mg specified in the CFR. Over the course of the entire in-use testing campaign (~6 months), three reference filters were used and each increased on the same order of < 1 µg. Although the reference filter weight gains were low over the course of the sampled filters, their net weights over the 6 months drifted up at around 1-2 µg. The spread of data was also on the order of 2 µg which makes it difficult to characterize these affects.

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 sampled before, during, and after the in-use testing campaign. In general, the filter weights were within expectations and varied from +0.005, to +0.003 mg for all the different checks. Several tunnel blanks were also performed. The tunnel blanks varied

from 0.008 to 0.005 mg for sampling over 1 m^3 of dilution air at the 1065 conditions of 47°C ±5°C.

All the filter check weights increased in this program, with the weight gain on the order of 1 μg. It is difficult to quantify if the filter weight contaminations are actual filter weight mass increases or just difficulty in weighting filters. It should be noted that during a previous in-use testing program (Durbin et al 2009a, b), the same filter checks showed slightly negative weight changes on the order of -0.002 mg.

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 constant volume sampling (CVS) system, 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 CVS flow SEE was less than the 3.5% of mean sample filter flow rate specified in the CFR. The proportionality metric covered all in-use operation from idling, decelerations, gear shifting and NTE operation.

Other internal audits performed
The MEL routinely performs other audits to help track system performance. These include, but are not limited to, NO_x converter efficiency, CO_2 injection (in addition to propane CFO injections), calibration gas blend audit, and fuel consumption carbon balance checks. These checks passed CFR and CE-CERT internal requirements and provide another level of confidence that the presented MEL data is valid.

In addition to the main required checks, a blind audit of the MEL analyzers was done CARB as part of another ongoing program (Durbin et al., 2010). The MEL met all 2% requirements for each of its analyzers for this blind audit. The MEL NO_x analyzer quench was also verified by the manufacturer of the instrument and it was found to be in compliance with 1065.370.

2.2   PM filter round robin

Prior to the main in-use validation testing, CE-CERT, SwRI, and the US-EPA conducted a round robin filter correlation exercise. During this exercise, 20 Whatman tares, 4 filters sampled from diesel exhaust, and a 200 mg span weight were analyzed for an inter-laboratory weighing comparison. The filters were initially weighted at US-EPA's Ann Arbor facilities, and then shipped to SwRI and then finally shipped to UCR. After analysis by UCR, they were shipped back to the US-EPA for final weighing and analysis.

Each facility employed their normal practices for weigh filters. UCR employs a weighing procedure where the filters are weighed until two consecutive weights within 3 μg are obtained. These two weights are then averaged for a final weight. This process typically only takes two weighings, but some filters require more.

The results from this analysis provide a feel for the variability between weighing filters at the different locations. The analysis involved calculating the 5th, 50th and 95th percentile differences from EPA weights for each filter. This gives a feel for each laboratory's ability to weigh a filter

and to manage its conditioning systems. The 5th, 50th, and 95th percentile differences for SwRI were -2.1, 0, and 2.1 µg, respectively, and UCR's were -3.1, 0, and 3.1 µg, respectively. This suggests that all weighing operations were fairly well managed and compared well.

2.3 PM PEMS audits and verifications

The audits and verifications were performed by UCR during commissioning based on the PM PEMS recommended practices, as per their manuals. Thus, the data presented here represent the state of condition the PEMS at the time of testing, according the PEMS internal criteria and UCR verification checks.

Three PEMS were considered as part of the model development, but only two, PEMS2 (the PPMD from Sensors, Inc.) and 3 (the AVL MSS 483), were used in this validation exercise and are presented here. The PEMS are described in more detail in Section 3.3 and Table 3-2.

The PEMS2 and 3 audits and verifications mostly covered zero, flow, linearity, and leak checks. Additionally, PEMS3 has a span verification process that attempts to maintain the integrity of their PM measurement system. The PEMS3 verification is based on a calibrated absorber window. If the light absorption detector is unchanged, then the span calibration should be rigorous. The absorber window process is directly tied to the EC/OC system which is traceable to NIST standards. The absorber window only spans for predominantly soot particles and thus does not span against total PM. The introduction of the gravimetric filter option and gravimetric traceability does tie this measurement principle very close to maintaining total PM traceability.

PEMS2 did not have an in-use span or verification process for its PM mass sensitivity measurement principle. It is assumed that the sensitivity is identical between crystals based on a factory calibration, and that it does not vary over time. PEMS2 manufacturer recently evaluated crystal-to-crystal sensitivity, and thus has intentions of individually calibrating the sensitivity for each crystal on an annual basis. The system still does not have a mechanism for in-use spanning or verification of the PM mass sensitivity. This current traceability for PEMS2, which is dependent on factory calibration, is not as ideal as would be daily PM mass verifications of some type.

The following two subsections discuss the PEMS2 and 3 audits and verifications that were performed. Some results are presented to show the status of the instruments as operated by UCR. Several issues were encountered while performing many of the audits. These are discussed in Section 6.1.

2.3.1 PEMS2

PEMS2 audits and verifications are presented here and include flow verifications, flow audits, leak checks, and temperature checks as per their manual (Sensors, 2009). PM zero checks are not a required process because each measurement is based on a difference in pre and post analysis of the crystal system, thus zero checks are somewhat integrated into each measurement. The more important verification is to have verification on the crystal sensitivity, which is not available as a daily procedure, and was thus not performed.

The primary verifications performed were using supplied reference meters and systems. Table 2-3 below shows a partial list of the main components verified (see Sensors (2009) Section 5.1 for the full list). Since the MPS2, which is required for secondary dilution, was not necessary for the PEMS2 operation, its systems were not audited. The checks in Table 2-3 represent sample conditioning checks where differential pressure transducers are zeroed and crystals are investigated for their behavior. All of the checks were performed as per the manual and demonstrated to be in compliance within the documented tolerances.

The leak check process used a method of overflow concentration detection and not pressure drop over time of loss of sample flow. Nitrogen gas was introduced into the system at the sample zone and compressor inlet and oxygen was sampled after the MPS1 diluter. This leak check method should identify leaks at slightly higher than normal sampling pressures. Depending on how the leak check was performed a pass/fail result could be obtained (see Section 6.2.1.6 for details). In general, all the leak checks performed passed the 0.1% oxygen concentration specification.

Table 2-3 PEMS2 verification and QC checks performed

Description	Frequency	Performed	Comment
CQCM tare	Daily	All Units	Zeros out mass weight gain for start of day
CQCM self check	Daily	All Units	Verifies crystal stability and proper operation
MPS1 zero	Daily	All Units	Zeros several flow related pressure transducers
MPS1 leak check	Monthly or cleaning	All Units	Nitrogen overflow leak check using an O2 analyzer. Verifies acceptable leak

Table 2-4 shows the systems audited and their required audit frequency. PEMS2 temperatures were not audited by UCR and are based on manufacturers as supplied results. The temperatures were checked against other MEL temperature sensors and found to be reasonable. The flows were all audited using a supplied TSI meter with a specified accuracy of ±2% of point reading. The audits performed were 1065 linearity checks for each flow measurement. The sample flow measurement is the most critical for the PEMS2 operation, and was thus verified daily. One reason for the high frequency of sample flow validation was the possible drift due to orifice diameter variation due to PM deposition. No sample flow drift was noticed at the 25 mg/hp-h sampling with a dilution ratio of six to one and daily orifice cleaning. It was noticed that the sample flow audit failed routinely due to the slope requirement (1.02 – 0.98) thus, suggesting the slope specification is too tight for this PEMS sample flow method (see Section 6.1 for details). The required solution was to repeat the sample flow procedure until a pass was achieved.

Table 2-4 PEMS2 1065 audits required

Description	Frequency	Performed	Comment
MPS1 temperatures	Annual	mfg	UCR verified temperatures
MPS1 sample flow	Daily	UCR	Repeated until sample flow passed
MPS1 dilution flow minor	Monthly	UCR	Verified
MPS1 dilution flow major	Monthly	UCR	Verified

In general, the results in Table 2-3 and Table 2-4 cover the ability of the PM PEMS system to sample flow, to eliminate faulty crystals, and to dilute flow accurately relative to a reference. The other PEMS tested did not have a process for auditing the flow in-use, but rather used an annual audit frequency.

2.3.2   PEMS3

PEMS3 audits and verifications include the laser linearity, the microphone linearity, and leak checks, as described in their operation manuals (AVL 2006 and 2009). The full list of checks is listed below in Table 2-5 and is described in AVL 2009 Section 6.2.2. PEMS3 system does include several flows, but they are verified internally as part of their startup automation process. An annual flow verification is also required according to the manual. Thus, no flow verifications were performed with the PEMS3 system.

Table 2-5 PEMS3 verification and QC checks performed.

Description	Frequency	Performed	Comment
Absorber window	Startup	All Units	Verifies span value to reference
Leak check	Daily	Manually	Function failure due to GFB (hand check with good engineering judgment after unit #1)
Pollution window	Daily	All Units	Daily verified clean startup status
Resonance test	Startup	All Units	Checks resonance frequency and signal intensity
Zero check	Pre test	All Units	Checks zero response on instrument
Linearity check	Startup	All Units	Laser and microphone linearity's

Each PEMS3 unit was calibrated prior to testing in the field with some daily checks as listed in Table 2-5 above. Typically the resonance, linearity, zero and pollution window checks were routine and passed easily following the manual. The leak check and absorber window calibration were more involved, and thus are explained in more detail in order to provide perspective to the PEMS3 results.

The leak check routine did not function due to the prototype gravimetric filter box module (GFM). According to the manufacturer the reason was due to additional GFB leak volumes not accounted for in the software. Thus, on unit 1 it turned out the failure of the leak check was actually an issue with the system that could have been caught with their production model. As such, on units 2, 3, and 4 UCR and PEMS3 manufacturer came up with an alternate leak check

method that prevented additional data loss and was easy to implement. Unit 1 data yield was low, but units 2, 3 and 4 data did not appear to have any leaks and the data is considered leak free. The leak method was performed by capping the sample line, while in service level #2, then turn off the pumps at 29 inHg and record the pressure drop over 1 minute. A pass was defined as less than 5 inHg pressure loss over 1 minute.

The PEMS3 manual Section 7 *Calibration and Checks* (AVL, 2009) describes the systems that can affect their measurement principle. These are listed in Table 2-6 for convenience. The measurement value is the only parameter that is listed in the manual that was verified by UCR. The other systems are calibrated by the manufacturer on an annual basis. The measurement value is listed in Table 2-5 as the "absorber window" check. In addition, UCR also verified the analog output due to some strange readings on the channels recorded by the gaseous PEMS2 system. The issue with the analog output was a result of gain settings for each gaseous PEMS2 system, as discussed in Section 6.1.

Table 2-6 PEMS3 calibration systems and recommended frequencies.

Description	Frequency	Performed	Comment
Temperature	annual	mgf	measuring cell temp control
Absolute pressure	annual	mgf	ambient pressure
Relative pressure	annual	mgf	relative pressure
Differential pressure	annual	mgf	Sample flow using diff pressure
Measurement value	annual	mgf	PEMS soot signal mV to mg/m3
Analog output	Setup	UCR	only for proper external records

The absorber window verification was performed for each unit and is documented in Table 2-7. Units 2 and 4 all meet the manufacturers tolerances for acceptable calibration deviations and were within the 10% tolerance, as listed in Table 2-7. Unit 1 and 3's deviations were significantly higher then the others and after discussion with PEMS3 manufacturer were corrected using their automated software. In the end, the unit 1 and 3 adjusted values used for validation were less than +1% and -1% deviation from the reference, respectively. In general, all PEMS3 data is based on original settings from the manufacturer with some adjustments to unit 1 and 3.

Table 2-7 PEMS2 absorber window span results, deviations and comments

Unit#	SN	Cal Verified Date	Ref Value mg/m3	Meas. Cal mg/m3	Deviation %. [1]	Comment
1	0273	09/21/2009	3.830	4.280	+11.8%	Adjusted to +1%
2	0429	10/28/2009	4.300	3.960	-7.90%	No action
3	0346	12/03/2009	3.615	4.188	+15.9%	Adjusted to -1%
4	0472	02/22/2009	3.800	3.929	+3.40%	No action

[1] PEMS3 manual states that no correction is needed if deviation is less than 5% and required if over 10%. Manufactured recommendations were used between 5% and 10%. Only PEMS unit 1 and 3 were adjusted.

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Although the measurement span value is unique for PEMS3 compared to other PM PEMS, it is still limited. The absorber window is only good for a particular unit, thus one cannot maintain a traceability from a signal cal value, but individual cal values. The sensitivity of the instrument may drift where the absorber window value could vary. Lastly, the measured value is dependent on linearity of the laser and microphone, which are confirmed. For a more detailed discussion see the PEMS3 manual (AVL 2009).

2.4 SwRI and MEL correlation audit

Prior to conducting the in-use validation testing, UCR's MEL was compared against SwRI emissions laboratory in San Antonio, TX. This correlation exercise was designed to verify UCR's PM system relative to SwRI. In addition it challenged UCR's ability to travel 1500 miles and be ready to test an engine for the first time and provide results quickly for calibrations, verifications and bsPM emissions.

UCR conditioned its MEL prior to traveling to SwRI using a NG heat source to remove and previous PM accumulation from previous test programs. At SwRI, UCR conditioned its MEL for an additional 5 hours on the SwRI test article prior to the engine comparison testing. The correlation focused first on propane recovery tests for the primary CVS and secondary dilution systems. Immediately following the propane verification tests the MEL was then compared against SwRI using the engine and test cell for the Monte Carlo model validation work. The correlation included PM and gaseous species.

The two reference laboratories targeted the specifications listed in Table 2-8 based on discussions while at SwRI. The primary CVS was set to 2380 scfm and the secondary dilution was set to 2.04 with a total max dilution of 6 to 1 based on the engine being sampled. The sample flow and control temperatures were also targeted to be the same. One difference between the labs was UCR dilution air is drawn from the ambient surroundings which varied from 15 to 35C and the RH varied from 20% to 40%. The SwRI dilution air is drawn from their building space which is maintained between 20 and 30 C with no specification on humidity. Another difference was with the exhaust transfer lines, they were designed to be of equal length, but the surrounding air temperature was lower for the MEL compared to SwRI as explained later.

Table 2-8 MEL and SwRI primary and secondary tunnel settings

Description	SwRI Settings	MEL Settings
Filter Temp	47 C	47 C
2nd DR	2.04 n/a	2.04 n/a
CVS total flow	2380 scfm	2380 scfm
2nd DR air temp	22.5 C	22.5 C
Sample flow	2.1 scfm	55.4 slpm 0C 1 atm

Figure 2-1 shows the MEL setup at SwRI for the correlation exercise. The red circled area is the transfer line used for the correlation testing. The MEL transfer line was removed from the system and a transfer line of equal length used at SwRI was installed. The transfer line was insulated to try and maintain the same temperature loss between the two laboratories. It should be noted that the SwRI transfer line was inside their test cell and the UCR insulated transfer line was outside.

The ambient temperature during the correlation exercise varied from 15°C to 35°C for the correlation samples taken. A discussion on the effects of thermophoretic losses is in the next subsection.

Figure 2-1 MEL sample setup from SwRI test cell during comparison

The correlation engine was a Volvo MP7 2007 DPF equipped 10.8 liter displacement engine. The engine was equipped with a variable geometry turbocharger (VGT) and a water cooled high pressure exhaust gas recirculation (EGR) loop. The engine intake system was based on the setup at SwRI which utilized their test-cell water cooled intercooler and charger air induction control systems. SwRI incorporated a bypass system that allowed the nominal 1 mg/hp-h emission level to be increased to the 25 mg/hp-h desired for the correlation. The bypass and its evaluation were shown to be sufficient as reported by Khalek et al (2010)

The test cycle performed was a test cycle developed for the MA program and was a series of 16 short NTE events with a combined duration of 755 seconds. Since simultaneous sample was not possible with both reference laboratories, the sampling was switched between SwRI and UCR over the course of 4 days. UCR and SwRI alternated between starting first in the morning as shown in Table 2-9. SwRI sampled in the morning twice and UCR sampled in the morning twice. This method was designed to prevent engine drift affecting one labs results over the other. The DPF was cycled through a regeneration procedure prior to a group of 4 tests to reduce any PM accumulation issues from affecting the comparison. A total of 12 tests were performed and were used for the inter comparisons. A 20 minute hot soak was performed between all tests. During the UCR day 4 morning test, the bypass system was capped and needed to be repeated.

Thus, on day 4 the AM preconditioning was a little different than the others due to additional run time and two regenerations.

Table 2-9 Test procedure used for the correlation exercise at SwRI

Day	Regen	AM Test1	AM Test2	AM Test3	AM Test4	Regen	PM Test1	PM Test2	PM Test3	PM Test4
1	1	SwRI	SwRI	SwRI	SwRI	1	UCR	UCR	UCR	UCR
2	1	UCR	UCR	UCR	UCR	1	SwRI	SwRI	SwRI	SwRI
3	1	SwRI	SwRI	SwRI	SwRI	1	UCR	UCR	UCR	UCR
4	1	UCR[1]	UCR	UCR	UCR	1	SwRI	SwRI	SwRI	SwRI

[1] During this test the bypass was left in regeneration mode and thus there was no PM and the test had to be repeated so the engine conditions were slightly different than the other AM tests.

2.4.1 Verification results

The verification results included primary and secondary propane recovery verification for both the UCR and SwRI reference laboratories. UCR performed their propane recovery tests using the SwRI propane kit. UCR provided their response value and then SwRI provided the deviation. During initial testing, a leak was found on the kit and was fixed prior to performing the tests. The results for both the primary and secondary recoveries are provided in Table 2-10. The primary verification test was slightly less than full recovery at -0.5% low or 99.5% recovery. The secondary test was slightly higher than full recover at 100.1% or 0.1% high. Both results are well within the 2% and 5% recovery tests for the primary and secondary systems, respectively.

Table 2-10 UCR primary and secondary propane recovery verifications

CVS Location	calc THC ppm	meas THC ppm	% error %
Primary	225.77	224.60	-0.5%
Secondary	268.15	268.44	0.1%

2.4.2 Tunnel blank results

Several tunnel blanks were performed and varied from 15 minute, 30 minute 60 minutes long to evaluate differences between sample duration and mass loading. The weight gains were similar for each laboratory and varied from 2 to 13 ug. It is interesting that longer sample times showed lower mass loading. The filter weight gains during testing were more than 300 ug which were well above the influence of the tunnel blanks.

2.4.3 Correlation results

The average SwRI bsPM was 28.7 mg/hp-h with a COV of 5.2% based on 16 repeats. The average UCR bsPM was 26.5 g/hp-h with a COV of 3.5% based on 15 tests. One of the UCR filter weights was deemed an outlier and was thus removed. The overall bsPM emissions for UCR were about 7.7% lower than that at SwRI. The UCR $bsCO_2$ emissions were also lower than

SwRI at 2.6%. Figure 2-2 shows the average bsPM results for each day for both UCR and SwRI of the 16 tests performed. The day to day comparisons were similar for all days except for the last day following a weekend. It is unclear how repeatable the test article is and if some of the deviation is due to the test article. The average deviation for the first three days averaged 6% where the last day showed a deviation of 13%. More analysis is needed to quantify the true difference between the UCR and SwRI laboratories, but for the purposes of the MA study the 7.7% is sufficiently small to continue with the testing program.

One other possible source of discrepancy could results from additional heat loss from UCR's transfer line, as described in the next section. Another possible deviation may result from different bypass conditions due to the design differences from the two CVS systems. The MEL is equipped with a throttled turbine and SwRI uses a positive displacement pump.
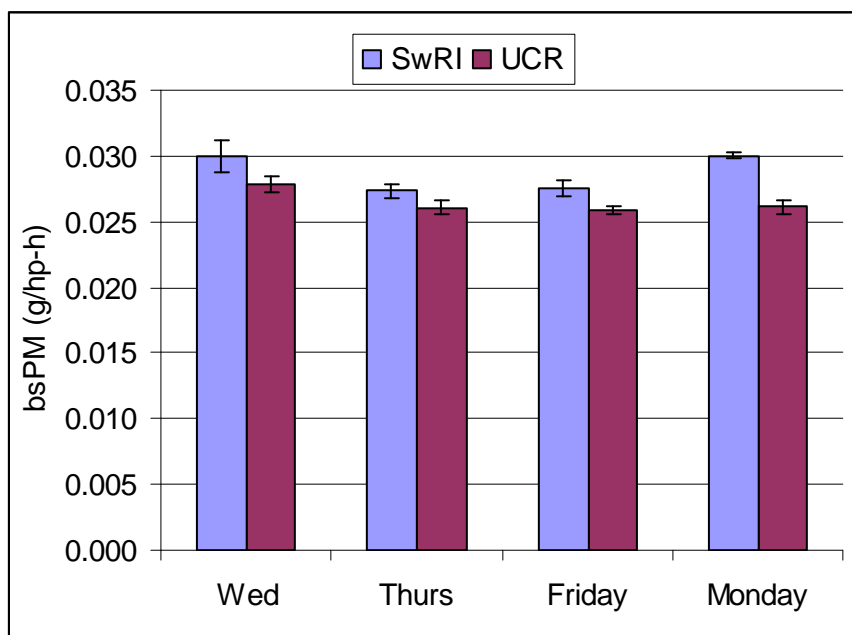
Figure 2-2 UCR engine testing comparison with SwRI

2.4.4   Thermophoretic loss evaluation

Thermophoretic losses could be a reason for some of the 7.7% low bias between the MEL and SwRI. Given that both laboratories primary and secondary CVS verifications had recoveries of 100% ±1%, it suggests that most of the difference may be due to PM sampling issues like thermophoretic losses. This section discusses briefly some trends for the thermophoretic loss difference between the MEL and SwRI laboratories and differences between the correlation and in-use validation.

Figure 2-3 shows a temperature profile of one the nine test runs for the NTE cycle used during the correlation. The exhaust temperature (pre and post catalyst) and CVS inlet temperature are on the left and INST4 and INST5 PM concentration is on the right. The NTE cycle was created where the load goes to idle between events. A consequence of this load cycling is unusual

cooling of the exhaust between events. The period with the largest temperature difference coincides with large PM spikes. Also, the ambient temperature that the MEL insulated transfer line was exposed to varied from 15°C to 35°C, where it is expected the test cell was at a nominally higher temperature. It is hard to measure the actual temperature difference with large thermo-well type TC's, thus, it is hard to quantify the effect of these dynamic thermophoretic losses. These trends show that integrated averages may not be the best approach.

In general, the average differential temperature between the exhausts stack and the CVS inlet was 27°C. The average in-use temperature difference was slightly less at 22°C as explained later. The correlation and in-use testing appeared to have similar temperature losses where the in-use testing was slightly lower. It is expected that the bias between the MEL and SwRI will be about the same or slightly less than for the in-use validation results.
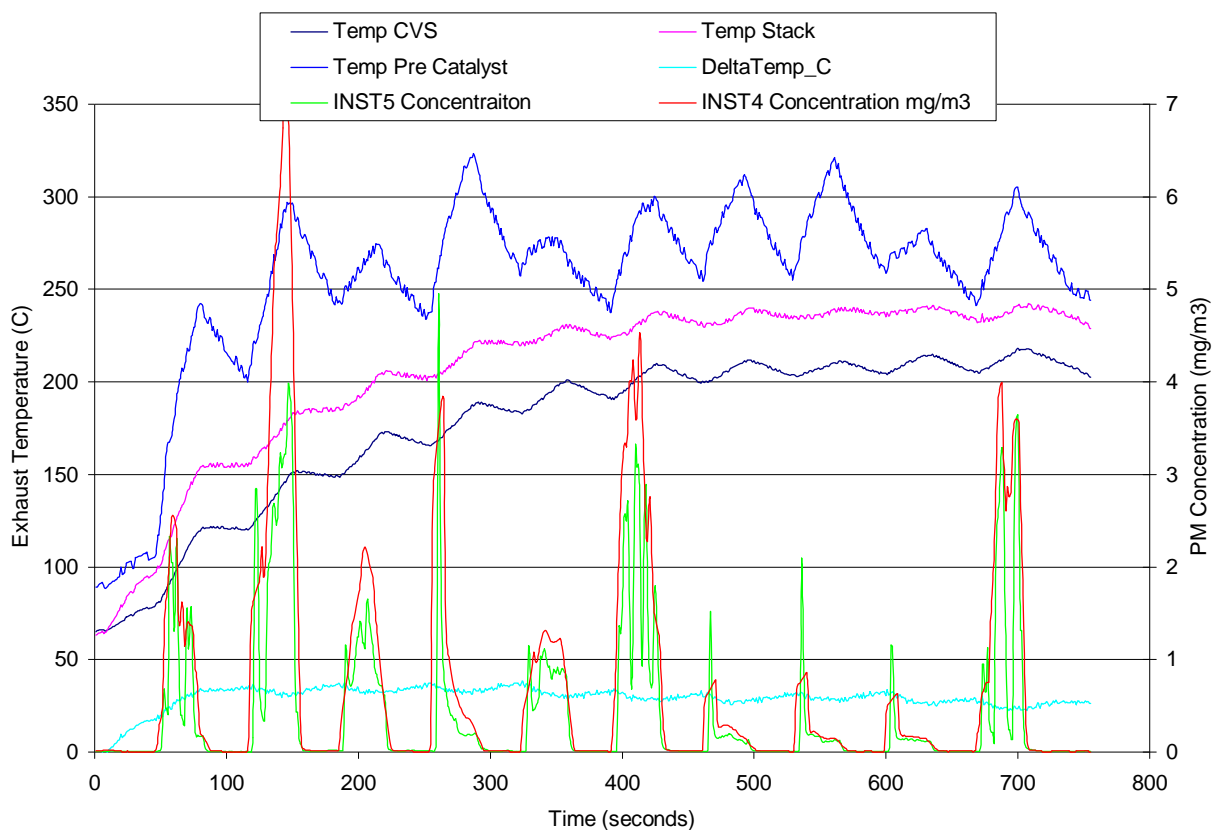
Figure 2-3 MEL example exhaust temperature profile from SwRI correlation

2.5   In-Use verifications

The in-use verifications included gaseous carbon balance and concentration audits. The carbon balance process utilizes the MEL and PEMS total carbon measurements from CO_2, CO, and THC for comparison to the ECM fuel consumption rate. The gas bottle audits were performed to ensure that gas analyzers were setup correctly during the validation testing.

2.5.1   MEL

Gaseous audits
The MEL routinely checks the calibrations from its automated calibration procedures for its gaseous analyzers. The checks involve injecting a 1% audit gas blends at the sample port with overflow. Then the MEL uses the daily calibration to verify the concentration in the audit. This was done at three concentrations 80%, 40% and 10% of full scale. All species were found to be with-in 2% of bottle concentration and were considered successful. This procedure was performed 6 times during the six month testing campaign.

During the gaseous MA study the MEL was audited from sea level to 8,000 ft to demonstrate the MEL's ability to correct for elevation affects. This same MEL and correction factors were used for this study as they are part of the MEL standard operating procedures. The correction for some gaseous species is on the order of 3% per 1,000 ft of elevation and varies by instrument.

Carbon balance
Carbon balance between the MEL and the ECM was performed daily to verify the MEL's consistency and proper operation during testing. ECM fuel consumption is not expected to be as accurate as the reference laboratory, but expected to be on the order of ±5% with-in the NTE zone based on discussions with MASC and reported by Imad et al (2010). Although it is not accurate one would expect the metric to be precise and consistent, thus making it a great tool for verification.

Routine checks are built into the MEL operation where one can easily verify proper operation. This benefit minimizes operational setup or other issues from occurring. During the in-use testing the MEL carbon was consistent between units and showed a high R^2 and near unity slope with an R^2 that ranged from 0.98 to 0.99 with a slope of 0.98 to 1.00 between units, see Section 5 for details. In general the high correlation and consistent results suggests the MEL's measurements are of sufficient quality for the PM comparison study.

2.5.2   PEMS

Gaseous audits
The PEMS performs pre and post-test zero and span calibrations as explained in Section 3. In addition, the PEMS manufacture recommends audits to verify the daily calibrations. These audits were performed in the morning and in the evening and were found to be with-in tolerances set by the manufacture at ±3% for all species except for THC. The THC measurements were low on this test article and as such the low 0-100 ppmC1 range was selected and calibrated with a 90 ppmC1 span bottle. The audit gas of 30 ppmC1 was used for verification and the audits routinely failed by around 5-10%. UCR made note of the deviation and proceeded with testing.

Carbon balance
Carbon balance between the PEMS and ECM was not performed routinely and could have prevented the issue with the switched exhaust flow tubes if a more additional analysis was performed during testing, see details Section 6. The focus of this program was on PM measurements and as such the gaseous results were mostly measured for Method2 analysis,

trouble shooting, and some basic comparisons between the MEL and the gaseous PEMS. Significant time was spent trouble shooting the PM PEMS systems thus taking away from these good engineering practices.

The corrected exhaust flow carbon balance results though did show good agreement with the ECM fuel consumption. The PEMS carbon balance showed a similar R^2 with a slightly wider slope with an R^2 from 0.87 to 0.99 and a slope of 1.0 to 1.08 between units, see Section 5 for more details. The high R^2 and near unit slope suggest the PEMS measurements were consistent with the ECM fuel consumption and between units. Given that the MEL and the PEMS both agreed well with the ECM this provides additional confidence that the bsPM comparisons will be of sufficient quality for the in-use validation comparison.

3 In-Use Testing – Experimental Procedures

Comparisons were made between the UCR MEL and 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, test routes and calculation methods, are described in this section. The comparisons are focused on PM with a secondary focus on gaseous species for method calculations and other diagnostic information.

3.1 Test article

The test article comprises the vehicle, DPF bypass system, and the regeneration controls. The vehicle was selected to represent a heavy duty diesel vehicle with DPF out bsPM emissions of approximately 0.001 g/hp-h. The bypass was incorporated to elevate those emissions from 0.001 g/hp-h to the targeted level of 0.025 g/hp-h. The regeneration control was added in order to exercise the PM PEMS during expected in-use NTE regeneration operation and to evaluate the anticipated regulations for in-use NTE regenerations.

3.1.1 Vehicle

One heavy-duty diesel vehicle was selected for this program due to budgetary limitations and the fact that it was believed that more variability would result from different serial number PEMS as apposed to different manufacturers of DPF-equipped heavy-duty diesel vehicles. The MEL trailer itself provided the load for all the on-road testing. The combined weight of the tractor and the MEL trailer was measured at 66,000 lbs for all the in-use testing performed.

The vehicle selected for this program was a model year (MY) 2009 Peterbilt tractor equipped with a 2008 Cummins ISX-485 diesel engine (serial number 79295033, engine family number 8CEXH0912XAL). The engine has a displacement of 15 liters, a peak horsepower power of 485 hp at 1800 rpm, and flat peak torque of 1683 ft-lb from 1150 to 1500 rpm. This engine was certified at the 0.01 g/hp-h PM and 1.25 g/hp-h NMHC + NO_x standard and used a DPF to meet this PM standard. The vehicle had 65,500 miles at the start of testing, so the DPF was considered sufficiently degreened for the PM PEMS validation study. The lug curve for the engine used to calculate the NTE thresholds and associated data are provided in Figure 3-1 and Table 3-1, respectively.

	SET CURVE	
RPM	Torque	Power
600	918	105
700	1020	136
800	1200	183
900	1322	226
965	1401	257
1150	1683	368
1200	**1683**	**385**
1300	1683	417
1400	1683	449
1500	1683	481
1600	1650	503
1700	1592	515
1800	**1489**	**510**
1900	1410	510
2000	1311	499
2030	1283	496
2031	0	0
2131	0	0
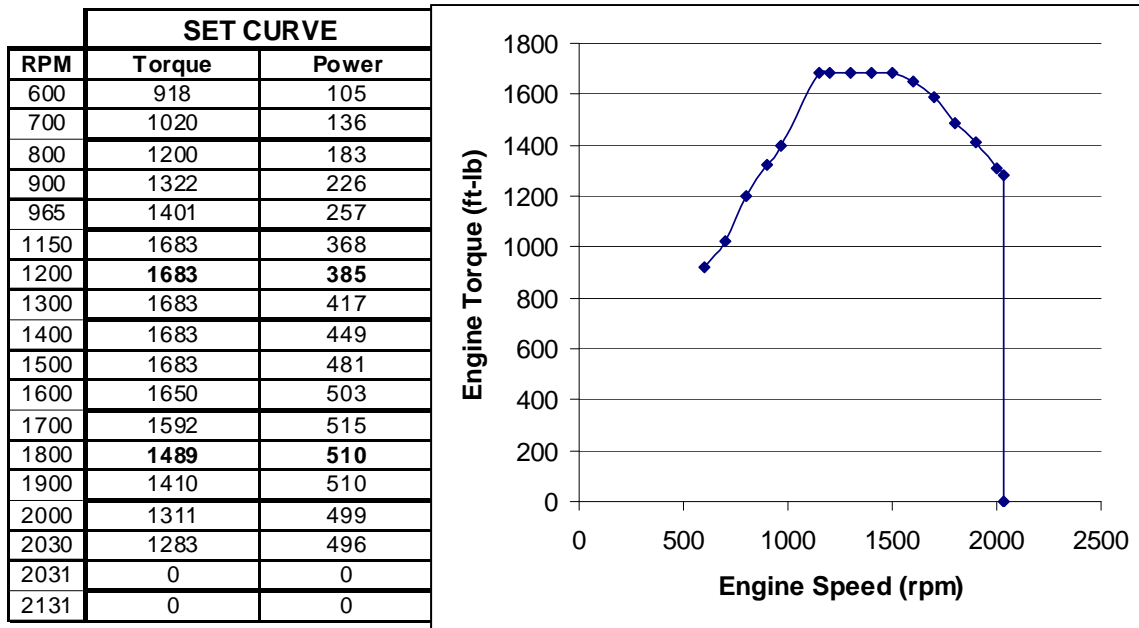
Figure 3-1 and Table 3-1 Cummins ISX485 lug curve for NTE threshold analysis.

3.1.2 DPF bypass evaluation

The PM emissions system modifications included varying levels of aftertreatment bypass and various portions of forced regenerations. The idea behind bypassing the aftertreatment system was to increase the tailpipe PM emissions rate to meet the targeted bsPM, but at the same time it was desired maintain the PM composition of a failed aftertreatment system.

3.1.2.1 Design

A 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 large concentrations 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.

Figure 3-2 shows the aftertreatment bypass system and related systems. The design includes a 4 inch bypass tube, an integrated close coupled DOC, two control valves, and a mixing zone. The 4 inch bypass tube was selected to allow sufficient bypass with the valves in maximum bypass position. The close coupled DOC was added to remove any HC and CO emissions in the bypass tubing. The control valves, one on the bypass leg and one on the main exhaust flow, were added to control and maintain exhaust back pressures and bypass PM emissions. The mixing zone was added to force additional mixing to ensure fully distributed PM emissions at the PEMS and reference sample zones, as discussed later in Section 3.1.2.3.

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After treatment system bypass

Mixing zone

DOC

Control valve

PM PEMS2 Install
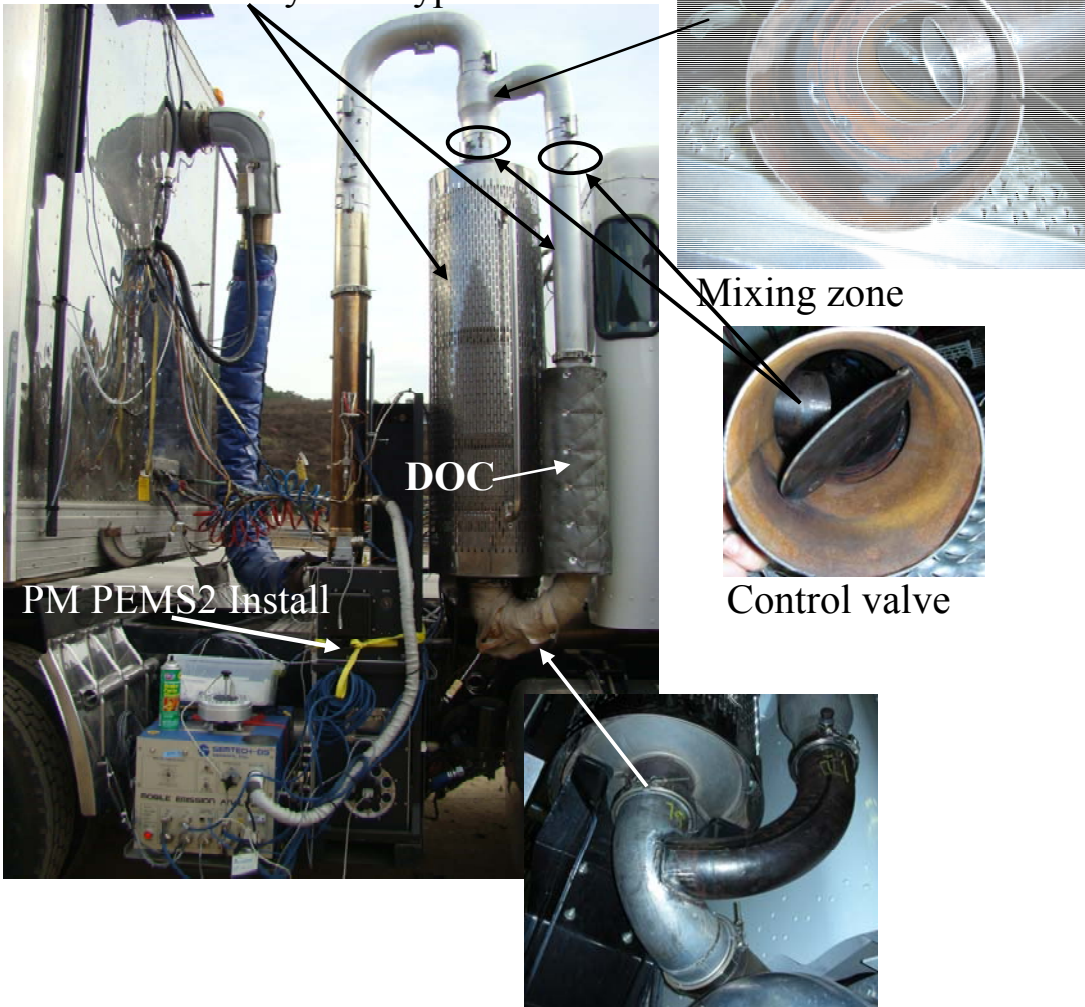
Figure 3-2 Aftertreatment bypass system on 2009 Peterbilt test vehicle

3.1.2.2   Evaluation: bsPM targeted PM emissions level

Several bypass settings were attempted to meet the targeted bsPM levels of 0.025 g/hp-h desired for this study. The targeted bsPM levels is a function of the bypass setting and the actual transient behavior for the specific event. It turns out that the range of bsPM emissions was more a function of the transient nature with-in the NTE like event than the bypass setting. In addition, high RPM type operation also seemed to show higher bsPM emission levels. In general, the bypass setting was selected for unit1 and slightly increased for units 2, 3, and 4.

The overall targeted bsPM was achieved for each unit tested. The overall and unit1, 2, and 3 histograms are shown in Figure 4-6 in Section 4.3.5. The 5th, 50th, and 95th percentile bsPM emission results were 11, 24, and 43 mg/hp-h, respectively, for the in-use testing, and are described in more detail in Section 4.3.5.

3.1.2.3   Evaluation: proper mixing

Proper mixing of the bypass is important to ensure that the PM measured at the PEMS is similar to that measured by the reference system. The extent of the mixing was evaluated by placing two PEMS3 MSS units at different locations and comparing their readings. One PEMS3 MSS was placed at the main PEMS sample location near the elbow of PEMS2 exhaust flow meter. A second PEMS3 MSS sampled from the raw exhaust just before entering the MEL CVS after an additional 15 ft of insulated transfer line. Prior to the comparisons between the two locations, the two MSS units sampled from the same location and were verified to have the same general measurement response over several conditional events. Then several in-use events were evaluated with both PEMS3 MSS units sampling from different locations.

Figure 3-3 and Figure 3-4 show a typical real time response of the PEMS3 measurement system sampling at the two different locations during the bypass mixing evaluation. Location "1" is the main PEMS sample zone and location "2" is the sample zone just before entering the MEL CVS. The figures show that all four events have about the same steady state response and the detail of event 1 is very similar between both locations. The data presented in the figure was typical for all the events and thus, suggests that the bypass system is well mixed.
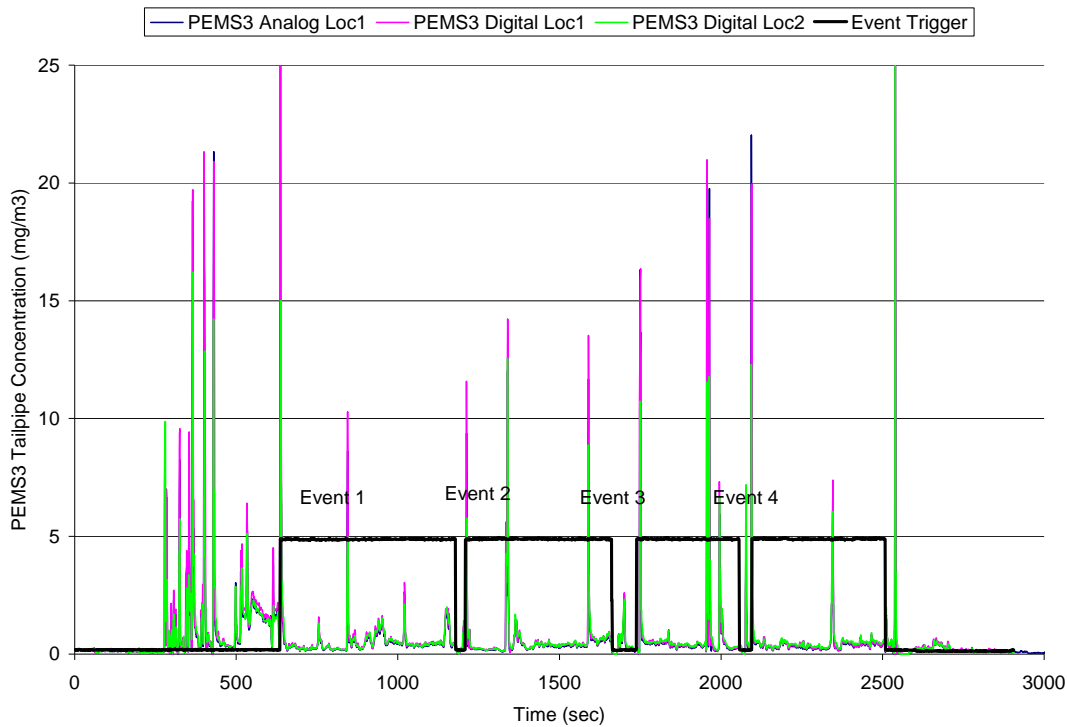
Figure 3-3 PEMS3 MSS mixing bypass system evaluation events 1, 2, 3 and 4
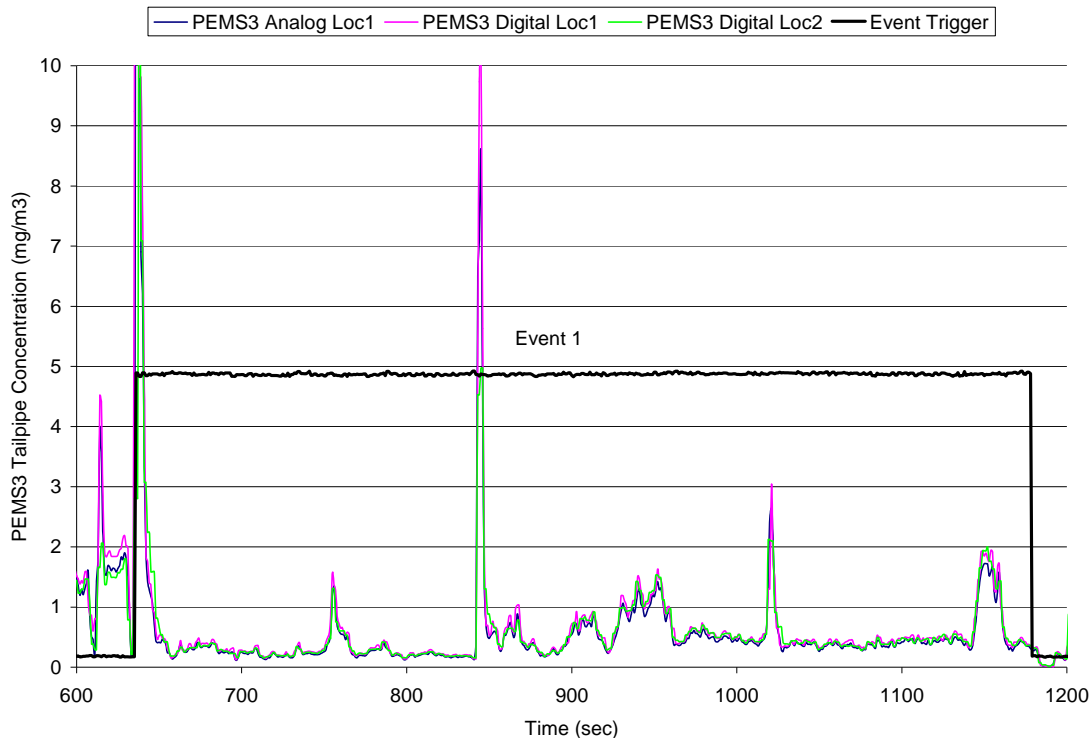
Figure 3-4 PEMS3 MSS mixing bypass system evaluation event 1

The figure also provides a comparison between analog and digital signals for location 1. The analog data is as measured by the gaseous Semtech DS analog input and the digital is the same signal measured by the PEMS3 software. Figure 3-4 shows that the difference between the analog recorded signal and digital recorded signal is very similar and shows about the same transient response. This suggests the Semtech DS is suitable at recording the PEMS3 analog signal. However, during testing there were several examples where the dilution ratio or concentration signal was not stable as recorded by the Semtech DS. In order to prevent errors associated with analog data records, all data in this report is based on the digital PEMS3 location 1 data.

3.1.2.4 MEL thermophoretic losses

Thermophoretic losses were compensated for each PEMS system, but not for the reference systems at SwRI and UCR. Temperature losses in transfer lines represent a contributing factor to PM line losses. The temperature during the correlation exercise was 27°C, as described in Section 2.4.4. The temperature during the in-use validation measurements is shown in Figure 3-5. The average temperature during the in-use validation testing was 22°C and increased slightly from unit 1 to unit 4. The temperature was slightly less for the in-use testing compared to the validation testing suggesting that some off the low bias between the MEL and SwRI may have been eliminated by the insulated transfer line.

22
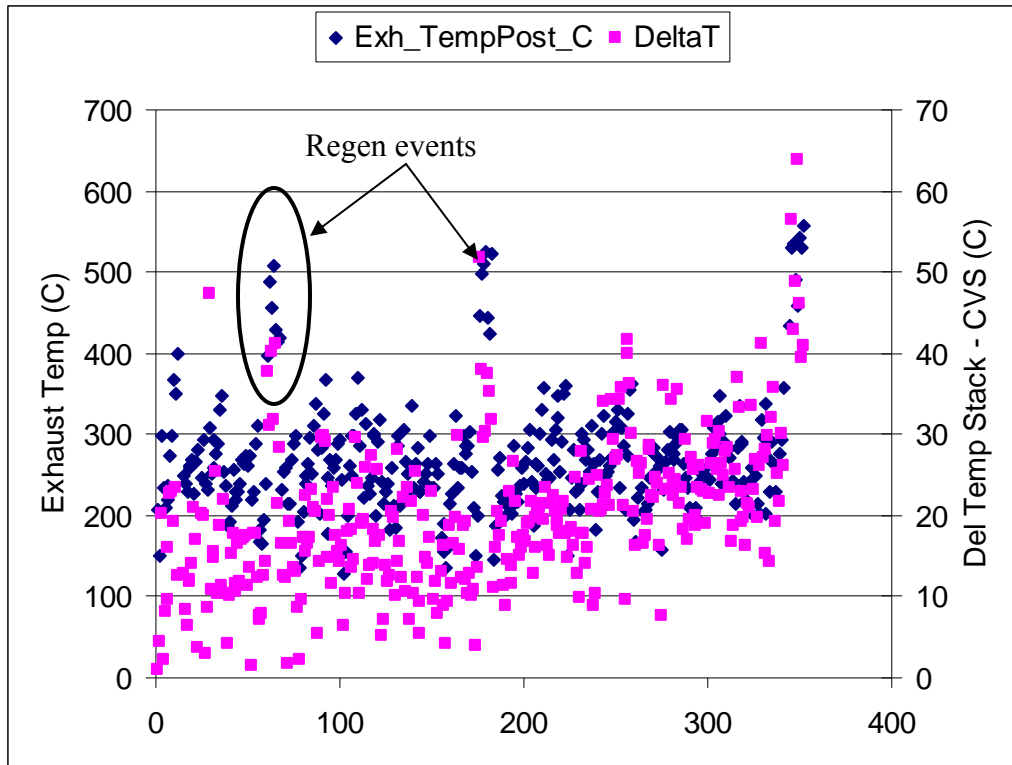
Figure 3-5 MEL transfer line temperature and relative exhaust temperature

3.1.3 Regeneration

3.1.3.1 Overview

Regeneration events were added to this study to evaluate measurement uncertainties during regenerations and PM emission levels during actual regenerations. This section covers the tools used to perform the regenerations and the types of levels measured by the reference system.

3.1.3.2 Design

Controlled regenerations were necessary in order to understand PEMS performance during routine regenerations. Regenerations were controlled through proprietary tools provided by Cummins support engineering. The tools comprised of recalibrating the ECM and providing a soot loading term to manage the regenerations. The recalibration involved Cummins e-mailing an ECM file to a local distributor who flashed the vehicle ECM on site. The purpose of the reflashed file was to allow use of the dash "Regen Override" digital input switch to control regens. In the off position, no regens would occur. In the on position, a regen would be requested and the engine would behave as if there was a normal request for a regen. Cummins support also provided a soot loading term on their proprietary change to allow UCR operators to monitor DPF status. The soot loading term was maintained below a certain range specified by Cummins.

During testing, regenerations were very easy to force, control, and monitor. Regenerations were performed on about 10% of the test events. During regenerations no bypass was employed. Thus,

all regeneration events should represent a functioning DOC/DPF without a crack in the DPF (i.e., with no bypass).

3.1.3.3 Evaluation

Figure 4-7 shows the summary statistics for sample duration, gravimetric filter loading, bsPM and PM concentrations for all the regeneration events with the bypass capped. The regeneration 50th percentile bsPM emissions were lower than the non-regen 50th percentile emissions at 9 mg/hp-h compared to 24 mg/hp-h and 52 µg/mol versus 175 µg/mol, respectively. The lower bsPM and PM concentration are expected for DPF regeneration PM. The bsPM emissions during regeneration can be put into context by comparison with the certification standards, even though regeneration events are excluded from the NTE. The 50th percentile bsPM was very close to the certification standard at 9.1 mg/hp-h. Higher values of 29.2 mg/hp-h are seen at the 95th percentile.

3.2 PEMS: selection for validation

Three PM PEMS were considered for the MA model development at SwRI, Horiba's Transient Response Particulate Matter (TRPM), Sensor's Portable Particulate Measurement Device (PPMD) and AVL's Micro Soot Sensor (MSS). The MASC developed pre-validated measurement allowances for each of these PM PEMS. The TRPM and PPMD were considered complete PM PEMS systems and the MSS was considered an alternate PM PEMS. At the time of development, the MSS PEMS would only be considered if both the TRPM and PPMD produced unreasonable measurement allowances. Only one of the two complete PM PEMS in addition to the MSS PM PEMS was considered for the on-road validation, with the MSS PM PEMS to be "piggy backed" on the complete PEMS.

The selection of the complete PM PEMS for model validation was based on the PM PEMS with the lowest positive pre-validated measurement allowance using the criteria as documented in the test plan between the MASC and SwRI (Khalek et al 2010). The Sensors PPMD showed the lowest positive pre-validation measurement allowance and was selected for the in-use testing comparison presented in this report. The MSS PM PEMS was also tested in a "piggy back" scenario in series with the PPMD system. The gaseous Semtech DS was used to measure all gaseous emissions, ECM information, and the exhaust flows for PEMS2 and 3. The PPMD is denoted as PEMS2 and the MSS is denoted by PEMS3, as listed in Table 3-2, where PEMS1 is only mentioned for consistency with a previous study (Durbin et al 2009a).

Table 3-2 PEMS nomenclature and principle of operation

PEMS #	Manufacture	Product Name	Principle of Detection	In-Use Testing
1	Horiba	TRPM	EAD+Filter	No
2	Sensors Inc	PPMD	QCM	Yes
3	AVL	MSS 483	Photo Acoustic	Yes
3b	AVL	MSS 483+GFM	Photo Acoustic + Filter	Yes[1]

[1]Although the AVL's MSS483+GFM was tested in-use it was not part of the independent data validation checks (ie the data was processed by the manufacture) and only one serial number conditioning unit and filter module were evaluated, but three MSS483's were tested

After the completion of the model development, but before the model validation, the AVL MSS was enhanced with an optional gravimetric filter module (GFM). The optional GFM system allowed the AVL MSS+GFM system to be considered for alternate approval at the time of this writing. The MSS+GFM was not available during model development, but was available during model validation and was thus evaluated as part of the MA validation program. Since the focus of this report is on model validation only, results describing the AVL MSS PEMS are presented in full. Some analysis of the MSS+GFM option will be provided. The GFM data was not used in any of the final model validation results submitted to SwRI or presented in the main analysis in this report.

3.3   PEMS: definition

An important and often misused concept is the definition of a PEMS. This report defines a PEMS as it pertains to in-use compliance testing under CFR40 Part 1065 regulations. A PEMS is defined as a comprehensive system that measures regulated raw exhaust species and reports brake-specific emissions factors over defined operating conditions during normal in-use operation. The defined in-use operation is the NTE zone in the U.S. and a work-based window in Europe. This report focuses on the U.S. NTE zone during in-use conditions and not the work-based window approach. The definition of in-use for this report is for on-highway conditions not non-road type applications. It is believed that the results of this study and the measurement allowances determined here should be sufficient to carry over to other areas of in-use measurement with the understanding that some differences may apply.

The measurement principles are also specified in the CFR where gaseous species are limited to approved traditional methods, but for PM a more general approach was provided given the difficulty and variety of options for measuring PM. The CFR is clear though that in order to measure PM, the measurement principles must be mass-based or directly tied to a mass-based approach. Only two measurement systems are currently approved as mass based PEMS the PPMD and TRPM, while the AVL MSS+GFM is being considered for alternate approval. The remaining instruments that measure PM are surrogates and will be referred to as PM instruments in the remainder of this report.

The surrogates considered in this report are the TSI Dustrak and the Dekati Mass Monitor (DMM). The surrogate instruments will be referred to as INST4 and INST5 to maintain consistency with figures and tables. The PM PEMS and PM instruments will be described in

more detail in Section 3.5. The focus of the report is on PEMS2 and 3. The surrogate PM instruments were used to help provide additional depth of understanding for real-time in-use PM measurements.

3.4 PEMS: test matrix

The testing performed for the in-use validation covered various PEMS manufacturers, different serial number PEMS from the same manufacturer, one heavy-duty diesel vehicle, and modifications to the engine exhaust aftertreatment emissions systems. There were three PEMS2 and four PEMS3 serial numbers tested, which are denoted as units1, 2, 3, and 4, see Table 3-3. The fourth PEMS3 serial number tested was added to this testing program under direct funding from the PEMS3 manufacturer. Only one serial number GFM system was utilized due to its level of development. Also there was only a single unit of INST4 and INST5 tested. PEMS2 and 3 were sampled off the vehicle's raw exhaust and INST4 and 5 were sampled out of the MEL primary dilution tunnel. INST4 and 5 are not approved PM measurement systems as explained in the previous section.

Table 3-3 Test matrix PM PEMS in-use evaluations

PEMS Unit #	Sensors PPMD	AVL MSS	AVL GFM	Semtech DS	EFM
1	G08-PD01	0273	1005	D06-SDS01	35321
2	E08-PD03	0429	1005	F06-SDS04	35498
3	A08-PD02	0346	1005	F06-SDS02	33350
4	n/a	0472	1005	F06-SDS02	34735[1]

[1] This EFM utilized the external flow box where EFM's were utilized the integrated MPS PPMD systems.

The primary goal of this validation effort was to evaluate the PM PEMS at the target bsPM of 0.025 g/hp-h with a range of bsPM from 0.01 to 0.06 g/hp-h. In order to target 0.025 g/hp-h a DPF-equipped vehicle certified at the 2007 PM standard of 0.01 g/hp-h was selected. Typical model year (MY) 2007 engines have PM emission levels at 0.001 g/hp-h. A DOC/DPF bypass system was used to achieve the target 0.025 g/hp-h bsPM emission level. In addition to the bsPM target, UCR also attempted to stay in the same concentration ranges as were observed at SwRI during model development. The concentration range was from 50 to 400 µg/mol for raw exhaust. UCR's MEL does not measure raw exhaust flow directly, but can calculate it by difference from their double CVS system (total and dilute), and thus report estimated raw concentration.

3.5 PEMS: Description

3.5.1 Overview

This section describes the two PM PEMS tested as part of this validation work and the two additional PM instruments used for comparative analysis. The two PM PEMS represent different levels of technology and technological advancement with respect to meeting the in-use testing requirements. PEMS1, 2, and 3 are all described, but only PEMS2 and 3 were tested as part of

the validation exercise. PEMS1 description is presented to describe the state of technology available for in-use testing.

3.5.2 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's 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 can be used as a direct comparison to the MEL or another reference method where similar dilution ratios, face velocities, and filter temperatures are maintained, as per 1065.

3.5.3   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 recommended QCM sensitivity of 150Hz/µg was used for all tests except with Unit#1, where the sensitivity was configured incorrectly at a 100Hz/ug. All the Unit#1 PEMS2 data and associated results were adjusted for this error. The adjustment was made by multiplying by a ratio of 150/100. This has the effect of increasing the PM mass by 1.5 times. The data in this report for Unit#1 was updated to reflect this increase in PM. At the time of this report, the PEMS2 manufacturer is considering an individual crystal sensitivity factor in order to reduce variability.

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.

3.5.4   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 systems. PEMS3 is 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 soot concentration. This PEMS uses constant dilution with the 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 from PEMS2, the data are converted to bsPM.

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), soluble organic fractions (SOF), ash or inorganics, nitrate particles and sulfate particles (and associated water mass with each unit of sulfate mass). In an effort to characterize total PM, the PEMS3 manufacturer updated their soot measurement with a modeled total PM output. The model uses empirical relationships between other exhaust measurements such as exhaust temperature, total

hydrocarbon, dilution ratios, catalyst volume, and sulfur content of the fuel to predict OC and sulfate masses to estimate a total PM mass.

SOF is typically broken down into fuel-derived SOF and lubrication oil SOF. It is expected that a properly functioning DPF-equipped engine will have 40% of the PM mass from lubrication oil SOF at bsPM levels of 0.001 g/hp-h. Their SOF 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 PEMS3 total PM model also accounts for the sulfate PM 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.

More recently PEMS3 developed a GFM module to enhancing their model-based approach with a gravimetric filter. The idea is that PEMS3 system can now calibrate their modeled approach with the gravimetric filter. The benefit is now the model is tied to the reference system and is less likely to produce unusual results. The first prototype of this system was evaluated as part of this study and some of the results are presented in this report. A more thorough investigation of the results is necessary to characterize the GFM system and to understand its implementation as it relates to other PM emission sources.

3.5.5   INST4 and 5

INST4 utilizes an optical scattering measurement technique. INST4 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.

INST5 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]. INST5 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.

3.6   PEMS: Installation

This section describes the installation of PEMS2 and 3. INST4 and 5 installations are also discussed even though these instruments are integrated into the MEL. In general, PEMS2 and 3 were installed on the frame outside of the MEL in the ambient environmental. INST4 and 5 were inside the air-conditioned, shock-isolated MEL

3.6.1 PEMS2

PEMS2 system includes both the gaseous Semtech DS and PM PEMS2 systems. The Semtech DS and PM PEMS2 system were mounted on the passenger side between the fuel tank and the tire cover, see Figure 3-6. The mounting location was not based on the manufacturer's recommendations, as shown in Figure 3-7, because of the need to route the exhaust from PEMS2 to the MEL.

The Semtech DS was mounted on a vibration isolating support and the PM PEMS2 was mounted directly on the frame with no vibration isolation as recommended in the manual (Sensors 2009). The PEMS2 systems operated directly off of 12 VDC batteries and did not need AC power from the MEL. For convenience a 120 VAC charger, supplied by PEMS2, was installed to keep the batteries charged. All compressed air and other resources needed by the PM PEMS2 system were supplied by the PEMS manufacturer.

Other systems needed by the gaseous Semtech DS were installed in the same general area, such as the exhaust flow meter, humidity sensor, GPS and ECM interface. The exhaust flow meter was installed more than ten diameters after the last elbow. The humidity sensor was mounted behind the driver side window away from the exhaust using the supplied weather shield as configured in Johnson et al. (2009). The remaining GPS and ECM interfaces were routed to the Semtech DS and transmitted to PEMS2 over a CAN network. Also for convenience the Semtech DS was supplied FID fuel from the MEL.

Figure 3-6. PEMS2 installation with Semtech DS system: passenger side on frame
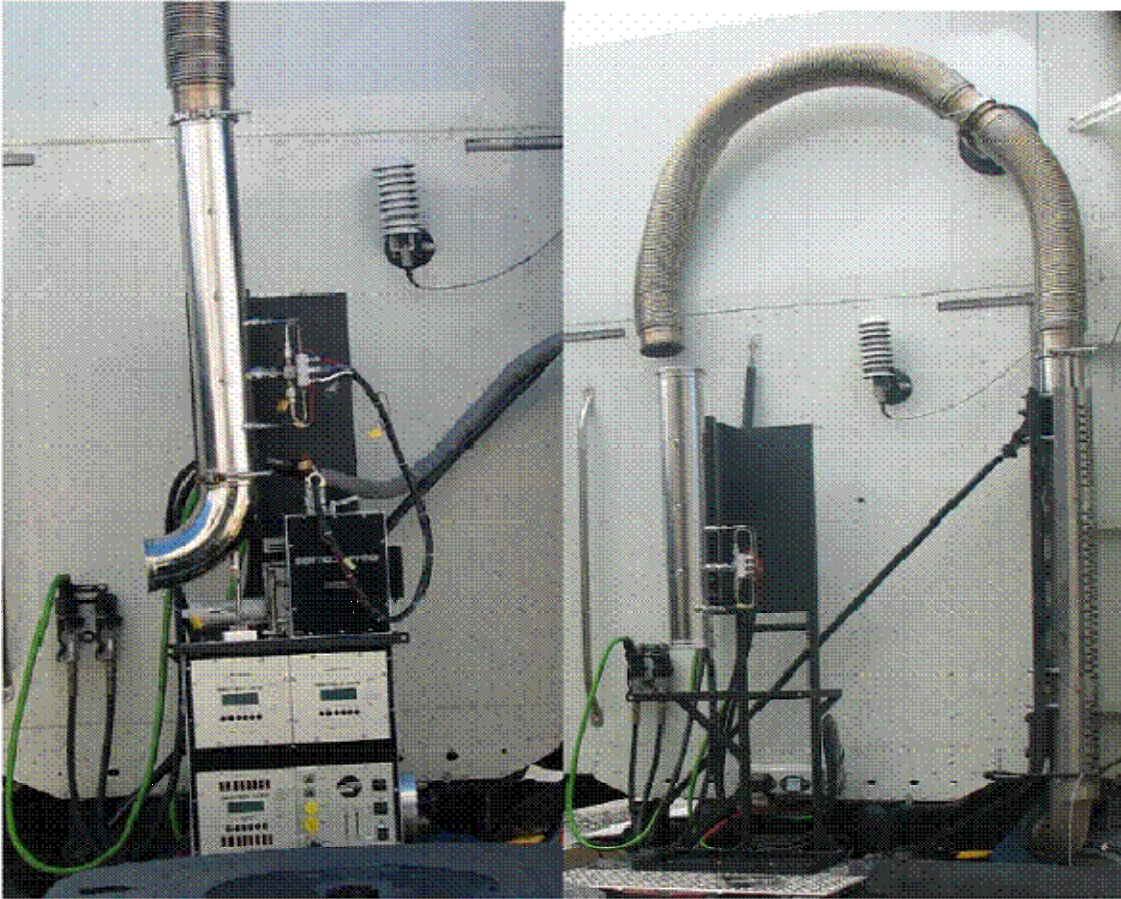
Figure 3-7 PEMS2 manufacturer recommended installation details (Sensors 2009)

The sample location for the PEMS2 PM and gaseous emissions were more than ten diameters from the last elbow where the PM 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 identical between units tested.

3.6.2   PEMS3

The PEMS3 installation involved the dilution sample probe, soot sensor, conditioning system and GFM system. These systems were installed according the PEMS3 manual (AVL, 2009), see Figure 3-8. It is expected the GFM and the conditioning system will be integrated into a single box for their production version of the GFM. The PEMS3 manufacturer provided a DC to AC converter, but to facilitate operations, UCR chose to provide the PEMS a single 120 VAC, 20 amp circuit (of which only 7 amps were used).

Previously a source of compressed air was needed to cool the system (Durbin et al. 2009a, b) that was not needed this time. Compressed air was provided from the PEMS system with an upgraded pump as part of their standard package. The compressed air was used to provide dilution air for the PEMS3 constant diluter. The PEMS3 conditioner and soot sensor systems were mounted on vibration isolation tables provided by the manufacturer. The GFM system was mounted to the

soot sensor and did not have a separate vibration isolation system, but used the one from the soot sensor system. The sample location for PEMS3 PM emissions were 24 inches down stream of the PEMS2 sample location.
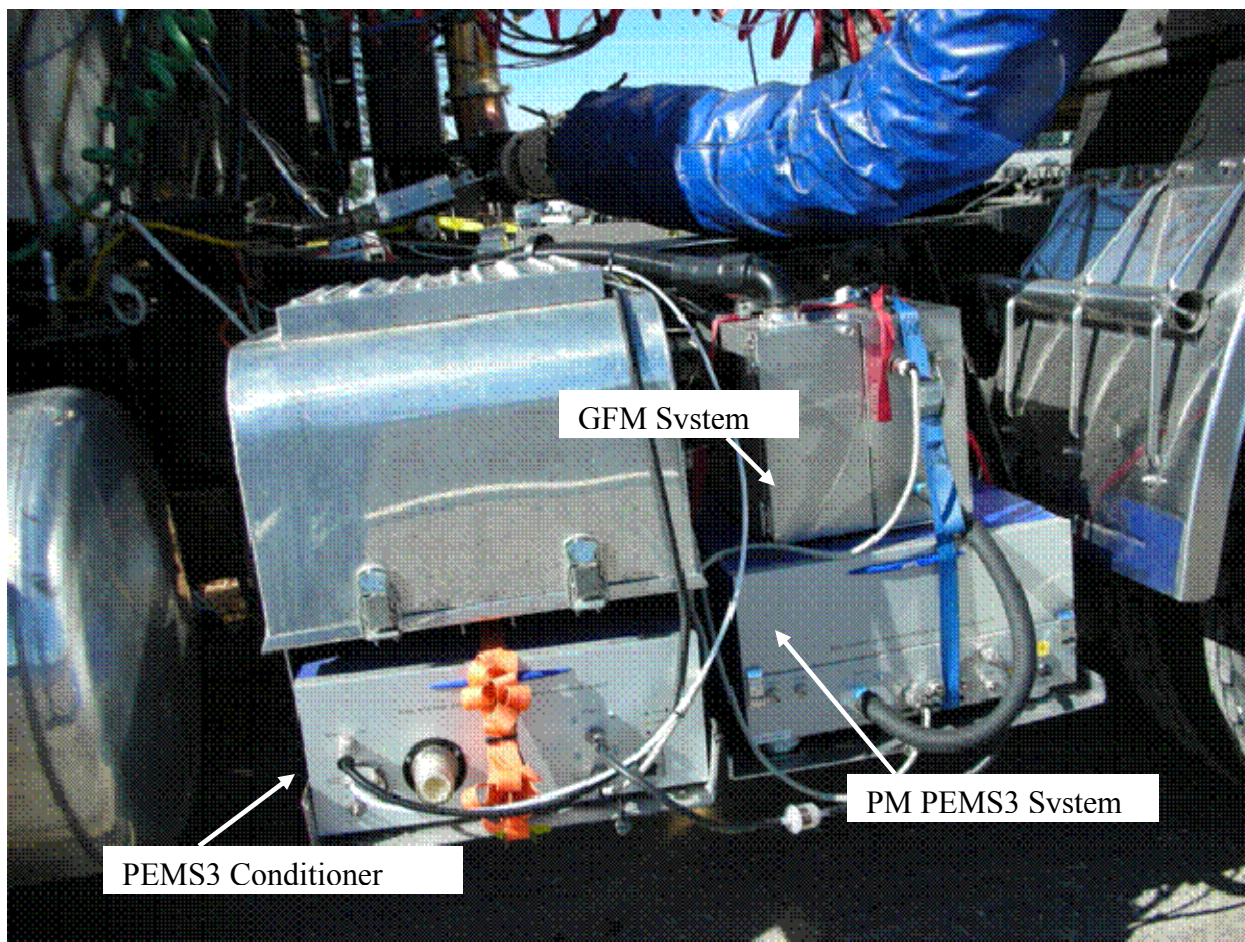
Figure 3-8 PEMS3 installation with GFM system: driver side on frame

3.6.3   INST4 and 5

INST4 and 5 were both installed in the MEL for all test runs and sampled from the MEL CVS. During a previous study, INST5 was sampled from a separate high dilution, secondary dilution tunnel (Durbin et al., 2009a). For this study, INST5 was sampled from the main CVS due to the nominally lower bsPM emissions compared to the previous Caterpillar testing. INST4 was sampled from the primary CVS in this and the previous comparison studies.

3.7   PEMS: Operation

UCR operated all PEMS following the recommended practices as per each manufacturer's manual and recommendations from the MASC meetings. This section is important for the presented results since varying operating parameters has been shown to affect the PM PEMS performance (Durbin et al., 2009 a, b).

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 manufacturer attempted to run in real NTE operation, but the real time NTE operation did not work and is discussed in Section 6.

3.7.1 PEMS2

PEMS2 system has several operational settings that make this PEMS very flexible in its measurement capabilities. These settings are critical for the measurement response as discovered during previous studies (Durbin et al., 2009a, b). This section describes the operation of the PEMS2 system. In general the PEMS2 manual (Sensors, 2009) was followed with some minor adjustments, as recommended by the PEMS2 manufacturer and/or the MASC.

PEMS2 system utilizes several parameters to control the environment and others are used to define the crystal sampling behavior. In both cases these operation parameters are needed in real-time and affect the final result of the PEMS2 system. The environmental controls include, but are not limited to, targeting a minimum dilution ratio of 6, crystal temperatures of 50°C, high voltage fixed output, crystal bypass flows of 4 slpm, and inlet temperature control of 50°C. Some parameters not listed here were also found to be important, such as sample bypass flows. These will be discussed in Section 6.

The PEMS2 crystal stabilization parameters are important for controlling crystal stabilization time and were mostly set according to the manual, except for some changes by the manufacturer (Sensors, 2009). The PEMS2 post sample stabilization delay, short event interval, and post sample time parameters were set at 300 seconds, 10 seconds, and 90 seconds, respectively.

Table 3-4 shows a list of the operation differences compared to what was listed in the PEMS2 manual. These parameters were either changed at the request of the MASC or by the PEMS2 manufacturer after observation of the results from previous units. The QCM was targeting 4 slpm, but varied from 4-5 slpm. The crystal sensitivity was incorrectly set on unit 1 compared to units 2 and 3, as will be discussed in Section 6. The maximum crystal sample time was decreased by the PEMS2 manufacturer from 1800 seconds (units 1 and 2) to 240 seconds for unit 3. The high voltage charger control was set to a fixed voltage, but during the unit 3 testing the setting changed automatically for most of unit's 3 data. The mean total flow also changed from unit to unit as a result of the block orifice settings between units 1 and 2. The difference between units 2 and 3 was a result of a change in orifice diameter where higher total flows were necessary. The results presented in this report reflect this PEMS measurement capabilities with these operational settings.

Table 3-4 PEMS2 operational settings for each unit

Operational Setting and Description	Unit 1	Unit 2	Unit 3
QCM flow (slpm)	4.5	4.5	4.5
Crystal Sensitivity (Hz/ug)	100 [3]	150	150
Maximum crystal sample time (sec)	1800	1800	240
High voltage charger control (volt/current)	Fixed voltage	Fixed voltage	Fixed voltage [1]
Targeted total flow (slpm)	8	8	10^2

[1] During in-use testing the fixed voltage changed unknowingly to fixed current for unit3
[2] Mean total flow was changed by the PEMS2 manufacturer to implement a new sample capillary design
[3] Crystal sensitivity was incorrectly setup in the instrument. Data was corrected to the correct value of 150.

3.7.2 PEMS3

This section describes the operation of the PEMS3 soot system and filter module. PEMS3 was operated following routine standard operating practices for the soot sensor (AVL 2009), but required additional manufacturer support for the gravimetric module. The soot sensor and associated systems were mature where the manuals were sufficient to setup these systems. The GFM manual was not available due to the level of prototype and required manufacturer support.

PEMS3 sampled with a fixed dilution of 6 to 1 for all four units tested. Previous studies with DPF out type emissions have been shown to use dilutions as low as 2 to 1 in order to increase this PEMS sensitivity (Durbin et al 2009b). The pollution window was verified to below 1 prior to all testing. A copy of the routine operating procedures employed for PEMS3 is in appendix D.

The GFM was operated using a series of low level AK commands to startup the warm up process and resetting the filter loading term. These details are described in detail in Appendix D. At the time of this writing, a fully integrated GFM software package was released that solved these low level operation problems.

3.7.3 INST4 and 5

INST4 was operated by UCR following typical operating procedures developed over the years of operation in the MEL. INST4 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 INST4 performance. INST4 was routinely verified during the CVS verification procedures.

INST5 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 INST5 zero was verified. The INST5 zero was not adjusted throughout the course of testing, however. Also, the INST5 flow rate was verified to make proper corrections for actual flow versus nominal flow. Each day the INST5 was cleaned following the manufacturer's procedures and the charger voltage was documented to establish the start up charger voltage.

The INST5 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 INST5 digital signal. UCR does not have the optional digital interface for INST5, 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. The INST5 zero was checked daily and was not adjusted between tests, similar to the operation for INST4.

3.8   MEL Description and Operation

The MEL was operated using settings identical to those used during the correlation at SwRI. The MEL primary tunnel flow rate was set to 2380 standard cubic feet per minute (scfm) and the secondary tunnel was set to provide a secondary dilution of 2.12. The primary dilution tunnel achieved a minimum DR of 2.7 under full load. This combined with the fixed secondary dilution ratio of 2.12 gave a minimum overall PM dilution of 2.12 * 2.7 = 6.0. A more detailed explanation of the MEL is given in Appendix A.

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 of the setup with the PM instruments and the priority given to those instruments. The MEL did not fill or analyze bags for ambient level concentrations, but used typical default concentrations during this program. The default concentrations came from averages from the audits for nominal concentrations found on previous studies for these types of driving routes. The affect of default ambient values may have an effect on the THC and CO results, but not the NO_x and CO_2 results.

In an attempt to synchronize signals between the MEL and multiple PEMS, the MEL provided a five volt signal to each PEMS that simulated a forced NTE event and corresponded to when the MEL was sampling on the gravimetric filters. 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. The lab was controlled through a display screen connected to the MEL, as shown in Figure 3-9.

3.8.1   PM measurement setup

The PM mass collection for the MEL is defined by the filter media (Watman 2 μm pore), sample temperature (47°C), backing screen (ambient backing screens), face velocities (100 cm/s), ambient dilution of 25°C and other conditions (2 second residence time). These settings were identical to those used during the correlation at SwRI.

3.8.2   Targeted filter weight gain

The MEL filter weights were targeted to achieve sufficient loading to prevent accuracy issues, but were limited to prevent overloading the PEMS2 crystal system. Thus, a trade off between accuracy and PEMS2 overloading was considered. Using the setup parameters for the PEMS2

system, a MEL filter weight gain of 100 to 150 µg was designed into this MA PM PEMS test program. Real-time PM accumulation was estimated using INST 4 and 5 to provide the operator a feel for mass loadings. These real-time feedback systems worked well, as can be seen by targeted bsPM and filter weight loadings meeting the desired levels, as shown in Figure 4-3.

The 50th percentile filter weight was within the targeted amounts and ranged from 133 to 147 µg for each of the units tested where Unit1 had the lowest filter weight and Unit2 had the highest and the overall 50th was 141 µg. The overall 5th and 95th were 69 and 205 µg, which suggests the targeted filterer weights were close to the desired values of 100 to 150 µg and that most of the filter weights were below 200 µg and above 50 µg.

Figure 3-9. MEL operators interface system

3.9   Test routes

The PEMS were tested over several different routes during the in-use 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 instrument was tested over the following test routes. The route to Palm Springs was performed the most due to the availability of large highway shoulders so that the truck could easily be pulled over when instrument problems arose.

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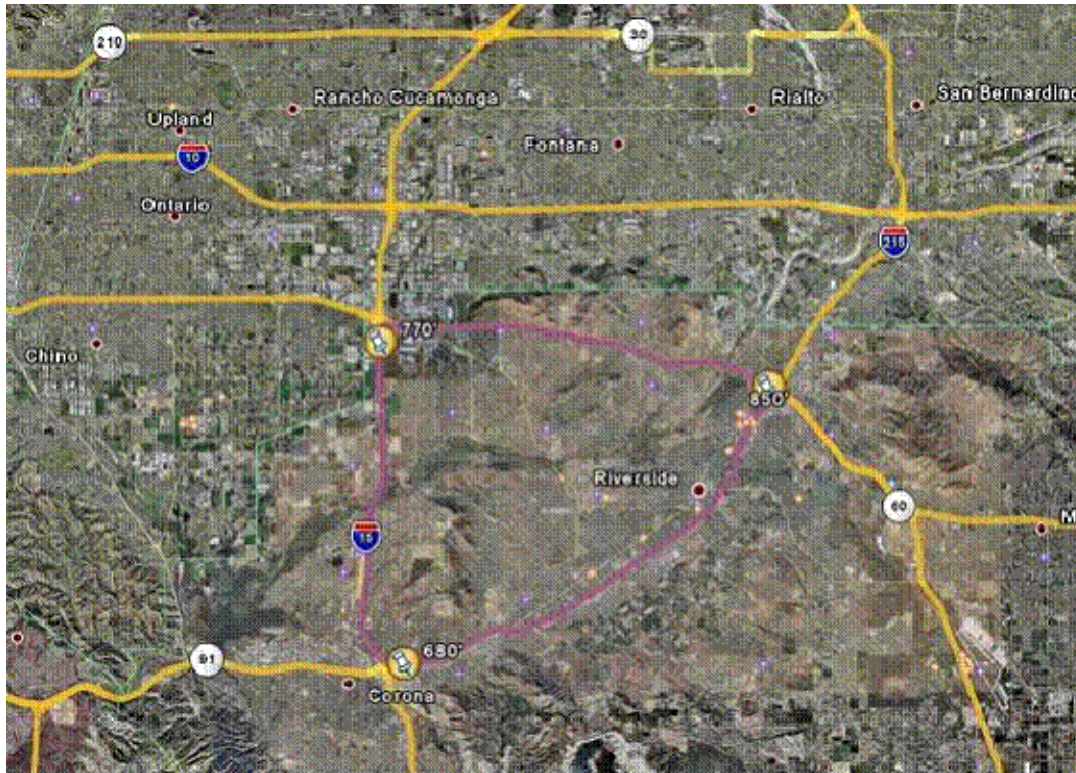
Figure 3-10. Riverside Local Freeway Route.

Route 2 – Riverside to San Diego Round trip
The second route for the in-use testing consisted of driving from Riverside to San Diego and then returning to Riverside. This route utilized Interstate-15 (I-15) and I-5, which are two of California's major freeways. This route is shown in Figure 3-11. Driving on this route is more rural with possible congestion around the San Diego region and around the Riverside area on the return trip. This route also included some power line crossings and potholes which contributed to road vibrations. This route has many elevation changes and uphill grades, which ensured a sufficient amount of operation in the NTE control zone of the engine. The total trip distance is approximately 200 miles.
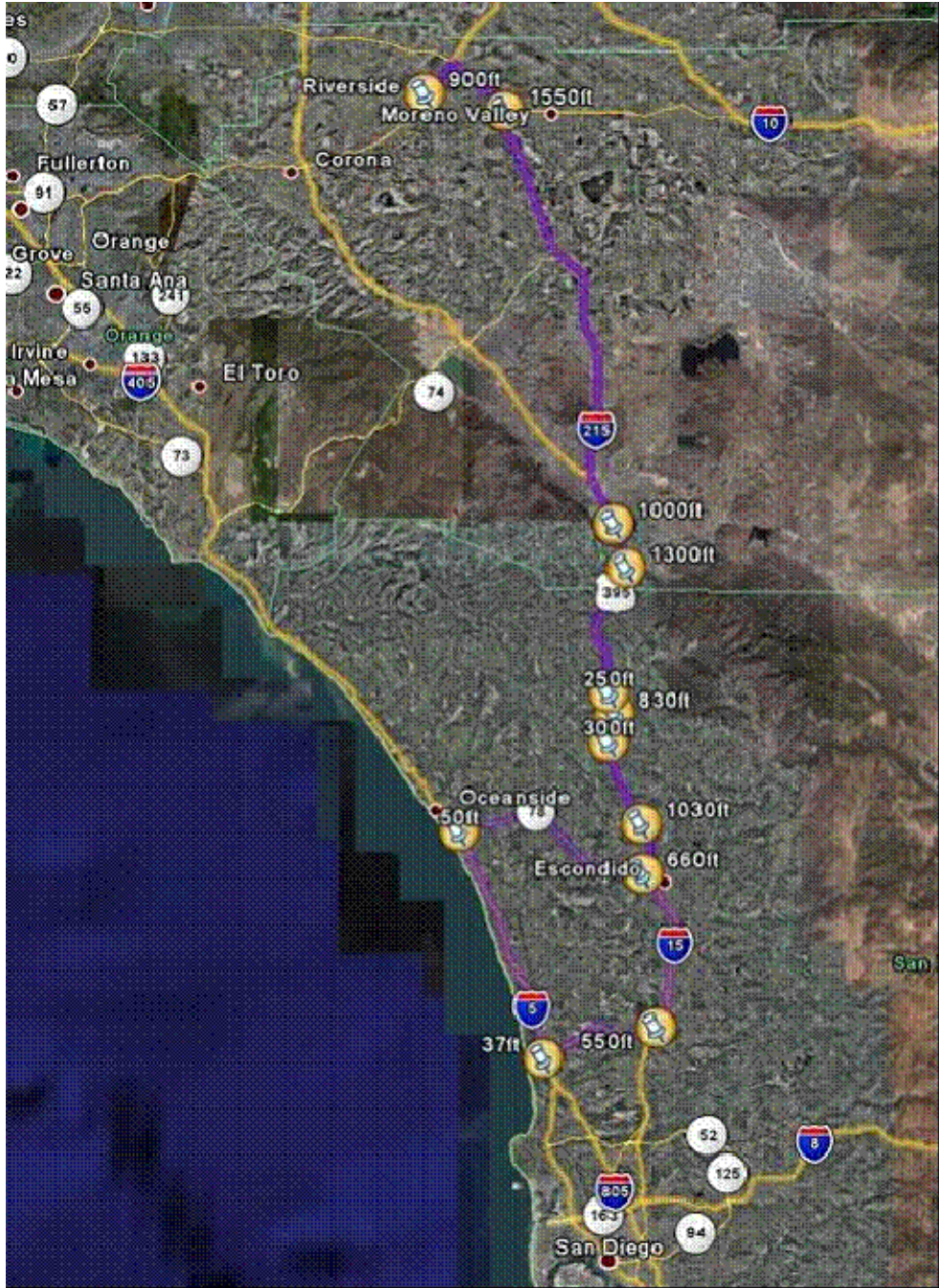
Figure 3-11. Riverside to San Diego Route

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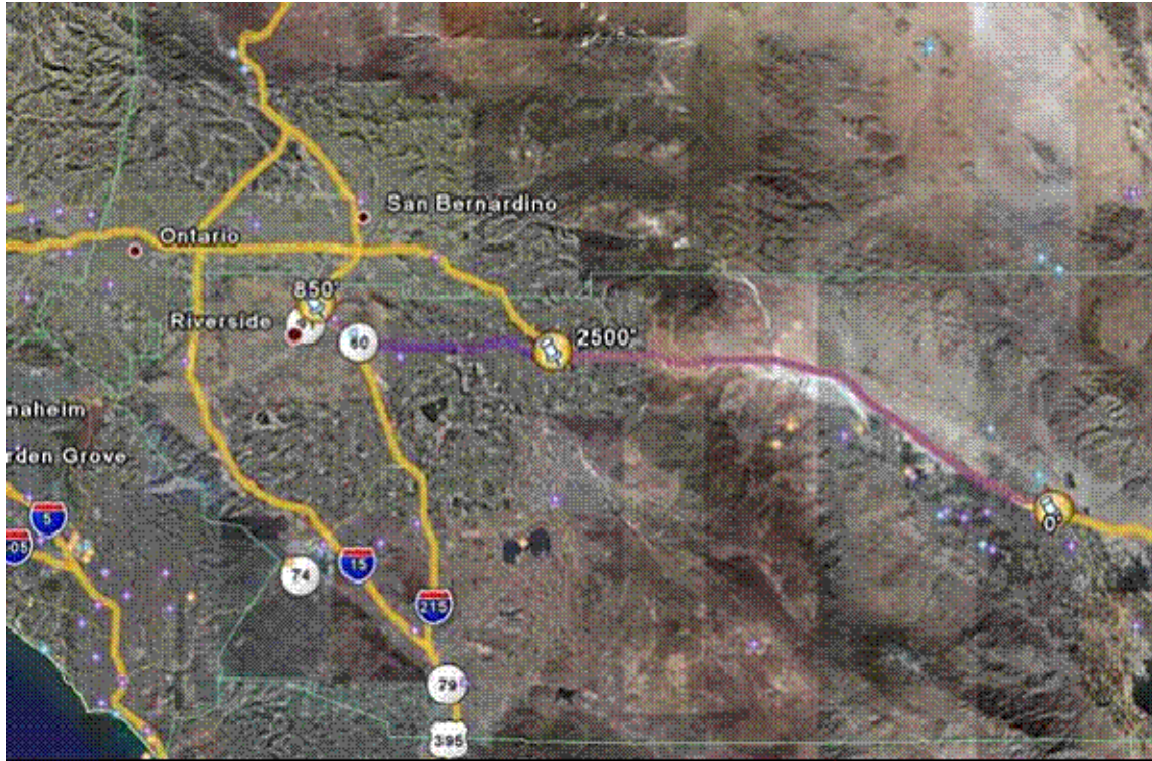
Figure 3-12. Riverside to Palm Springs/Indio, CA Route

Route 4. Riverside toward Baker, CA and over the Baker grade
The final route consisted of driving along I-15 towards Baker and the Las Vegas state line. This route is shown in Figure 3-13. This route is commonly used by vehicles traveling from Southern California to Las Vegas, NV. The Baker grade is also reportedly used by different engine manufacturers for performance testing. The route has many elevation changes, providing a sufficient amount of operation in the NTE control zone of the engine, and reaches an elevation above 5000 feet. The total trip distance is approximately 240 miles.

Figure 3-13. Riverside to Baker/State Line Route.
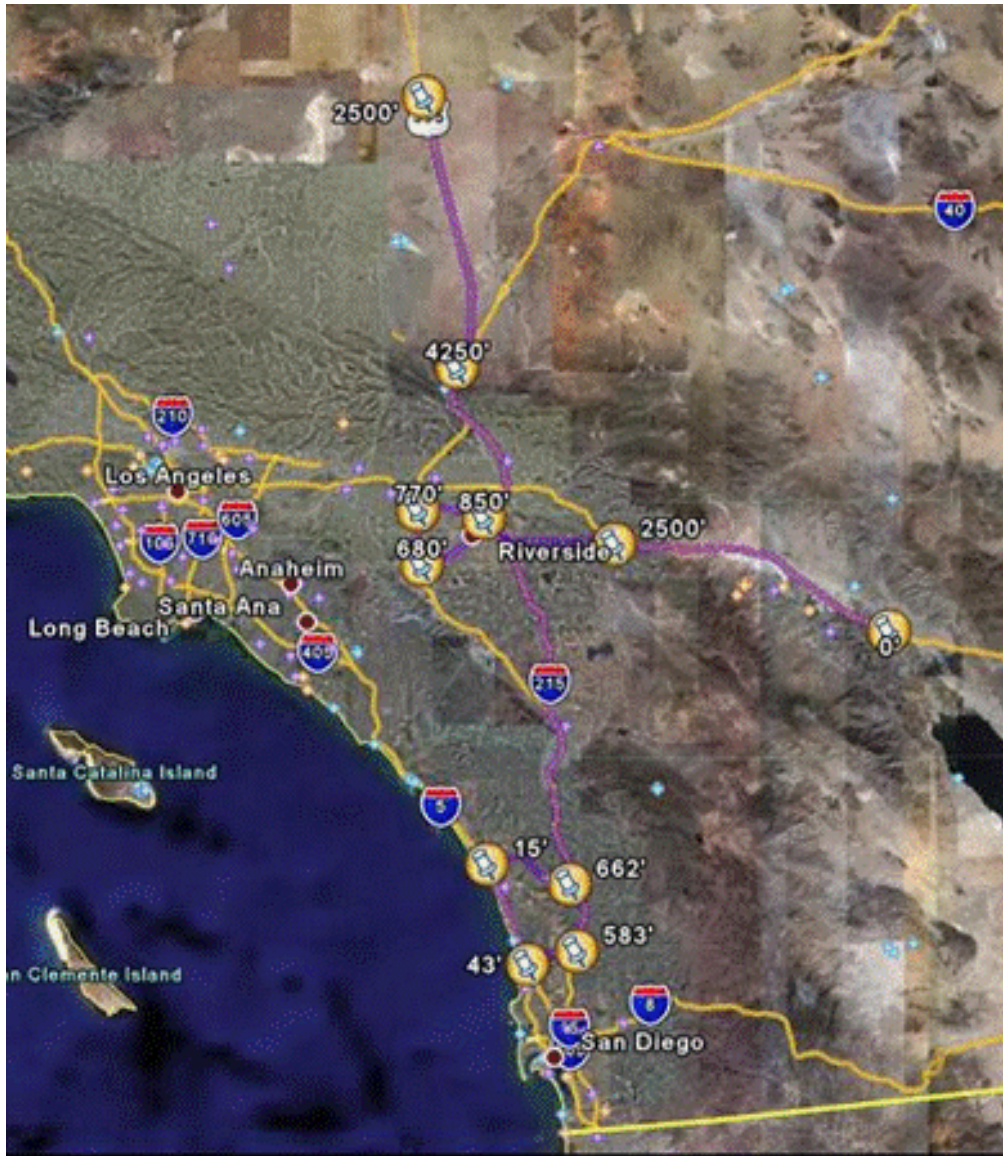
Figure 3-14 Overview of all routes relative to Riverside and LA area.

3.10 Method calculations and analysis

This section describes the three method calculations used for the PM PEMS. These methods are slightly modified from the gaseous methods due to limitations for integrated results of PEMS2. Method1 and 2 were calculated for PEMS2 and 3 and Method3 was calculated for PEMS3. PEMS1 would also be capable of producing Methods 1, 2 and 3 given their real time signal capabilities, as discussed in Khalek et al (2010).

3.10.1 Method 1

Method 1 calculation is straight forward and represents mass of PM emissions divided by work. This equation is presented in its simple form in Equation 1 and with the full formula details in

Khalek et al. (2010). The Method 1 calculation includes uncertainties in exhaust flow, concentration measurements, and work measurements. The other method calculations incorporate terms to try and eliminate exhaust flow uncertainties using broadcast parameters from the engine.

$$Method.1 = \frac{\sum g}{\sum work}$$

Equation 1

3.10.2 Method 2

The Method 2 calculation method is presented here. The second method uses the brake specific fuel consumption to determine the brake specific emission factors. Data analysis with engines outside of the NTE requires additional data processing for Method 2. For the Method 2 calculation there is a summation of the inverse of fuel rate. The fuel rate on some conditions outside the NTE can go to zero causing the calculation to go to infinity. In these situations, it was decided to freeze the bsFC, Equation 3, to a constant value during out-of-NTE operation using the last valid bsFC NTE value. The out-of NTE threshold was determined as 10% of the maximum advertised fuel rate, see Figure 3-15. For the Cummins engine tested the maximum published fuel rate was calculated from Equation 4 to be 28.1 cm^3/sec, giving a threshold of 2.81 cm^3/sec. The data presented for the PEMS2 and 3 Method 2 results are based on this analysis
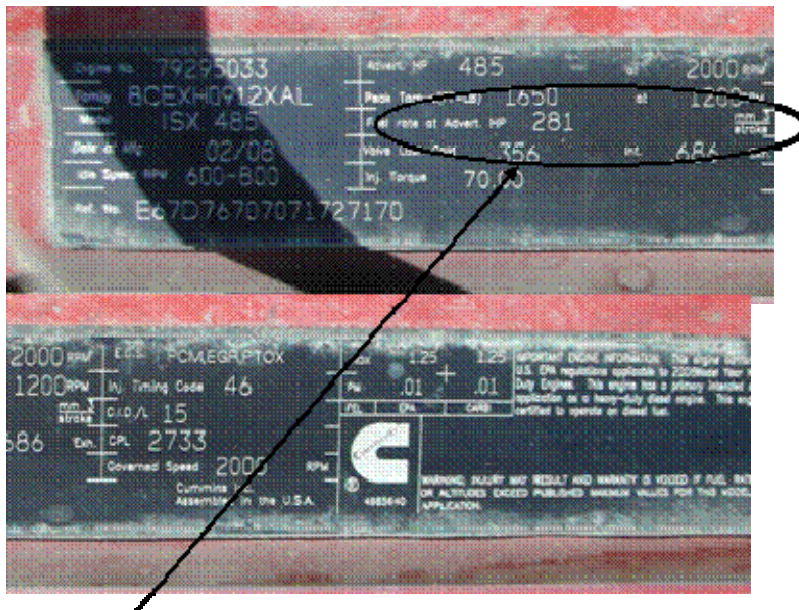
Figure 3-15 Method2 name plate max fuel consumption from engine nameplate

$$Method2 = \frac{\sum g}{\sum \left[\frac{Carbon_{fuel}}{ECM_{fuel}} \times Work \right]}$$

Equation 2

$$\frac{Carbon_{fuel}}{ECM_{fuel}}$$

Equation 3

$$FuelRate_{\max} = \frac{281mm^3}{fuel-stroke} * \frac{6\,fuel-strokes}{2rev} * \frac{2000rev}{1\min} * \frac{1\min}{60\sec} * \frac{1cm^3}{1000mm^3}$$

Equation 4

3.10.3 Method 3

Only PEMS3 was capable of processing with the Method 3 calculation method. The third method uses the mass fuel flow or a fuel specific method to determine the brake specific emission factors. PEMS1 is also capable of producing Method 3 calculations, but PEMS1 was not part of this analysis. Equation 5 shows the simplified calculation formula for Method 3, with the full detailed formula presented in Khalek et al. (2010).

$$Method3 = \frac{\sum\left[g \times \dfrac{ECM_{fuel}}{Carbon_{fuel}}\right]}{\sum Work}$$

Equation 5

3.11 Reference PM Measurement Confidence

This section discusses the ability of the MEL reference method to make filter weight measurements. Due to some light MEL filter loadings, some analysis of the MEL filter weighing uncertainty is necessary to have confidence in the PEMS comparison. During non-regenerations the 5th percentile filter weight was 70 µg and during regenerations it was 16 µg.

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 for a 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 10 minute to 1 hr tunnel blanks.

During this validation exercise, reference and tunnel blank filters were lower than usual, with the tunnel blanks just under 5 µg for 10 minute to 1 hr tunnel blanks. Balance reference filter uncertainties were around 1-3 µg, or a 5 µg uncertainty at a 95% confidence level. Trip, static, and dynamic blanks were also all less than 5 µg. Trip blanks travel with the testing program, but is not inserted into any filter holders. The static blanks get loaded into the filter holder and then are unloaded immediately. Dynamic blanks get loaded and left there for a test run, but are not sampled on. Each blank provides different contamination possibilities and all were found to be within the same uncertainty ranges as the reference filters.

Typically, filter contamination (background, handling, and artifacts) increases mass loading, while loses from evaporation of volatile compounds can lead to lower filter weights. With low (25 μg) regeneration 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.

4   In-Use Testing – PM Experimental Results

In this section the experimental results are presented for the MA validation testing program. All the results presented are from in-use testing with UCR's MEL simultaneously measuring with all the PM PEMS and other real time PM instruments. This section covers only the PM emissions, with some gaseous results are provided in the next section.

There were several unique requirements for performing in-use validation PM measurements that were not applicable for the gaseous in-use validation testing program. These included meeting desired filter loading, maintaining NTE conditions while meeting time constraints and bypassing the aftertreatment system to target a bsPM emission level near the in-use standard of 0.03 (1st year) and 0.02 g/hp-h (2nd year). As such, subsections were included to the PM results section to specifically address the ability of UCR to meet the above requirements.

Several sections are included here to provide context for the results. There is a section that describes the forced events, data removal, event statistics, and the results on a unit by unit basis and combined basis. The forced events discuss how the NTE type behavior was characterized. The data removal discusses the problems and what data was removed due to what problems. The event statistics show the ability of UCR to meet the program objectives. The results are then based on only valid data as collected by each PEMS.

Characterization of the PM composition and size distribution for both non-regenerations and regenerations is also included to provide context for measurement differences. The composition analysis includes elemental and organic carbon (EC and OC) composition analysis using UCR's in-house EC/CO system, see Appendix E. Sulfate analysis was performed using ion chromatography. Particle size distribution is presented from UCR's in-house particle counter CPC 3776 and UCR's fSMPS as described in Appendix F – Size Distribution and Particle Count Measurement.

4.1   Sample event description

In this section the definition of the events used for the in-use comparison is described. One of the primary goals of the MA program was to perform in-use NTE comparisons between the MEL and the different PM PEMS simultaneously. The beginning of an NTE event is predictable, but the length or end of the event is not predictable. Several factors can cause an event to end suddenly, such as traffic and road surfaces. This required some trade offs between filter loading and true in-use NTE operation.

The length of the event needs to be controlled in order to achieve the targeted mass loading for the reference and PEMS2 systems. The reference requires time to deposit particles on a Teflon filter and PEMS2 requires time to deposit particles on a crystalline surface. Both systems acquire integrated batched samples where the length of time and sample concentrations determine the PM mass loading, see Section 3.8 for more details. The MEL targeted filter weight gain was determined to be 100 to 150 µg as described in Section 3.8. It takes a specific amount of time to achieve these filter loadings, thus the event duration needed to be controlled. If the duration of

the events is controlled, the characteristics of the NTE events also need to be controlled. Thus, the comparison events used in this report are events that were controlled events and are referred to as "forced" events for this report.

Forced events

The goal behind the forced events used in this program was to be as close as possible to true NTE events. UCR used an approach that allowed the forced event to start at the beginning of an NTE (naturally), but the length of the event (forced) was controlled. Since the event length was controlled, the forced events could have transitions in and out of an NTE within the forced event. During the gaseous MA program, the average in-use NTE's events were about 65 seconds (Miller et al., 2007). The NTEs performed in this study were slightly longer and had 5th, 50th and 95th percentile sampling times of 85, 179 and 360 seconds, respectively, as shown in Figure 4-4 in a later section. The longer sampling times in this study compared to the previous MA study was related to the targeted MEL filter loadings.

These forced events are based on manually triggered signals to all the PEMS and reference system to synchronize the events, as described in detail in Section 3.8. A control signal from the MEL was used to force the PEMS to keep sampling until the MEL filter was at the targeted filter loading. The beginning of the NTE was also manually controlled, but was performed by watching the real-time PEMS2 NTE indicators and observations within the vehicle. Each event was triggered by these observations and became a natural process and was easy to implement. This method of operation allowed measurement issues associated with the beginning of real NTE's to be captured, while preventing issues with low MEL filter loadings. An interesting consequence of the NTE start time triggering, was the discovery of a negative bias between the PEMS and the MEL, as will be discussed later in Section 4.9.1.

Real NTE operation

In order to stress the PEMS capability to handle short NTE operation, the PEMS systems were allowed to trigger naturally for periods of time randomly throughout the testing program. When it was time to record a "forced" event, UCR would put the PEMS back into forced event mode and start the next test. The real NTE operation only affects PEMS2 because PEMS3 is a real-time signal and is not affected by operational modes. The PEMS3 optional gravimetric filter module samples during NTE and non-NTE operation, and thus is also not affected by the event specifics. For PEMS2, there is an additional source of error in capturing real-time NTE where multiple crystal loadings are needed. This issue caused a negative bias between the PEMS2 and the MEL. The details behind the PEMS2 bias will be discussed in more detail in the PM results Section 4.4.1.1 and Section 6.1.1 below.

Example of forced events

Figure 4-1 shows a typical PM concentration real time plot with four forced events. The figure show that the average PM concentration is low during steady state operation and increases significantly during transient behavior. A significant fraction of the PM is accumulated in the first few seconds of the event and can be up to 50% of the event mass depending on sample duration. This figure is typical for non-regeneration type behavior and represents the majority of the data presented in this report. There were some operating modes with the bypass system that produced significantly higher steady state emissions at about five times what is shown in this

figure that resulted from engine RPM, engine load, DPF back pressure and other conditions that varied between regeneration events.
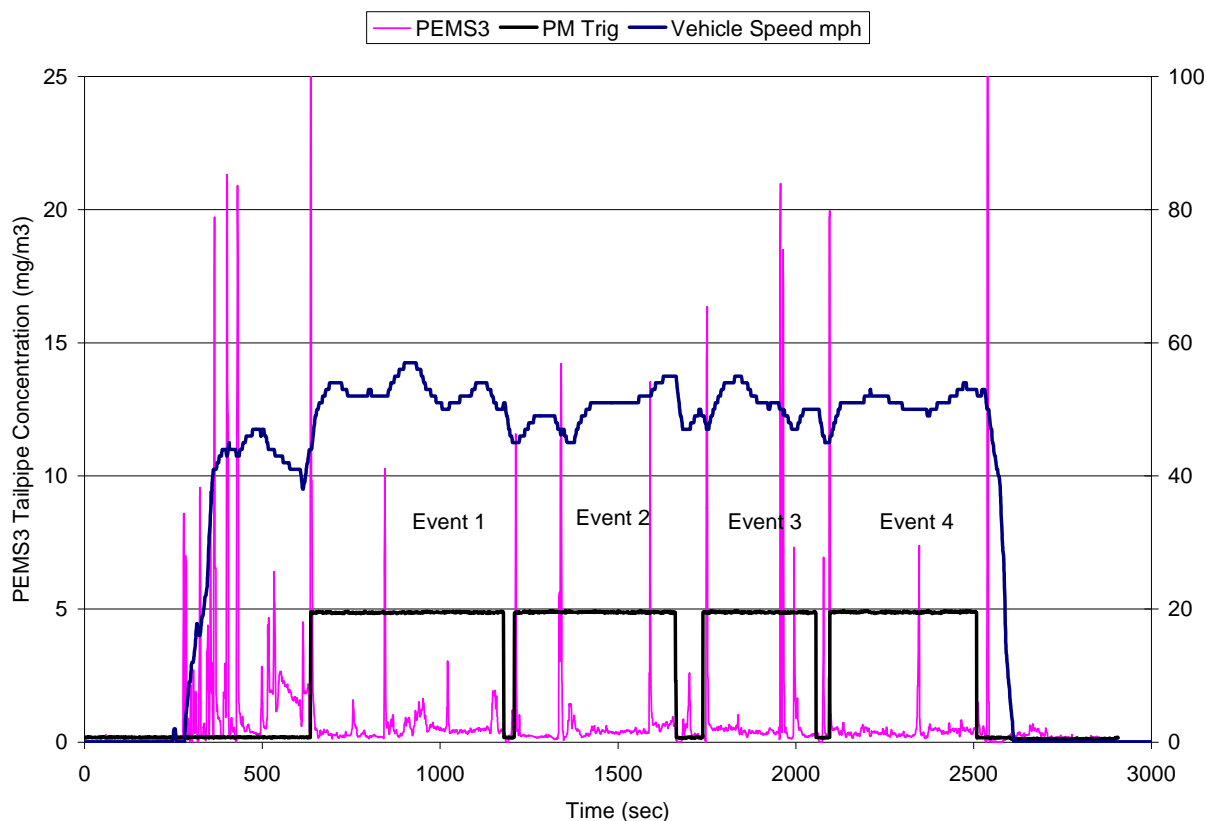
Figure 4-1 Real time PM concentration sec by sec example of four typical forced events

In general, the targeted bsPM emissions were still achieved with all the variables of in-use testing. The 5th 50th and 95th percentiles for combined sampled unites were 11, 24, and 43 mg/hp-h, respectively, as shown in Figure 4-6.

4.2 Data reduction and yield

The results presented in this report are based on a subset of the actual data sampled. During the gaseous program, data exclusion was minimal and typically not a serious issue. During this program and a previous "pre-measurement allowance" pilot program, significantly lower data yield were found, and thus this topic is addressed here to provide context to the PM PEMS results.

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 is continuing on an ongoing basis. Nevertheless, all PEMS were considered to be commercially available at the time of testing. PEMS2 and 3 both have commissioned many versions commercially and being used in-use, where PEMS3 is more mature than PEMS2. PEMS3 recently released their GFM which was not

commercially available at the time of this research and thus represents a prototype design. This should be taken into account for PEMS3 when considering data yield and reliability.

There were several issues that caused large fractions of the data to be invalidated for both PEMS systems. The details of these issues are presented in Section 6 on Lessons Learned and Issues. The issues included those related to environmental conditions, instrument operation, and data processing. Table 4-1 shows a breakdown of the non-regeneration forced events sampled and the percentage of events for which bsPM data were submitted to SwRI for validation by PEMS. Data available (shown in column 2) is data that the MEL measured and was deemed good. The PEMS data is the data that the PEMS measured that was submitted to SwRI for validation.

Table 4-1. PEMS data summary of forced events for all units tested.

Unit #	Non Regen Events [a]	PEMS 2 [b] Ver1	PEMS2 [c] Ver2	PEMS 3 + GFM [d]	PEMS 2 Final Yield	PEMS 3 [d] Final Yield
1	97	58	51	15	53%	15%
2	153	89	76	134	50%	88%
3	97	90	84	95	87%	98%
Totals	347	237	211	143	61%	70%

[a] Non regeneration good MEL events are only included in this column
[b] Original data submitted using post processor version 3.10 build 10
[c] Officially final data set filtered and reduced using best available version of post processor versions 3.40 build 25
[d] PEMS 3 Unit#1 was not given time for diagnosis and repairs due to guides of the MA program and as such data yield was very low. The MA committee agreed to allow PEMS 3 manufacturer to submit Unit #4 self sponsored data which had a yield of 91% and a total of 42 submitted data points. Excluding Unit#1 PEMS3 yield is > 90% for Units#2, 3, and 4.

PEMS2
PEMS2 utilized two version of the post processer that are considered separately here and in the table. The original PEMS2 case is data processed with the same post processor version (3.10 build 10) used during SwRI model development. The PEMS2 Ver2 case used the best available post processor version (3.40 build 25) at the time of this report, see Section 6 for more details. The final PEMS2 data yield averaged close to 50% for Units 1 and 2 and up to 87% for unit #3 with an overall yield of 61%. The PEMS2 yield may have been higher for Unit1 if some of the configuration issues were caught prior to testing, such as crystal mass sensitivity. Crystal mass sensitivity has the affect of masking issues that could not be caught by the post processor flagging system. Based on some preliminary analysis, described in Section 6.3.1, an additional 4 data points could have been included for the unit 1/version 1 testing, thus potentially increasing the yield from 53% to 58%.

It is also important to consider that this program was high profile program where these types of incorrect setups should not have happened. Thus, it is possible similar configuration settings may be incorrect for other users who may not be familiar with how and what configurations need to be configured. UCR also had the advantage of knowing the PM level from several different measurement systems so that made these issues could more readily be identified in this study. This additional information would not be available for the typical user. Although there were also configuration setting that were incorrect for Unit 2 and 3, see Section 6.1.1, these setting should not affect the data yield. The PEMS2 operator manually made changes to maximize the data

yield for things like frozen crystals, band QCM flows, loss of EFM measurements as will be described in detail in Section 6.1.1. Similar optimization of data yield was also done for testing at SwRI, as discussed in their final report (Khalek et al., 2010). In general, the data yield would likely be lower if the PEMS was operated by untrained operators, who would just be following simple manufacturer recommendations via the operating manuals.

PEMS3
PEMS3 yield was low for Unit 1, and much higher for Unit 2, 3, and 4, where the data yield went from 15% to 88%, 98%, and 91%, respectively. The main issue with data yields for Unit1 was not due to the PEMS3 MSS system, but rather the optional GFM system. The GFM system was the manufacturer's first prototype and was first field tested during the validation at UCR. The reason for the lack of testing was a result of its recent conception and lack of time to evaluate before shipping to UCR. A more detailed description of the PEMS3 and GFM issues is included in Section 6.1.2, but in general the issues were software bugs, leaks, pinched tubes, bad electrical connections and other issues caused by in-use testing. The PEMS3 data yield was much higher for the next three units (same GFM) as a result of the lessons learned on Unit1.

PEMS3 was also operated under the agreement that PEMS3 was only an alternate candidate PEMS and not the primary PEMS. The consequence of this was UCR focused on the PEMS2 issues and not on PEMS3 issues. For example, if PEMS3 was not ready UCR would continue with out repairs to PEMS3. The only time PEMS3 repairs or trouble shooting was performed was when PEMS2 was down, being calibrated, adjusted or there was some other program delay. In this light, PEMS3 unit 4 data was accepted into the results of this MA testing program. Also, this suggests PEMS3 data yield may have been higher if more time was allocated for its repairs and start up trouble shooting.

Additional Unit
The PEMS3 manufacturer also sponsored additional testing using a 4th SN Unit4 system with the same GFM conditioning system. This unit called "Unit4" met all the requirements of the MA program and was tested over the same routes and with the same bypass settings and targeted emission levels. Given the PEMS2 issues with exhaust flow system, see barometric pressure in Section 6.1.1.3, UCR and the manufacturer agreed to run PEMS3 Unit4 with the external flow system. The Unit4 data yield was similar to Unit2 and 3 at 91% suggesting the low data yield for Unit1 may be an isolated experience. The average data yield for Units 2, 3, and 4 was greater than 90%.

In summary, PEMS3 data yield was on average greater than 90% and the PEMS2 data yield was around 61%.

PM results and analysis
The data presented in the following analysis is primarily based on the final data sets submitted to SwRI for validation. For PEMS2 this is the "Ver2 case" data set and for PEMS3 this is the data based on the MSS signal only, not the GFM adjusted data. Some discussion will be made to other data sets to show the impact of their contributions, but the focus is on the final validated data sets. This includes data for Units 1, 2 and 3 for PEMS2 and for Units 1, 2, 3, and 4 for PEMS3.

The analysis provided was based on UCR operating the PEMS and UCR processing the data with supplied post processors. PEMS2 data was filtered using version 3.40 build 25 and processed using version 3.10 build 10. The PEMS3 post processor performed all three method calculations, but both of PEMS2 post processors versions did not offer the Method2 calculation, thus, UCR performed calculations for Method 2 for PEMS2.

4.3   MEL event statistics

This section looks at the data statistics as a whole for the non-regeneration events for all units combined and individually to see where the 5th, 50th and 95th percentiles lie for average power, sample time, filter weight, tailpipe concentration, and brake specific PM emissions. This section gives the reader a feel for the distribution of work, sample times, filter weights, tailpipe PM concentrations, and bsPM 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, sample times, and PM emission levels.

The event statistics are based on the MEL data sampled and not on valid PEMS2 or 3 data. Because the PEMS yield was not 100%, the comparison is not directly related, but it gives the reader a feel for the range of variability in the PEMS testing.

4.3.1   Event horsepower

The NTE work zone is an integral part of in-use compliance testing and is the basis of the "forced" events 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 events where the work momentarily drops out of the NTE zone, making it not a "true" NTE event. UCR operated the PM PEMS in conditions that was predominantly NTE and avoided conditions that would not be representative of NTE behavior. The 5th, 50th and 95th percentile average event power was 138, 295, and 468 Hp, respectively, see Figure 4-2 Section 4.3.1. The high average power levels support the fact that the events reported are representative of NTE type operation and are thus reasonable for the validation experiment presented in this report.

Figure 4-2 shows the distribution of average power for all units combined and individually. These figures show that the average power on Unit1 was slightly less than units 2 and 3, where the 50th percentile power increased from 253 to 298 and 333 hp, respectively. All the units combined and individually show reasonable distributions. The possible reason for the change in 50th percentile average hp from Unit 1 to Unit 2 and 3 may come from repeating different routes as a result of PEMS failures and needing retests. Each route was deigned to be operated one time, but to get the data collection count up to 75 events, as many as 150 events would be needed at 50% data yield.

Overall, the combined effort showed that the majority of the average power was above the engines NTE calculated hp thresholds of 154 hp. 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 representative of 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.
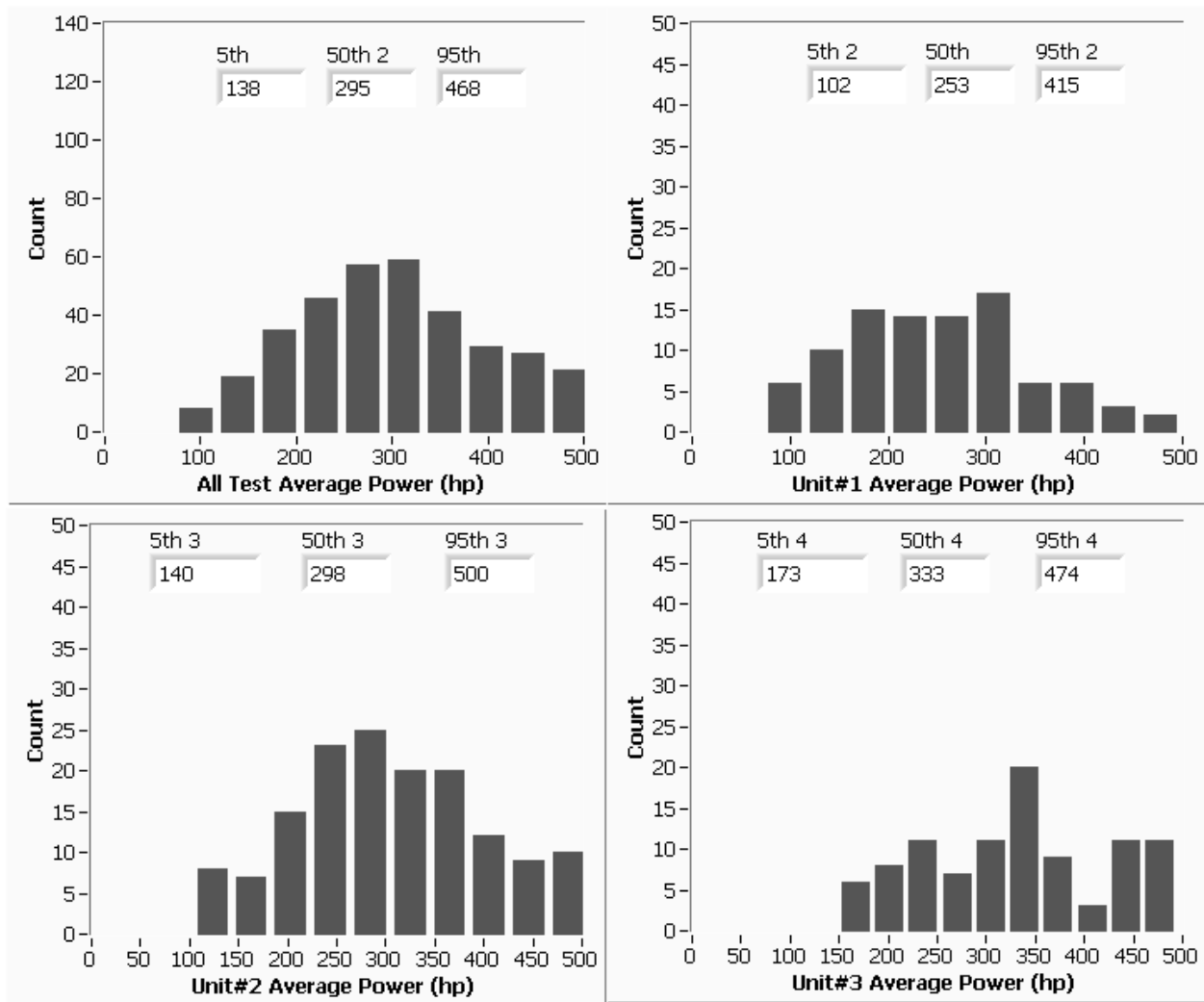
Figure 4-2 Histogram of event average power for all valid MEL events

4.3.2 Event filter loading

It is important to understand the gravimetric filter mass and sample times to provide a perspective for interpreting the PM emissions comparisons. The UCR MEL was upgraded for the MA program to provide filter sample flow rates with face velocities of ~95 cc/sec (at 47°C and 740 mmHg absolute pressure for Riverside), as described in Section 3.8. Given that the MEL reference is at the maximum flow rate, the minimum dilution ratio, and the targeted bsPM emissions, there are no other metrics for reducing sample times without changing one of these

parameters. This section shows the statistics relating to the PM measurements targets during the in-use testing campaign.

The filter masses were targeted to be between 100 and 150 µg during the forced events for PEMS2 and the MEL integrating systems. 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 units individually. The 50th percentile filter weight was within the targeted amounts and ranged from 133 to 147 for each of the units tested where Unit1 had the lowest filter weight and Unit2 had the highest and the overall 50th percentile was 141 µg. The overall 5th and 95th percentiles were 69 and 205 µg which suggests the targeted filterer weights were close to the desired values of 100 to 150 µg and that most of the filter weights were below 200 µg and above 50 µg.
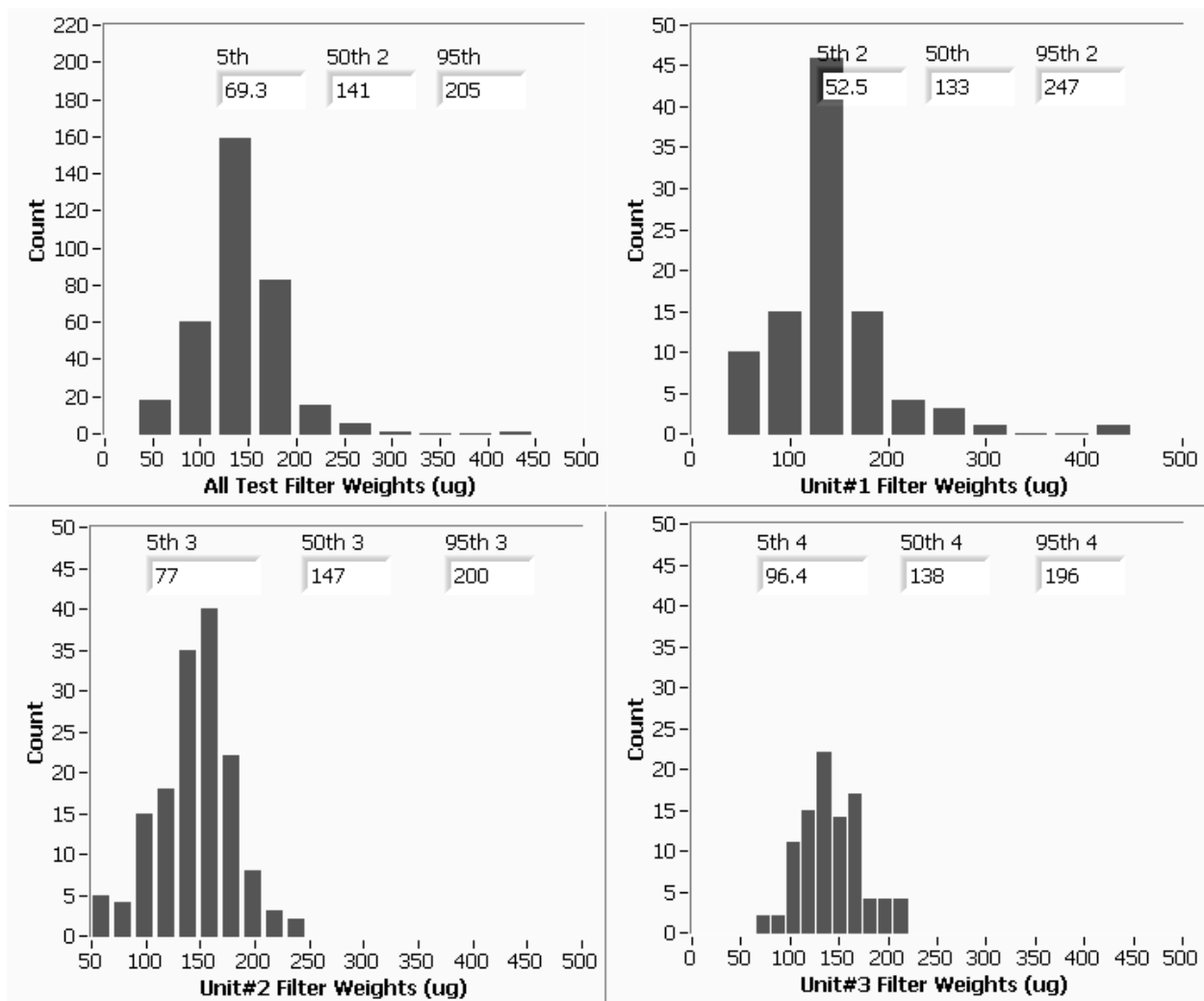
Figure 4-3. Histogram of event filter weights for all valid MEL events

Figure 4-3 also shows that the 5th percentile weights increased and the 95th percentile decreased from Unit 1 to Unit 3. One reason for the increase in the 5th percentile filter weights was a desire to increase the concentrations and reduce sample times in order to more closely represent in-use,

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on-road NTE behavior. It is expected that shorter sample times exist for real NTE behavior, as reported during our gaseous MA validation study (Johnson et al 2009). Also, there was a desire to increase the bypass from Unit1 to Unit2 and 3 because the bsPM emissions were slightly low for Unit1, as will be described in Section 4.3.5. A reason for the decrease in the 95th percentile was an improvement in predicting the filter loading and minimizing filter loadings over 150 μg from Unit 1 to Unit 3.

4.3.3 Event sample times

Sample duration is typically not an issue for a measurement system, but the PEMS2 measurement principle could produce different results based on sample durations. The sample durations are added here to give the reader a feel for the variability and the differences between units tested. Figure 4-4 shows the sample time for all the data pooled together and for each unit individually. The 50th percentile sample time for Unit1 is longer than for Units 2 and 3 at 164, 163 and 150 seconds, respectively. The slightly shorter sample times for Units 2 and 3 are a result of increasing the concentration of the bypass system slightly, as discussed earlier. It is also interesting to note that overall distributions tend to be normal with some skewed trends to high sample durations. Most of the long sample times were during Unit 1 testing, where concentrations were less and sample durations needed to be longer to get the desired filter loadings. The Unit 2 and 3 sample durations were more controlled, as can be seen by the much lower 95th percentile dropping from 470 seconds for Unit1 to 300 and 260 seconds for Unit 2 and 3.
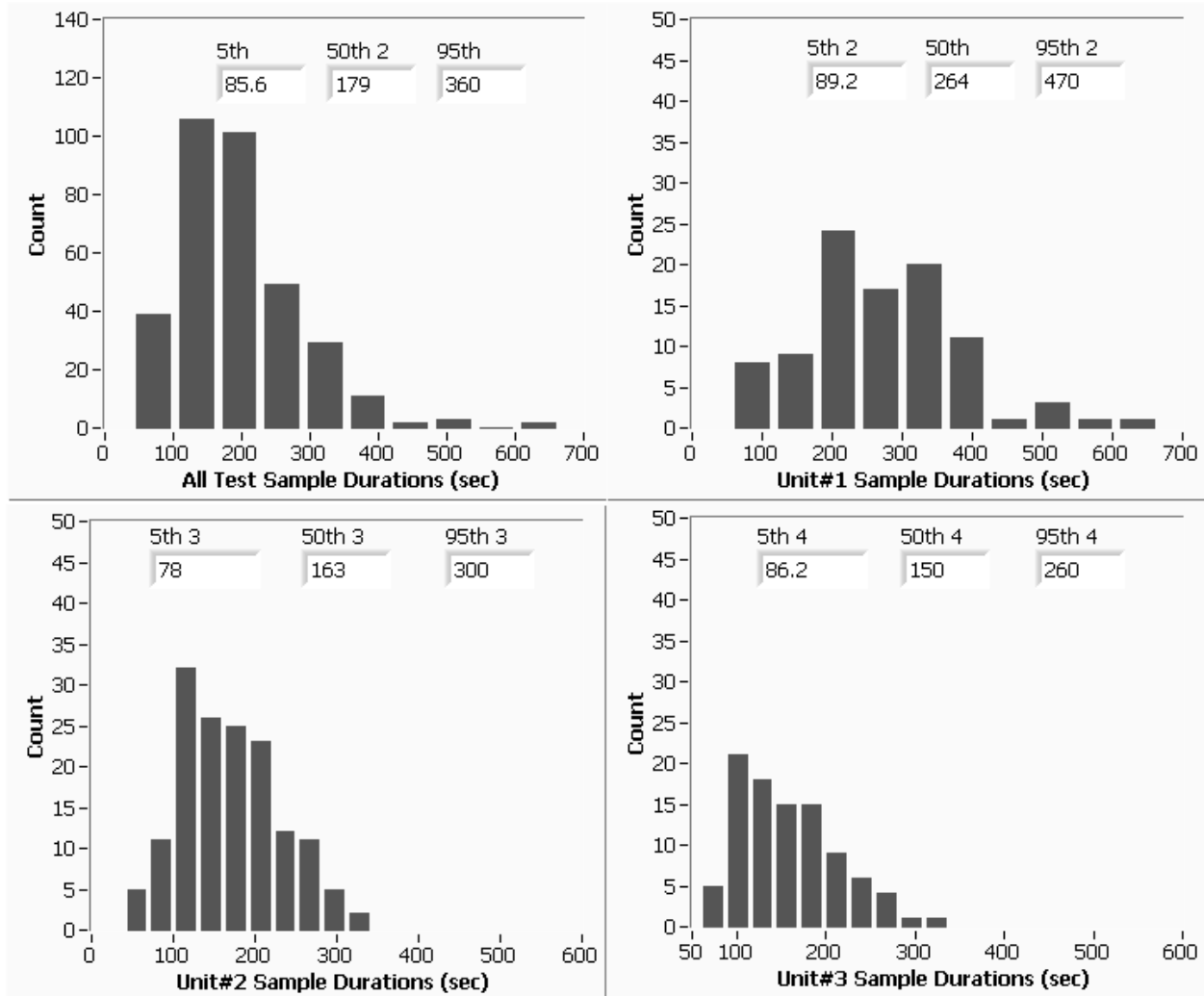
Figure 4-4 Histogram of event sample time for all valid MEL events

4.3.4 Event PM tailpipe concentrations

The distribution of PM tailpipe concentrations is shown by the histograms in Figure 4-5, where the results are pooled together are in the top left figure and the other histograms show the results for the three units individually. The overall 5th 50th and 95th percentile PM concentrations were 65, 130 and 230 μg/mol. The concentrations increased from Unit1 to Unit2 and 3 as expected based on the desire to reduce sample time and increase bsPM emissions. Unit1 had the most skewed distribution of light concentrations with a relatively flat tail of concentrations up to 250 μg/mol and no concentrations over 300 μg. Units 2 and 3 were also skewed to lower concentrations with tails up to 350 μg/mol. These unique concentration distributions may contribute to differences in bsPM emissions between units for each PEMS

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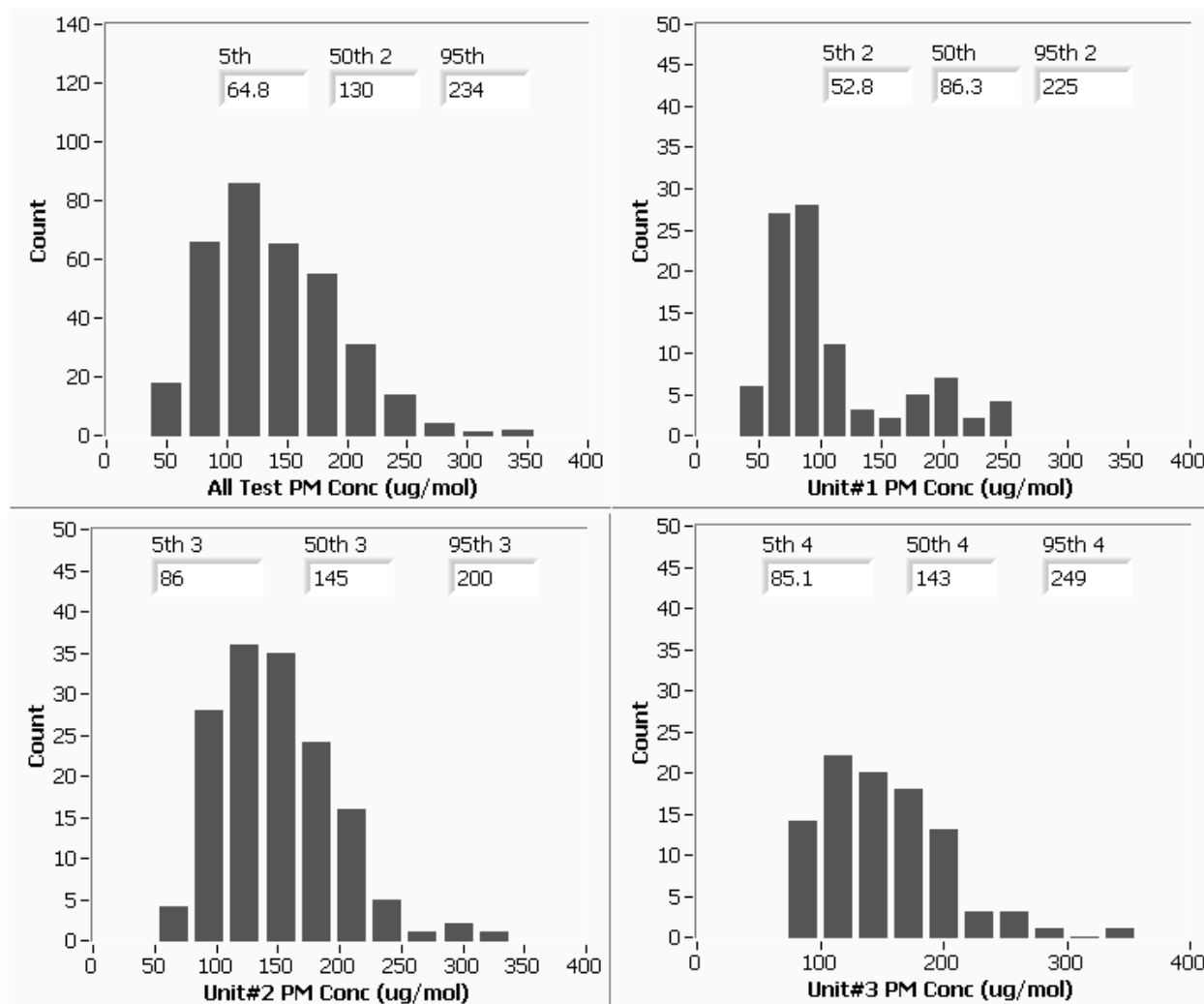
Figure 4-5 Histogram of gravimetric tailpipe concentrations for all valid MEL events

4.3.5 Event brake specific PM (bsPM) emissions

One of the primary objectives for the MA validation program was to target a bsPM around 25 mg/hp-h. The model development threshold was 20 mg/hp-h (Khalek et al 2010) where steady state and transient emission tests also targeted a bsPM emissions level of 25 mg/hp-h. The reason for these targets was to develop the PEMS measurement allowance at a level slightly below, but close to, the in-use PM standard of 30 mg/hp-h. The range of valid bsPM emissions was also limited from 10 to 60 mg/hp-h. Emissions outside these ranges were not considered as part of the validation data sets. The goal of this measurement campaign was to target a bsPM emissions of 25 mg/hp-h and control the bsPM emissions in the range of 10 to 60 mg/hp-h.

The distribution of bsPM emissions is shown by the histograms in Figure 4-6, where the results are pooled together are in the top left figure and the other histograms show the results for the three units individually. The overall 5th 50th and 95th percentile bsPM emissions were 11, 24 and 43 mg/hp-h. The bsPM emissions increased from Unit1 to Unit2 and 3 as expected based on desires to reduce sample time and increase bsPM emissions. Unit1 had the most skewed

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distribution of light bsPM emissions with a relatively flat tail of concentrations up to 60 mg/hp-h and no measurements over 60 mg/hp-h. Units 2 and 3 showed less low level bsPM skewing as seen in the figures. Overall, the bsPM level provided reasonable comparisons from 10 to 60 mg/hp-h with a target of 25 mg/hp-h.

There were a few points below 10 mg/hp-h that were sampled. These were below the minimum target and thus not part of the validation data submission to SwRI. These points are added to the correlation results presented later to discuss measurement differences at DPF-out conditions. It was discovered during these low mass measurements that passive regenerations may be contributing to some of the PM mass that were not detected on the DPF bypass results.
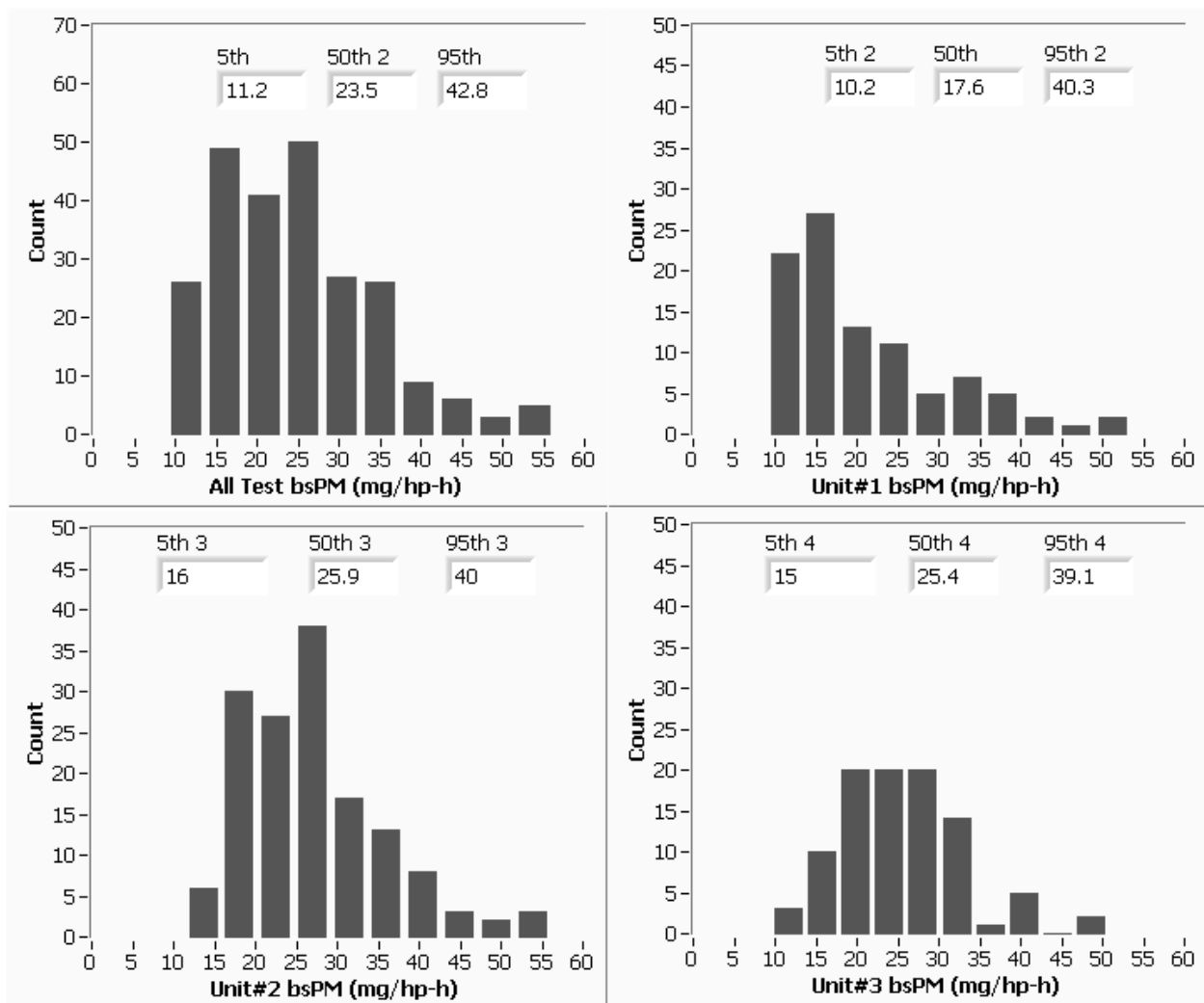
Figure 4-6 bsPM Histograms for all non-regeneration events

4.3.6   Regeneration event summary

The regenerations performed for this study were based on regenerations with the bypass removed (i.e., capped the bypass) as presented earlier. The goal was to perform about 10% of the data during regeneration conditions. Each day the DPF reached the soot loading necessary for

regenerations, thus the regenerations performed were fairly representative of in-use testing. The main difference is UCR had control over when they occurred. UCR performed daily parked regenerations to prevent overloading the DPF system.

Figure 4-7 shows the summary statistics for sample duration, gravimetric filter loading, bsPM and PM concentrations for all the regeneration events with the bypass capped. The sample duration was much longer for the regeneration tests and showed longer 5th, 50th and 95th percentile sample times of 195, 338 and 962 seconds, which is about 2-3 times longer compared to the non-regeneration case. Longer sample times could have an effect on the PEMS2 crystal weight gain, as was discussed during many of the HDIUT SC meetings.

The regeneration 50th percentile bsPM emissions were lower than the non-regen emissions at 9 mg/hp-h compared to 24 mg/hp-h and 52 µg/mol versus 175 µg/mol. The lower bsPM and PM concentration are expected for DPF regeneration PM. The 50th percentile bsPM was very close to the certification standard at 9.1 mg/hp-h and the 95th percentile was well over the standard at 29.2 mg/hp-h.
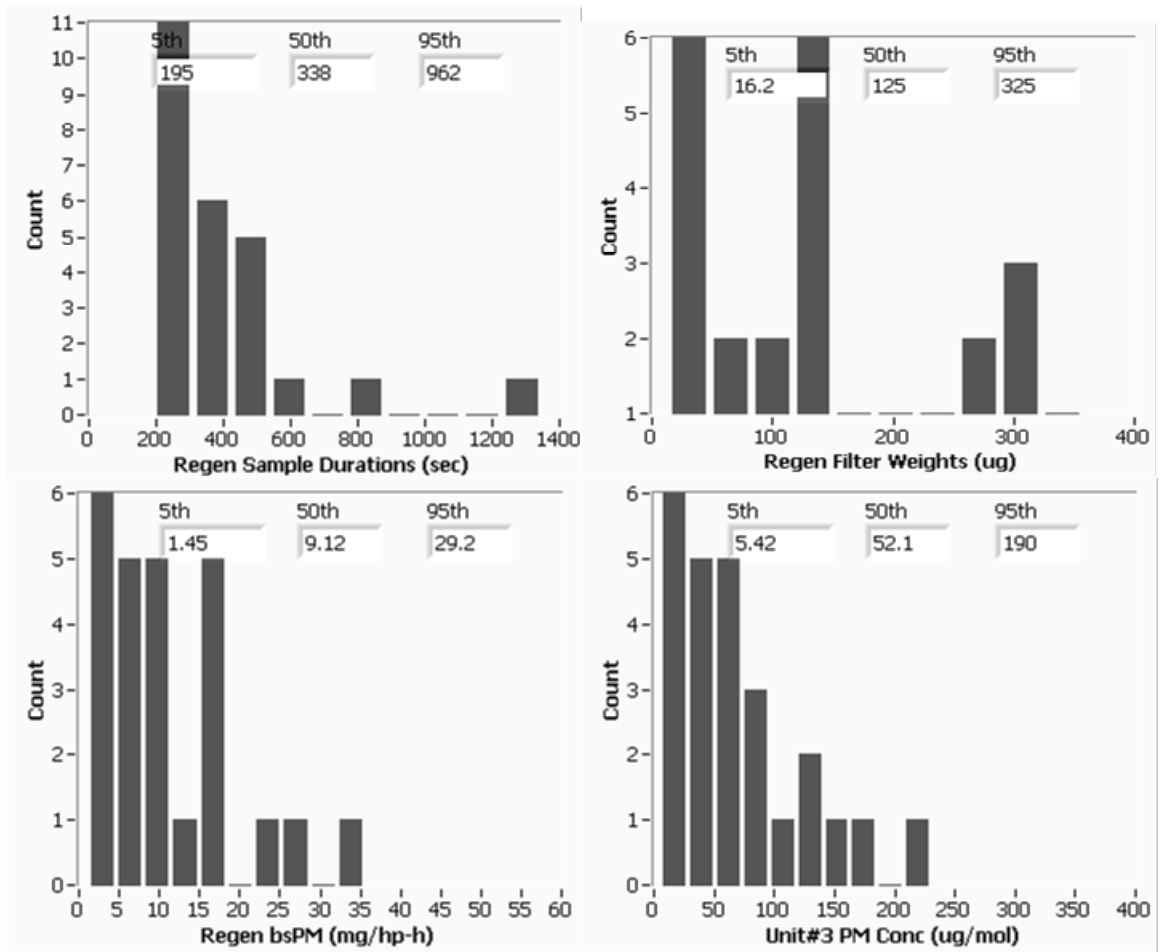
Figure 4-7 Regeneration with no bypass summary statistics

4.4   PM PEMS comparisons: Method 1

This section covers the PM correlations for the PEMS2 and 3 systems compared to the MEL on the Cummins ISX485 test vehicle. Additional analysis is provided from CE-CERT's in-house PM instruments to provide supporting information for comparisons between units. The main analysis presented is based on non-regeneration testing with some analysis on comparisons with regenerations and DPF-out conditions. Three serial number PEMS2 and 3 were used.

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 PM instruments measure properties of PM that infer the mass, such as particle mobility, surface area, size, composition, and combinations of these. Those that measure all PM mass directly like PEMS2 still require particle charging to deposit the PM and have absorbing surfaces that are different then a Teflon filter. PEMS3 also measures PM mass directly, but only the soot portion of the mass. A new gravimetric filter option will allow PEMS3 to improve the estimation of the non-soot parts of the PM and thus improve their ability to measure total PM as a gravimetric system.

The reference system is not technically the only correct answer, but due to historical purposes the definition of PM has stemmed from this measurement method. 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 measurements compared to the reference method.

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 in the context of in-use measurement requirements. It is thus important to consider the differences for the PM PEMS to the gravimetric reference system in what is called the measurement allowance.

As a consequence of the difficulty in measuring PM, both PEMS2 and PEMS3 systems incorporate a theoretical loss compensator for thermophoretic losses. Each manufacturer presented their loss correction algorithms to a committee and these loss correction models were incorporated in their respective post processors. Thus, all the data presented from PEMS2 and 3 includes their individual loss compensator models. The gravimetric reference system also has

thermophoretic losses, but no corrections were made to either the MEL or SwRI data. Thus, one might expect the reference systems to under report PM mass relative to the PEMS.

The following linear correlation analysis is 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 also. The reference system uncertainty was evaluated at SwRI as part of this program and was presented earlier. The MEL uncertainty was established at about 7% low bias with a variability of ±3% compared to SwRI where the modeled measurement allowance was determined.

The analysis presented considers the differences between two PEMS and the MEL over one vehicle, three different PEMS serial numbers, DPF bypass with no regenerations, and no DPF bypass with regenerations. In addition to PM mass measurements, particle composition, particle size distribution and particle number are also analyzed and provided in Section 4.7.

PEMS3 Gravimetric Filter Module (GFM) option
The prototype GFM system was sampled during the entire validation study, but only some of the results are presented here. The notation for the total PEMS3 GFM results used throughout the following analysis is tPEMS3. It should be noted that all the tPEMS3 PM data are based on the manufacturers processed data using a processor version from April 2010. It is expected that the results may change slightly as the manufacturer gains experience with the gravimetric filter module total PM model and calculation approach.

Measurement Cases
The non-regeneration MA validation data submitted to SwRI did not include points below 10 mg/hp-h or above 60 mg/hp-h, as specified in the test plan. UCR did not collect any valid data above 60 mg/hp-h, but did have some measurements below 10 mg/hp-h. The results below 10 mg/hp-h are provided to show the PEMS response during these low measurements that are expected for a properly functioning DPF. There was evidence of passive regenerations at these low measurements where low soot concentrations allowed for this observation. The passive regeneration affect on each PEMS will be discussed.

All comparisons cover linear regression analysis on a brake specific, concentration, delta and % of point basis. This analysis first considers the unit-to-unit differences and later a combined analysis to consider the differences between the PEMS and INST tested. Each figure shows the regression lines, but the slope, intercept, R^2, and standard error estimate (SEE) results are presented in summary tables in Section 4.4.5 for direct comparisons between units. The bsPM results show comparison relative to the emissions standards and the concentration analysis provides a more direct comparison for the measurement principles. Concentration allows the analysis to consider effects of mass level on the measurement error and removes the work term from the analysis.

The Method 1 calculation is the method used for the basis of most of the figures presented. A separate section shows the differences between the method calculations for PEMS2 and 3. The method calculations show possible errors in the exhaust flow that could lower correlation slopes slightly, on the order of 5%, as will be discussed.

PEMS measurement issues and resolutions

There were several significant measurement/configuration issues during the validation testing. These are explained in Section 6 and summarized here to provide context for the results. Table 4-2 lists the more significant issues that impacted the overall bsPM comparisons. These included, but are not limited to; exhaust flow, crystal sensitivity, sample flow, crystal loading limits, and crystal burn-in procedures. It should be pointed out that the PEMS were shipped to UCR in a "ready state" and that only verifications were needed to perform the in-use testing.

PEMS2 and 3 were both affected by exhaust flow since this measurement is needed for flow weighting the PM concentration measurements for Method 1. The exhaust flow is not necessary for Methods 2 and 3, as will be discussed in a later section. The exhaust flow internal tubing was changed from units 1 to units 2 and 3, as UCR found out after testing. This caused a change in the performance of the measurement system where the data was still valid, but the calibration factor changed by a factor of 1.5 and 1.52 for units 2 and 3 relative to the original settings, see Section 6.2.1.1 for details. In addition, the barometric pressure deviation affected the exhaust flow measurement. This is an internal part of the PM PEMS system and varied with elevation for all three units. The barometric pressure initially also varied between PEMS units, but was nominally in the ±15% range, see Section 6.1.1.3. New calibration coefficients were implemented for units 2 and 3 and the barometric pressure was corrected by utilizing a different pressure sensor from the gaseous part of the PEMS3 system and reprocessing the data on an event by event basis, as explained in Section 6.1.1.3. Analysis shows that the corrections for exhaust flow, bsCO2 and carbon balance all agree now within 10% suggesting the implementation was successful.

The remaining issues were only for the PEMS2 system. These issues affected all units, except for the mass sensitivity setting issues. The detailed explanation of these issues is left for Section 6.1.1 and summarized here. The mass sensitivity issue only affected PEMS2 unit 1 and was correct prior to testing units 2 and 3. The unit 1 data was corrected by multiplying all integrated PM results by a factor of 1.5. The mass sensitivity also affected the mass limit threshold, as explained in Section 4.2 earlier. The unit 1 data was corrected for the mass sensitivity through the 1.5 correction factor and four points were removed, due to overloading.

The remaining sample flow, crystal loading, and crystal burn-in issues were identified, but were not corrected for in the data presented. The issues were discovered after the validation testing was completed. It should be noted here that a term called the temperature ratio was lower for the in-use validation testing as compared to SwRI laboratory testing, which could cause negative bias of around 10%, as suggested by the PEMS2 manufacturer. The impact on the overall bsPM comparison has not been quantified, and as such these issues and their associated errors are part of the bias and difference presented in the results sections. Given the complexity in discussing these issues, they are only briefly described in Section 6.1.1.

Table 4-2 Summary of significant issues that affected the overall bsPM correlation results

Issue	PEMS Affected	Approximate Factor [2]	Units Affected	Corrected
Mass sensitivity: Wrong value	2	1.5	1	yes
Exhaust flow: Internal plumbing	2 and 3	1.5 & 1.52	2 and 3	yes
Exhaust flow: Pressure measure	2 and 3	$0.85 < x < 1.15$	1, 2, 3[1]	yes
Sample Flow: Temperature ratio	2	$1.00 < x < 1.10$	1, 2, 3	no
Crystal Loading: Reduce limit	2	n/a	1, 2, 3	no
Crystal burn-in: Modify procedure	2	n/a	1, 2, 3	no

[1] Unit 4 PEMS3 was not affected by the pressure measurements because the external flow meter was used on Unit 4.
[2] The factor is a multiplier to the PEMS bsPM results to correct for associated issue

Common figure formats and description
In all the figures the red dotted lines for the correlation plots represent a one-to-one line. The red and blue dotted lines for the delta plots represent the 100% and 34% measurement uncertainties, respectively. The red dotted line below the 0 y-axis represents the -100% measurement error where the PEMS did not have any response relative to the MEL. The blue dotted line below the 0 x-axis represents the deltas where the PEMS response was at 34% of the MEL measurements. The 34% delta lines were selected to represent a constant Method 1 measurement allowance of 0.0069 g/hp-h at 0.02 g/hp-h or an uncertainty of 34%. The 34% delta lines give the reader a quick feel for the level of the measurement error relative to the Method 1 final allowances reported for PEMS2 (Khalek et al., 2010).

4.4.1 PEMS2 unit comparison

The following analysis and results are for PEMS2 during non-regeneration and regeneration cases. The first section is for the main non-regeneration cases used for the MA validation evaluation and covers all valid results submitted to SwRI. The second section covers the same analysis, but for the regeneration only case. The last section considers the difference between method calculations. The first two sections utilized the Method 1 calculation.

4.4.1.1 non-regenerations

This section covers the results used for the MA validation for the non-regeneration case. Figure 4-8 through Figure 4-13 show the correlation comparisons between PEMS2 and the MEL for units 1, 2, and 3. Table 4-4 through Table 4-8 list the correlation statistics for each of the figures for direct comparisons of all PEMS and INST tested. Figure 4-8 through Figure 4-10 show the comparison on a brake specific basis, Figure 4-11 and Figure 4-12 on a concentration basis, and Figure 4-13 on a percent of point basis. Figure 4-10 shows the same results as Figure 4-9, but with lower x and y scales to see the errors near the no-bypass conditions (i.e., DPF conditions).

bsPM correlation
Figure 4-8 shows that the bsPM correlation between PEMS2 and the MEL was poor for all units where the R^2 was around 0.4 and ranged from 0.52 to 0.2. Unit 1 showed the highest R^2 and unit 3 showed the lowest R^2, see Table 4-4. Unit 1 also had the closest to unity slope at 0.3 and unit 3

the lowest at 0.14. The less than unity slope suggests PEMS2 underestimated the bsPM by more than 70% and the low R^2 suggests this PEMS did not correlate well. Units 1, 2, and 3 all showed positive intercepts with unit 3 showing an intercept of 8.2 mg/hp-h. The positive intercepts suggests the possibility for large positive errors near zero measurements such as DPF out conditions. Some discussion will follow on DPF out conditions later in this section.

In addition to slope, intercept, and R^2, the SEE is useful for characterizing measurement variability. The SEE is a measure of the variability about a least squared regression line. A low SEE means there is low variably. The PEMS2 SEE was relatively high compared to the other PM measurement instruments and to the 25 mg/hp-h target (Note the 50th percentile measurement was 17, 26, 25 mg/hp-h for units 1, 2, and 3, respectively). The SEE ranged from 4.8 g/hp-h to 5.8 g/hp-h for units 1 and 3, respectively, and increased from unit 1 to 3. The SEE percent of the target measurement (i.e., SEE/25 mg/hp-h*100%) was 30% for all units combined.

The poor correlation for PEMS2 agrees with the results from a previous study reported by Durbin et al. (2009a). In this study three vehicles were tested with PEMS2 and 3. One vehicle showed a similar PM composition, but at slightly higher emission level to the current test article with a 50th percentile of 40 mg/hp-h (Durbin et al. 2009a). The PEMS2 system was setup based on the best available information for 2007. The results showed the PEMS2 slope at around 2.2 with an R^2 of 0.33 and a SEE of 30 mg/hp-h. The slope suggests the previous PEMS2 was over reporting PM mass and the current version is underreporting the PM mass. The SEE was also much larger, but this could be a result of the higher measurement levels. The SEE as a percent of typical measurement (i.e., SEE/50th percentile) was 75% for the previous study and 30% for the current study.
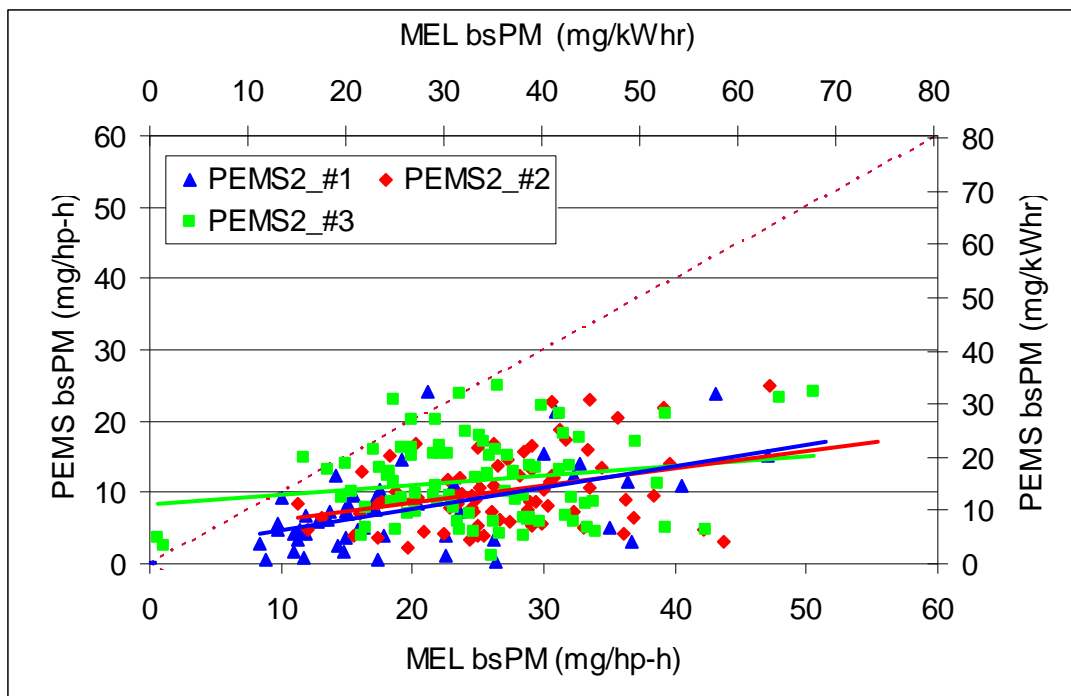
Figure 4-8 PEMS2 bsPM correlation: unit comparison

bsPM delta correlation

Figure 4-9 shows the PEMS2 bsPM deltas for each unit tested and the regression results are presented in Table 4-5. The delta correlation shows the absolute error differences as a function of the MEL bsPM level. The slope varied from -0.70 to -0.86 and the intercept from +1.5 to 8.2 mg/hp-h. Using the slope and intercept, the net measurement error at 20 mg/hp-h is 12 mg/hp-h or 62% of 20 mg/hp-h for Unit 1. Units 2 and 3 show a lower error, with the error decreasing from 57% for Unit 1 to 45% for Unit 3. The combined uncertainty presented later was 55%. The negative bias is visually shown as most of the deltas in the figure are below the proposed measurement allowance reference line (blue dotted -34% reference line). Although unit 3 showed the lowest absolute error of 45%, the high variability and low data count suggest that the combined uncertainty could be higher and closer to 55%.
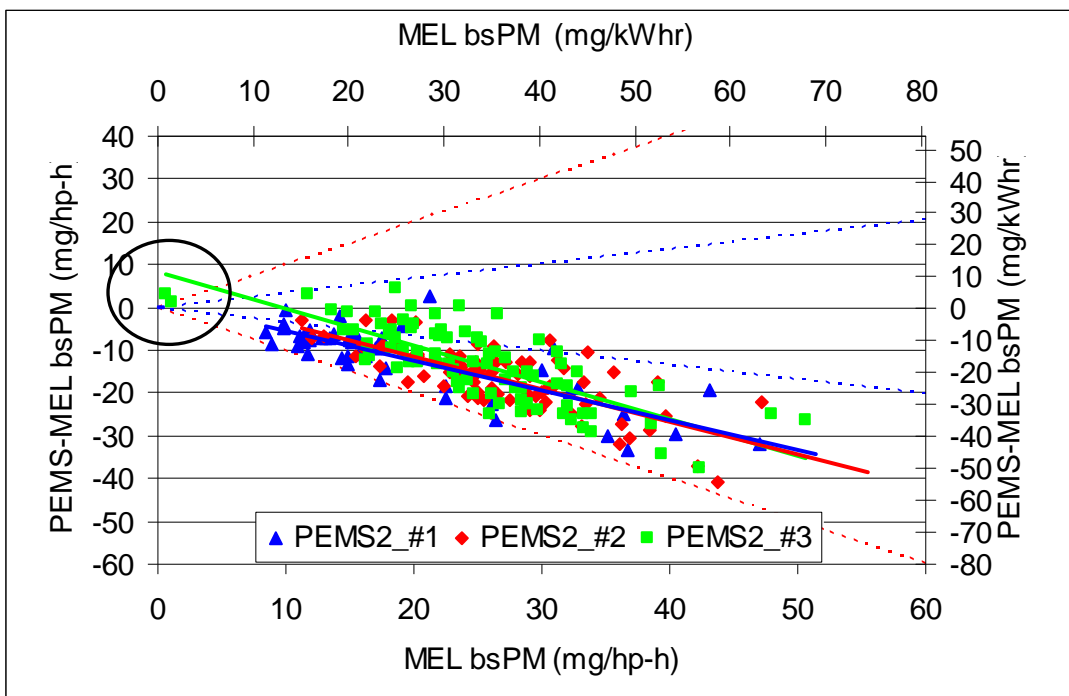
Figure 4-9 PEMS2 bsPM delta correlation: unit comparison

DPF conditions special case

Figure 4-10 shows a close view of the PEMS2 bsPM deltas below 10 mg/hp-h. Unit 3 had two measurements at DPF out conditions. The MEL measured 0.6 and 1.1 mg/hp-h where the PEMS measured 3.7 and 2.5 mg/hp-h, respectively, see the circled points in Figure 4-10. One of the reasons for the large PEMS2 bsPM for these points could be due to long sample time (~1000 seconds) and the usage of multiple crystal usages for each of these events. The PEMS2 manufacturer lowered the maximum sample time from 1800 seconds to 240 seconds on unit3. Thus any event over 240 seconds would use more than one crystal. The larger bsPM results used 5 crystals and the lower one used 4 crystals. The low measurement issue is also clearly identified in Figure 4-13 where the measurements at 0.6 and 1.1 mg/hp-h showed +124% and +500% positive error. The multiple crystal usage, as shown in Figure 4-14, also appears to be affecting

the regeneration response as explained in the Section 4.4.1.2. It is uncertain what impact the sample duration and multiple crystal usage will have on DPF out emissions without more analysis.

Real-time analysis of the large positive bias (+124 and +500%) events is presented in the real time analysis Section 4.9.2. There is some evidence that the MEL filter may have some sulfuric acid particles due to the elevated particle count between the 0.6 and the 1.1 mg/hp-h. Other comparisons have shown that PM measured at the PEMS and at the entrance to the CVS (i.e., after the MEL transfer line) were the same, as discussed in section 3.1.2.3.
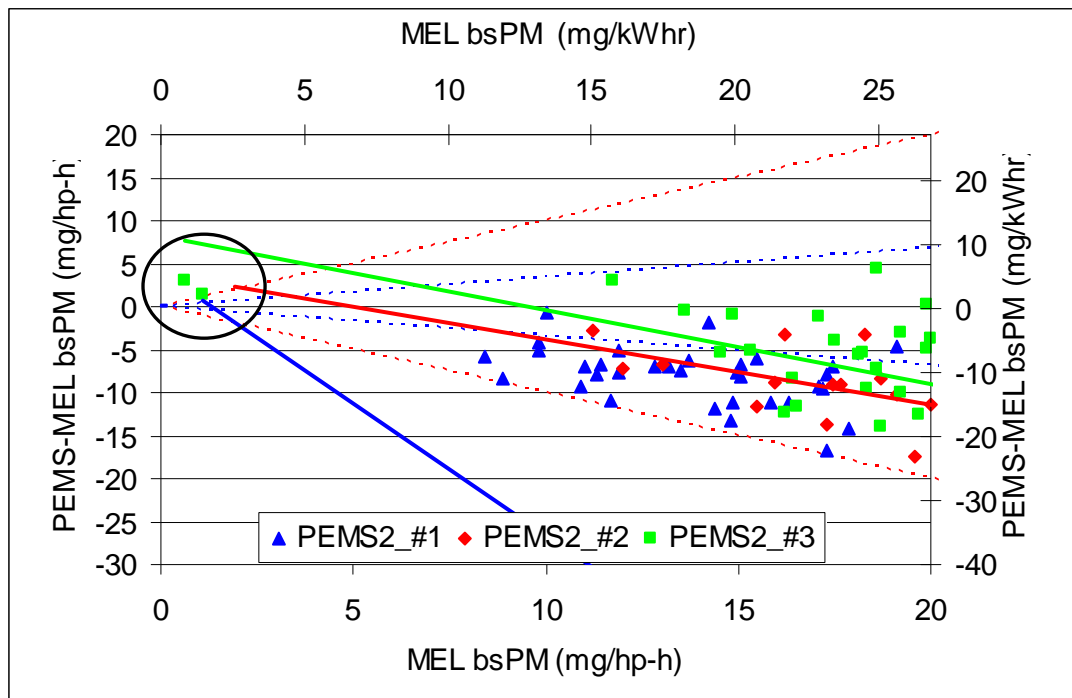
Figure 4-10 PEMS2 bsPM delta correlation: unit comparison, zoomed in

PM concentration correlation
Figure 4-11 shows the PEMS2 correlation for tail pipe PM concentration for both µg/mol and mg/m^3 units. The data is listed in Table 4-5. The MEL estimated tailpipe concentration were determined using direct measurements of total and dilute CVS flow rates. Concentration directly compares the measurement methods without work influencing the results. The concentration figure shows there is a noticeable bias between units not seen with the bsPM correlation figure. Unit 1 showed the lowest correlation and unit 3 the closest correlation to the MEL. The slope between unit 2 and 3 were similar, but unit 3 had a larger positive bias, with a zero intercept at 50 µg/mol (2 mg/m^3). The concentration SEE is also larger relative to the bsPM SEE. The concentration SEE ranged from 23 µg/mol to 54 µg/mol for units 1 and 3, respectively, which is about 30% of the 50th percentile concentration measurement. The bsPM SEE was about 10% of the 50th percentile bsPM measurement as a comparison.
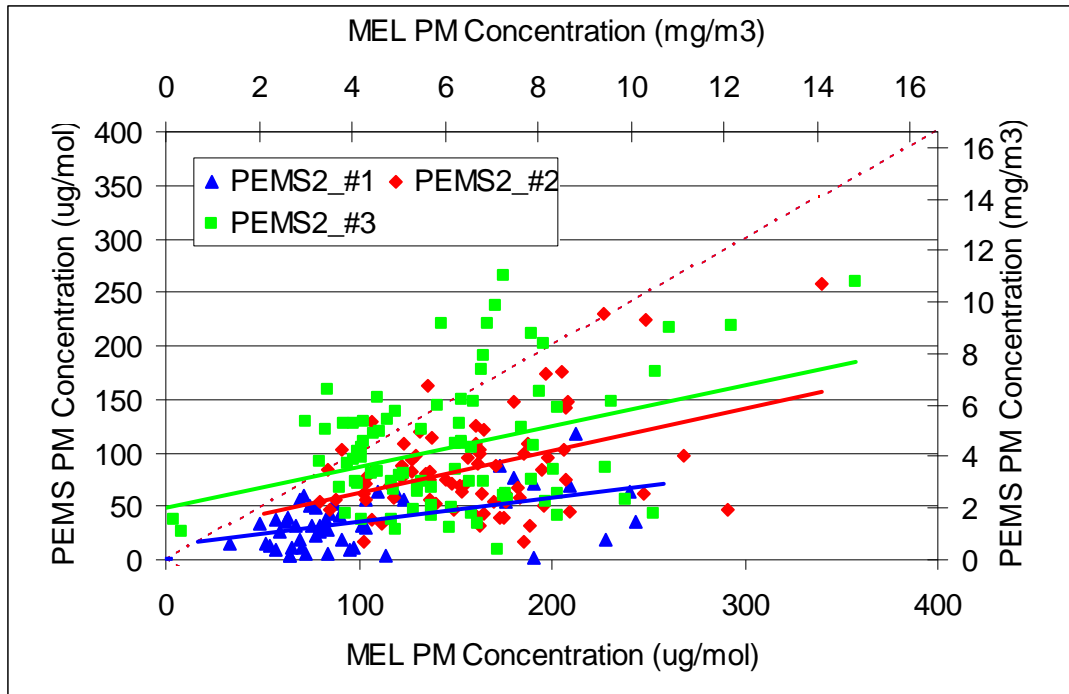
Figure 4-11 PEMS2 concentration correlation: unit comparison

PM concentration delta and percent of point correlation

The delta concentrations are shown in Figure 4-12 and Table 4-7 where unit 1 showed the lowest correlation and unit 3 the best. This figure shows that the unit 3 deltas where just slightly below the 34% error line, which was closer than for the bsPM delta figure. Figure 4-13 shows the bsPM percent of point errors. This figure provides the reader a feel for the measurement error as a function of bsPM level.

All three units show an increasing % error with increasing level. Unit 3 shows the steepest error resulting from the very high % error at the two DPF out points discussed earlier. These two points showed errors of 506 and 128%. With these points removed, the slope is more similar to the other two units. The unit 3 concentration intercept was a positive 48 µg/mol (2 mg/m³).

Variability

The concentration SEE on units 2 and 3 were similar at 42 and 54 µg/mol, respectively, while the unit 1 was lower at 23 µg/mol. Unit 1 had was operated where crystal overloading could be the reason for the lower unit 1 SEE, thus it is expected the overall variability will be closer to that seen by units 2 and 3. The average PEMS3 combined measured concentration was 81 µg/mol for units 1, 2, and 3 where a 50 µg/mol SEE variability would represent about 60% of the average measurements. PEMS2 appears to have a lot of noise and/or variability in its measurement to have a more than 50% measurement variability. The variability may come from the fact that PEMS2 system employs 7 different crystals, where each can have a different PM mass sensitivity, thus contributing to the variability.
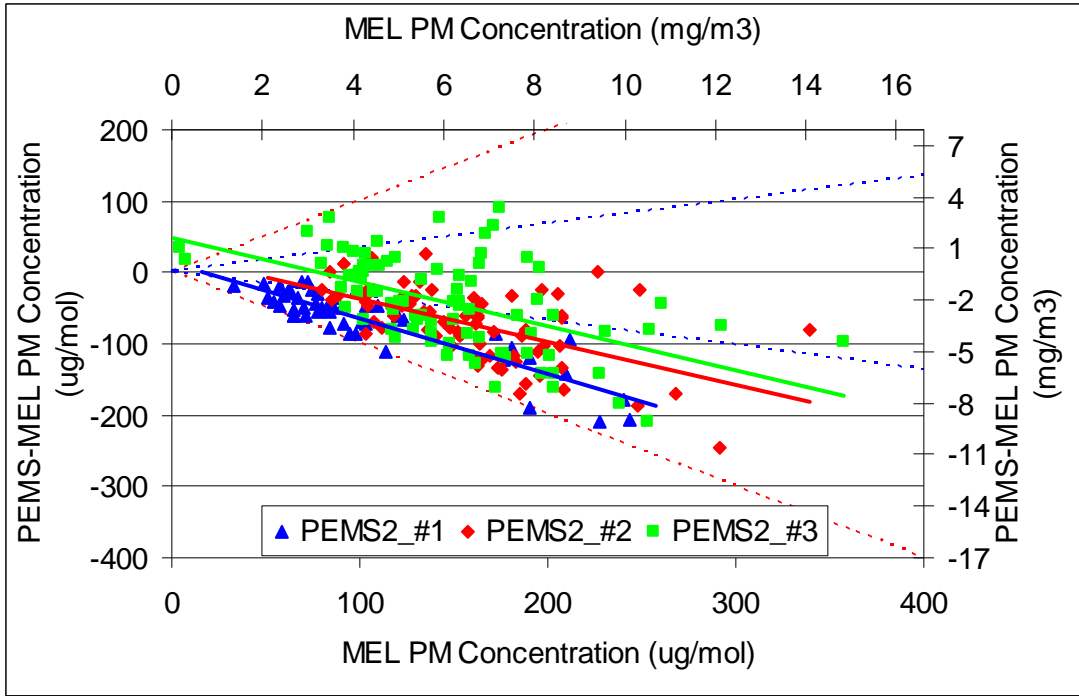
Figure 4-12 PEMS2 concentration delta correlation: unit comparison
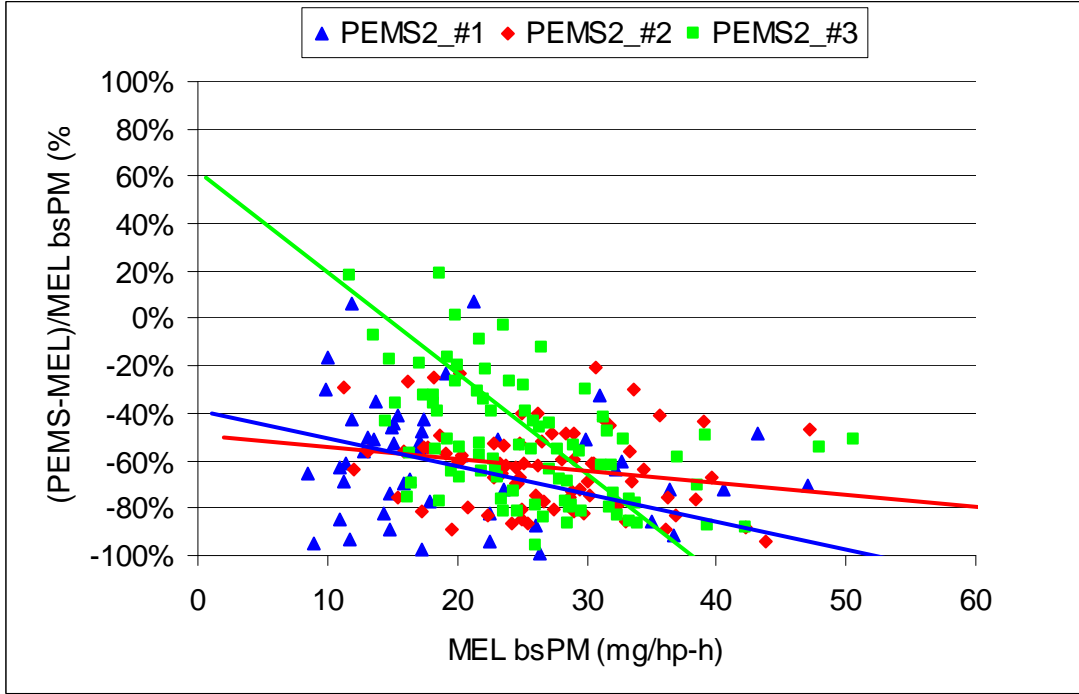
Figure 4-13 PEMS2 bsPM percent of point correlation: unit comparison

Summary

The low bias of PEMS2 has also been identified as a special source of error experienced both in the laboratory and in-use, with the in-use testing showed a slightly lower overall negative bias

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compared to laboratory testing. There have been several discussions about why there is such a low bias. These discussions are presented in the combined analysis to provide the reader a comparison between different PM measurements that shows the bias is not an issue of the reference system.

In summary, it appears the behavior of the PEMS2 system, in it's present state of development, was similar between the units tested. It also appears that the measurement error is dependent on level where the percent of point error increased with level and was largest for unit3. As improvements or changes are made for this PEMS, a greater number of PEMS may need to be tested to better characterize the differences between units. Although there were not significant differences between the PEMS unit for this study, there are still large differences compared to units tested in previous studies. The variability of the PEMS2 improved in this study, but is still large at 70% to 50%

4.4.1.2   Regenerations

The regeneration tests were performed with the bypass removed, as described earlier. During some testing with unit 1, UCR operated some regenerations with the bypass installed. Although these results are not part of the MA program, they are presented here as additional information Each day the DPF reached the soot loading necessary for regeneration, thus the regenerations performed were fairly representative of in-use testing. UCR performed daily parked regenerations to prevent overloading the DPF system.

Regen with no bypass case
Figure 4-14 and Figure 4-15 show the regeneration results and Table 4-9 through Table 4-12 list the statistical results. Figure 4-14 shows the comparison on a bsPM basis and Figure 4-15 shows the information on a concentration basis. Both figures show the same trends, where units 1 and 2 both showed essentially no response, as can be seen by the low R^2 and near zero slopes. The slope ranged from 0 to 0.27 and increased from unit 1 to unit 3. The R^2 ranged from negative to 0.74 and also increased from unit 1 to unit 3. The low slope and poor correlation for regeneration type events agrees with an earlier study by Durbin et al (2009b). During this study, the slope was 0.039 and the R^2 was 0.45.

Sample times are much longer for the regenerations conditions where the 50th percentile sample duration was 338 second compared to 175 seconds for the 50th percentile non-regeneration case, as shown in Figure 4-7. The longer sample times could affect the PEMS2 measurement principle as discussed during the HDIUT SC meetings. More than half of the unit 3 events used two crystals where for units1 and 2 only one crystal was used. This suggests that multiple crystal usage could be causing a positive bias and a special source of error.
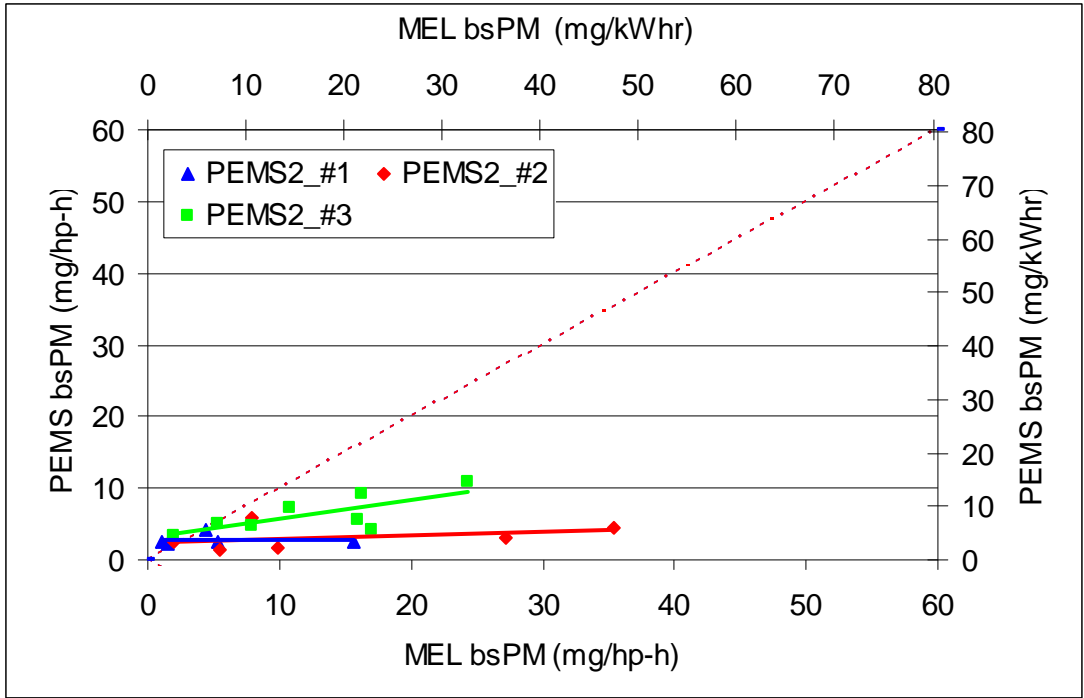
Figure 4-14 PEMS2 bsPM correlation: unit comparison: regenerations
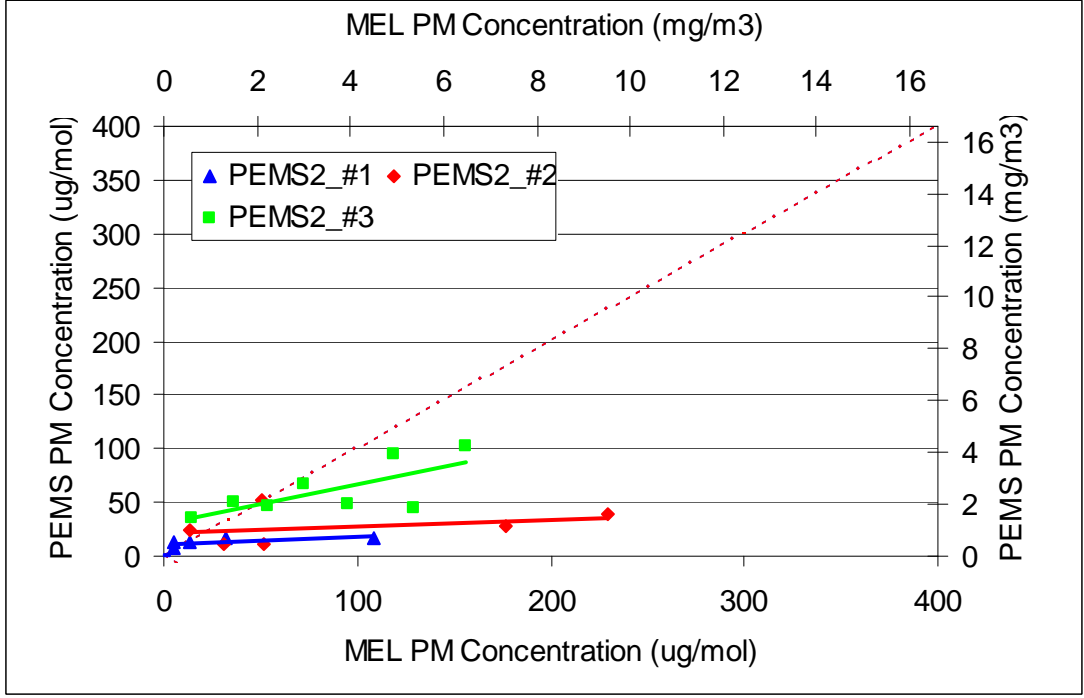
Figure 4-15 PEMS2 concentration correlation: unit comparison: regenerations

Regeneration with bypass special case
Figure 4-16 shows a special case where the bypass was not removed during unit 1 testing. After analyzing the filters it was realized that the PM levels were outside the scope of the project so the data is was not submitted to SwRI for validation consideration. The information is, however, interesting and is presented in the context that the PEMS2 measurement system exceeded the crystal loading for some, but not all events. The PM was mostly organic in nature based on some very large OC measurements and high HC concentrations. The results show PEMS2 measurement capabilities for PM resulting from this type of operation which could represent a failed DPF and catalyst system. The figure shows both measured bsPM and crystal loading on the vertical y-axis.

During a previous study, similar regenerations with a bypass were performed where the OC represented 90% of the PM (Durbin et al, 2009b). During the previous study the PEMS2 correlated better than is shown in Figure 4-16. During the previous study, a similar high correlation of 0.9 was found, but the slope was closer to unit at 0.83 vs 0.4 for this study. It is not clear what differences there were since that study used a lower crystal sensitivity which should have biased their numbers low thus making the difference greater. Also, that study was based on configurations considered ideal in 2008 vs. the system configured for 2009. More analysis is necessary to understand the differences.
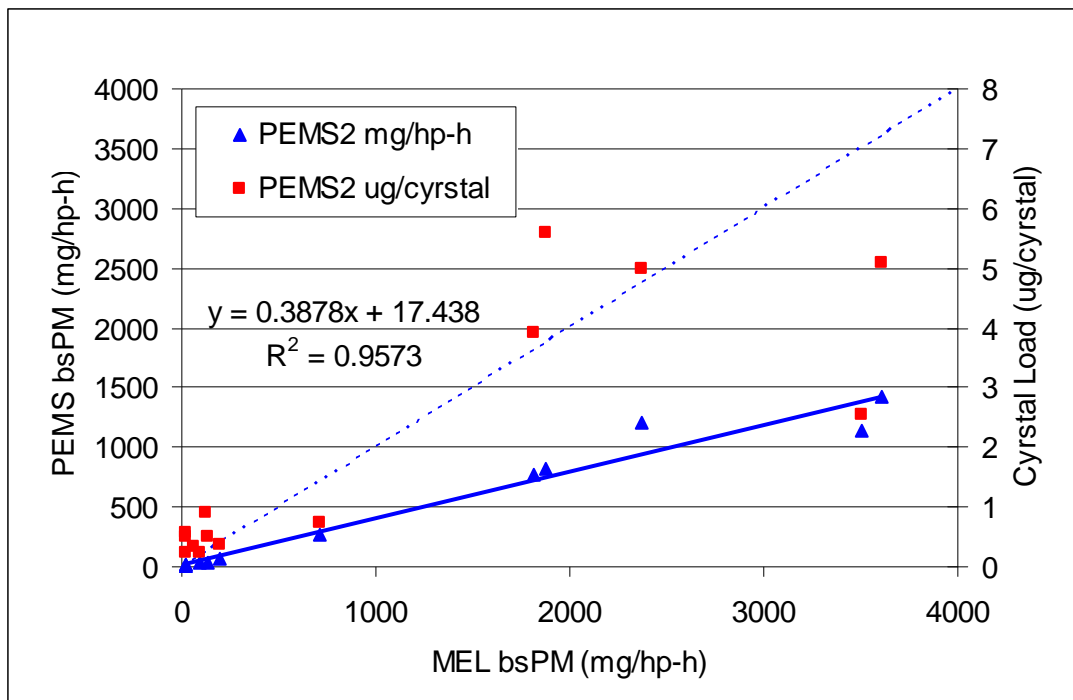
Figure 4-16 PEMS2 bsPM correlation during regenerations with bypass

4.4.2   PEMS3 Unit Comparison: MSS Only

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The following analysis and results are for PEMS3 during non-regeneration and regeneration cases. The first section is for the main non-regeneration case used for the MA validation evaluation and covers all valid results submitted to SwRI. The second section covers the same analysis, but for the regeneration-only case. The first two sections utilized the Method 1 calculation. Other method calculations will be discussed in a later section.

PEMS3 prototype gravimetric filter module caused some measurement difficulties for unit 1, and thus a significant amount of data was invalidated for unit 1, see Section 6.1.3 for details. As such, the manufacturer, at their cost, provided a fourth unit for testing. The fourth unit presented in the following analysis was a typical commercial unit and was tested in the same way as the previous units. One unique difference is this PEMS3 system was setup with a properly configured flow meter without the issues associated with the PM PEMS2 measurement system, see Section 6.2.1.1 for details. In general, the figures and statistical analysis presented for PEMS3 represent primarily units 2, 3, and 4.

4.4.2.1 Non-Regenerations

This section covers the results used for the MA validation for the non-regeneration case. Figure 4-17 through Figure 4-22 show the correlation comparisons between PEMS3 and the MEL for units 1, 2, 3 and 4. Table 4-4 through Table 4-8 list the correlation statistics for each of the figures for direct comparison between all PEMS and INST tested. Figure 4-17 and Figure 4-19 show the comparison on a brake specific basis, Figure 4-20 and Figure 4-21 on a concentration basis, and Figure 4-22 on a percent of point basis. Figure 4-10 shows the same results as Figure 4-9, but with a lower x and y scale to see the errors under nonbypass conditions (i.e., DPF-out conditions).

bsPM correlation
Figure 4-17 shows that the bsPM correlation between PEMS3 and the MEL was good for all units with the R^2 around 0.95 and ranging from 0.87 to 0.98, with unit 2 showing the lowest R^2 and unit 4 showed the highest R^2, see Table 4-4 and Table 4-5. Unit 2 had the closest to unity slope at 0.98 and unit 3 the lowest at 0.87. The less than unity slope suggests PEMS3 slightly under estimated the bsPM from 2% to 13% and the high R^2 suggests this PEMS did correlate well to the reference system. Units 2, 3, and 4 all showed slightly negative intercepts at around --0.4 mg/hp-h. The slightly negative intercepts suggests this PEMS measurement principle would not over report bsPM near zero measurements such as during DPF out conditions. Some discussion will follow on DPF-out conditions later in this section.

Method 2 Evaluation
The near unity slope for unit 2 appears high given the system measures only soot and it is expected that around 10% of the PM composition is not soot and is most likely organic carbon PM, see discussion on PM composition section. The near unity comparisons can be due to several things such as variations between PEMS units or biased high exhaust flow measurements. To investigate the theory about the exhaust flow, the Method2 calculation was investigated. Figure 4-18 shows the same bsPM correlation, but for Method 2 instead of Method 1 calculations. Method 2, as explained earlier, has the effect of elimination errors in the exhaust flow using fuel consumption from the ECM. The slope decreased from 0.98, 0.87, and 0.92

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(Method 1) to 0.95, 0.83, and 0.86 (Method 2) for each unit, respectively, where the overall averages decreased from 0.95 to 0.90 from method1 to method2. The 0.9 slope agrees better with a previous correlation study (Durbin et al 2009a) and with expected EC/OC ratios estimated for the test article. This suggests that the PEMS3 system correlation slope is more likely to be around 0.9 as indicated by the Method 2 combined analysis. This also suggests the exhaust flow measurements are slightly high. The $bsCO_2$ method comparison also shows a similar trend where Method 2 and 3 delta correlations show no bias where Method 1 deltas show a positive bias, see Figure 5-7 in Section 5.4.1.

The bsPM SEE was lowest for this PEMS compared to all the other PEMS and INST. The bsPM SEE varied from 3.3 to 2.0 mg/hp-h for units 2 through 4, respectively. The range of SEE is reasonable and suggests this instrument measurement principle is robust and reliable for the type of PM composition and particle size sampled. It is known that PEMS3 measurement principle primarily responds to PM soot. Soot is a product of combustion and not dilution and thus would not be affected by dilution and sampling systems like the other fractions in PM. If the instrument measured OC and sulfate PM as well it is expected that the SEE would likely be larger. Although this soot limitation exists, it is important to realize that the PEMS3 soot measurement is very reliable between units, which makes this measurement of value to the scientific and regulatory communities. Their integrated gravimetric filter was integrated in order to quantify total PM in combination with their soot measurement, as will be discussed in Section 4.4.3.
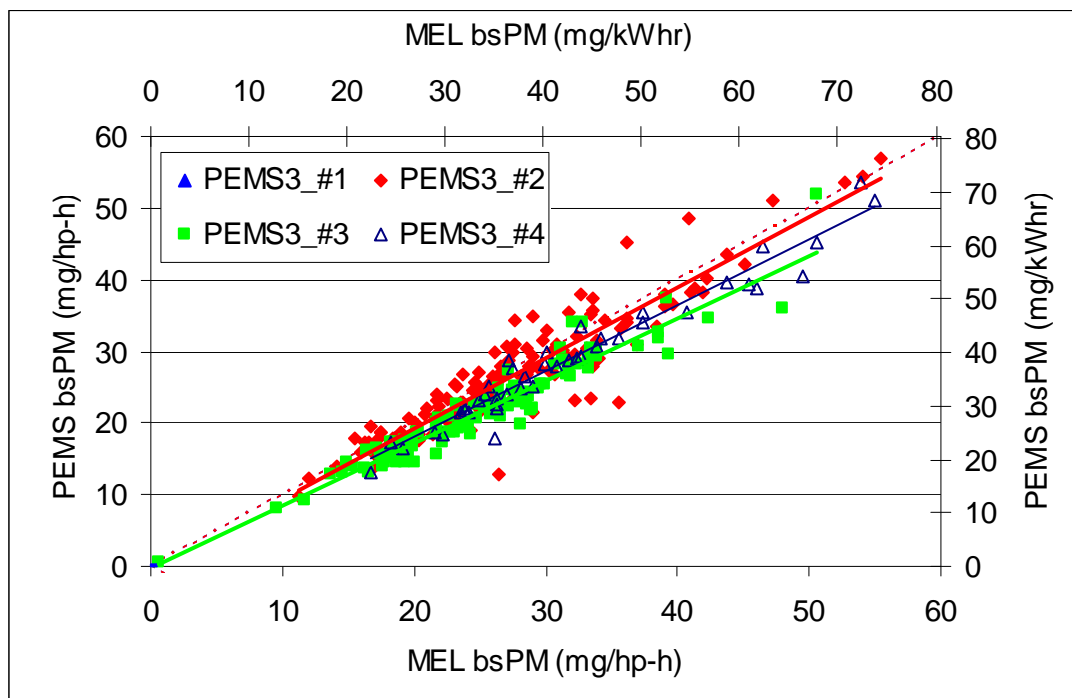
Figure 4-17 PEMS3 bsPM correlation: unit comparison: Method 1
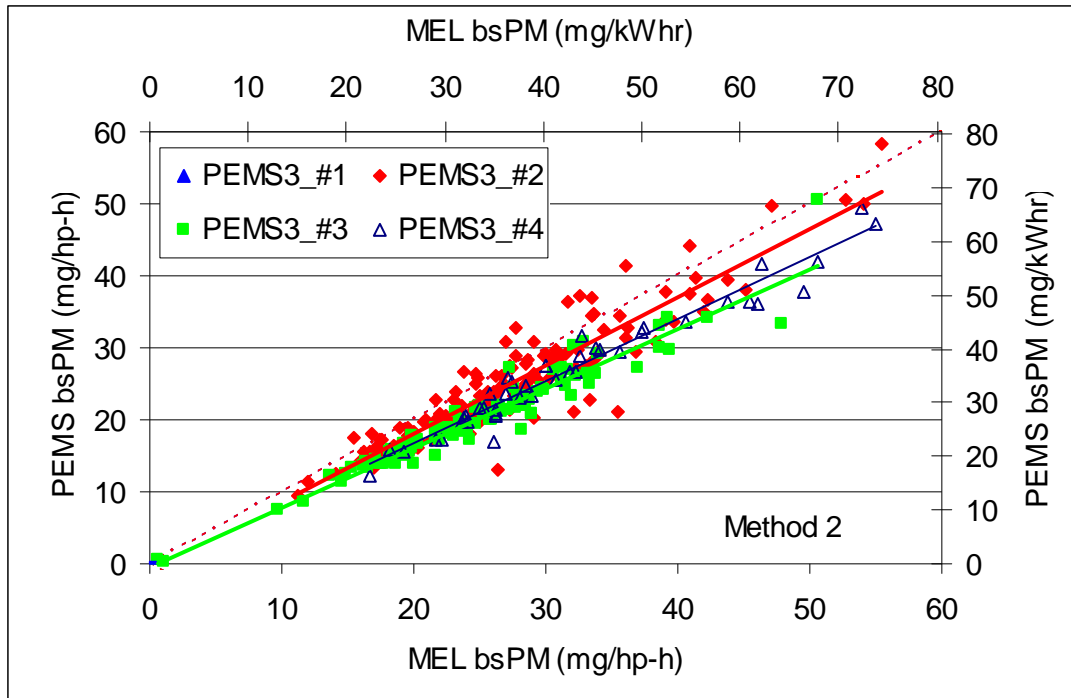
Figure 4-18 PEMS3 bsPM correlation: unit comparison: Method 2

bsPM delta correlation

Figure 4-19 shows the PEMS3 bsPM deltas for each unit tested and the regression results are presented in Table 4-5. The delta correlation shows the absolute error differences as a function of the MEL bsPM level. The slope varied from -0.02 to -0.13 and the intercept from -0.3 to -0.5 g/hp-h. Using the slope and intercept, the net measurement error at 20 mg/hp-h is 2.8 mg/hp-h or 14% of 20 mg/hp-h for unit 3. Units 2 and 4 show a lower error at 4% and 10%, respectively. The combined uncertainty presented later was 9%. The negative bias is visually shown as most of the deltas in the figure are between the blue dotted -34% reference line and the zero axis in the middle of the figure.

DPF conditions special case

DPF conditions are of special importance for in-use compliance testing as most measurements will be made well below the MA 20 mg/hp-h determination level. As such special attention to these conditions was given for PEMS2 and now for PEMS3. PEMS3 measures predominantly soot and as such should be able to quantify DPF-out conditions as well as during the bypass conditions. During the two DPF out conditions, this PEMS showed a response of 0.5 and 0.4 mg/hp-h where the referenced measured 0.6 and 1.0 mg/hp-h respectively. The difference is shown more dramatically as a percent error, which was -24 to -60% as visually shown in Figure 4-22.

Real-time analysis of the low bias (-60%) events is provided in the real-time analysis Section 4.9.2. Additional tests showed that the low bias was not a result of PM coming from the MEL transfer line. This bias could be due to sulfuric acid particles since there was an elevated particle number count for this event. The dilution ratio for PEMS3 was also set for higher levels and it is

expected that lower dilutions from 6 down to 2 might be more optimal for DPF-out conditions, since improved low level sensitive could be achieved.
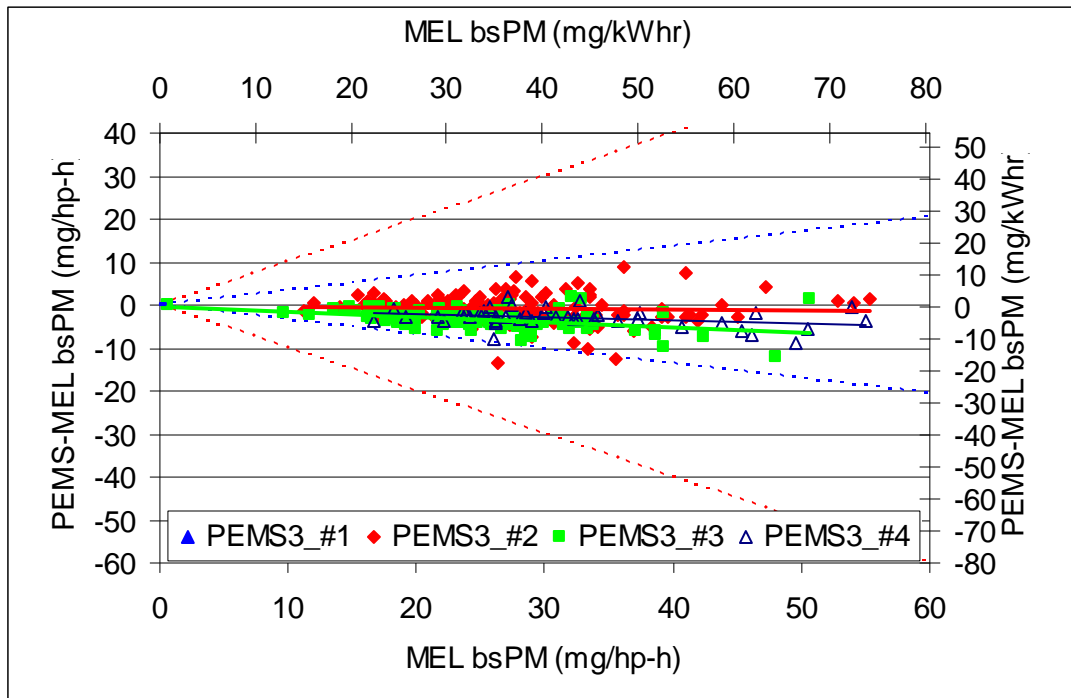
Figure 4-19 PEMS3 bsPM delta correlation: unit comparison

PM concentration correlation

Figure 4-20 shows the PEMS3 correlation for tailpipe PM concentrations for both µg/mol and mg/m^3 units. The corresponding statistics are provided in Table 4-5. The concentration figure shows about the same trends as the bsPM correlation figure. The interesting difference is that units 3 and 4 switched positions and unit 2 stayed the same. The R^2 varied from 0.98 to 91 and the slope varied from 0.97 to 0.85 where unit 2 had the slope closest to unity and this time unit 4 had the lowest slope of 0.85, where for the bsPM correlation the lowest slope was on unit 3. Another interesting difference is the zero intercept for unit 2 went from -0.5 g/hp-h to +3 µg/mol (0.12 mg/m^3) between the bsPM and concentration correlation. Units 3 and 4 both showed a negative intercept, as one would expect for the PEMS3 measurement principle. Later analysis will show that errors in the exhaust flow may be the cause for unit 3 positive intercept. Analysis of INST 4 and 5 suggests the concentration correlation is a more direct approach for evaluating PM measurements errors between units, as will be discussed later.

The concentration SEE is also larger relative to the bsPM SEE. The concentration SEE ranged from 23 µg/mol to 54 µg/mol for units 1 and 3, respectively, which is about 30% of the 50th percentile concentration measurement. The bsPM SEE was only about 10% of the 50th percentile bsPM measurement as a comparison.
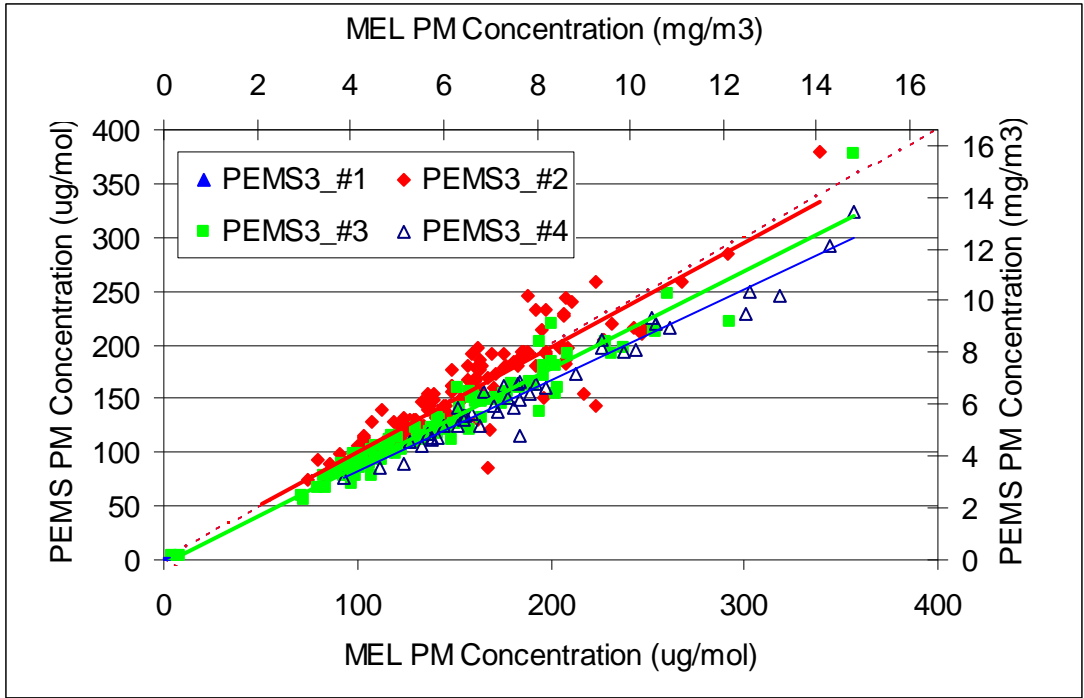
Figure 4-20 PEMS3 concentration correlation: unit comparison

PM delta concentration and percent of point correlation

Figure 4-21 shows the PM concentration deltas and Figure 4-22 shows the bsPM percent of point differences from the MEL both as a function of the reference level. The concentration deltas show the same general trend, where the concentration differences are mostly between the -34% line and the zero axis. The percent of point figure shows how the PEMS3 measurement principle has a flat slope, where the slope varies from 0, +0.2% and +0.1% for units 2, 3 and 4, respectively. The near zero slopes suggests PEMS3 measurement principle is does not trend with PM concentration.

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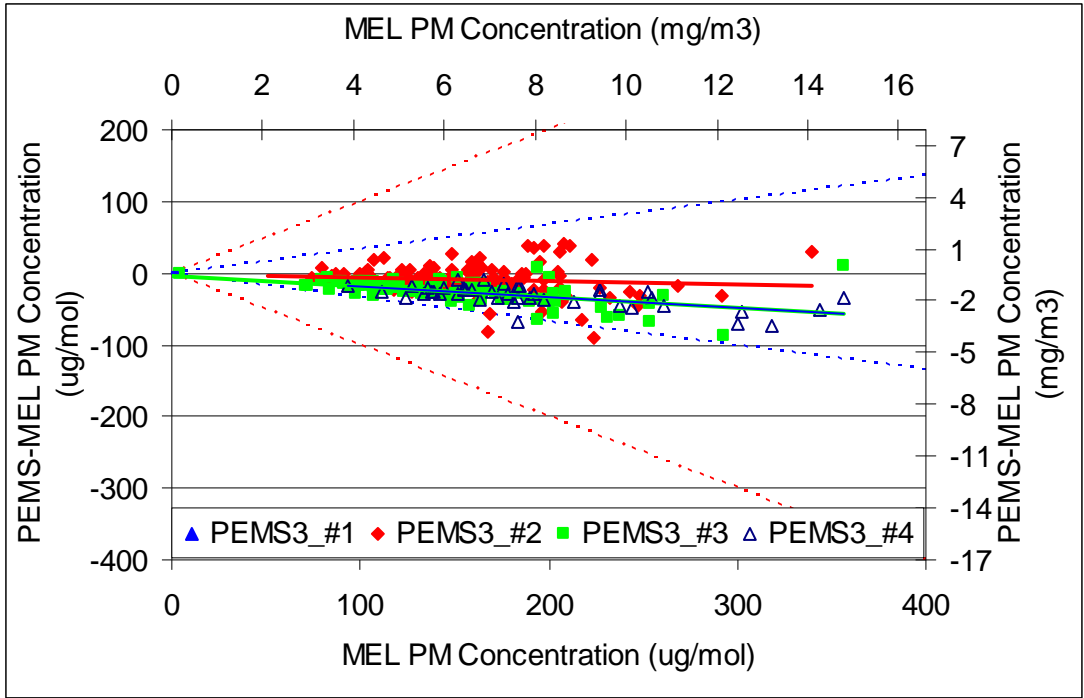
Figure 4-21 PEMS3 concentration delta correlation: unit comparison
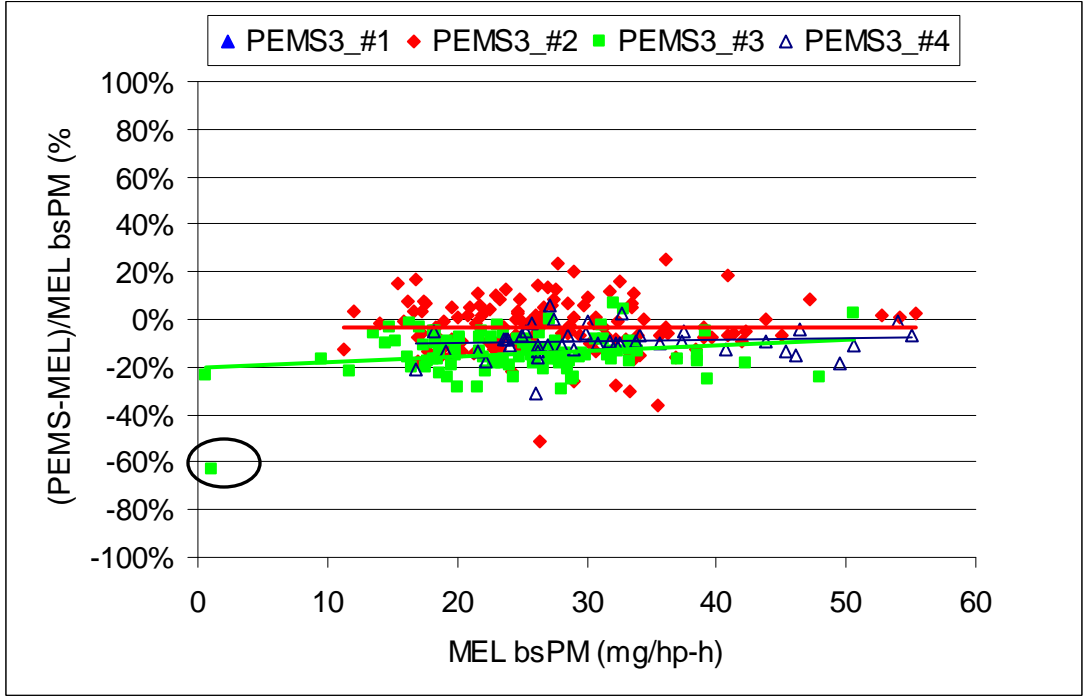
Figure 4-22 PEMS3 bsPM percent of point correlation: unit comparison

4.4.2.2 Regenerations

The data presented in this section covers PEMS3 regeneration results. Since the PEMS3 measurement principle is based on PM soot, it is expected that the regeneration correlation will be much lower than the non-regeneration correlation. Unit 1 and 4 had no valid regeneration data and units 2 and 3 are presented in Figure 4-23 and as listed in Table 4-9 below. The slope is around 0 and showed a negative R^2 suggesting a very poor correlation. PM composition analysis, presented later, suggests the PM was dominated by sulfuric acid particles, and thus the low correlation is expected. The concentration correlation figure showed the same basic trend, and is thus not presented in this report.
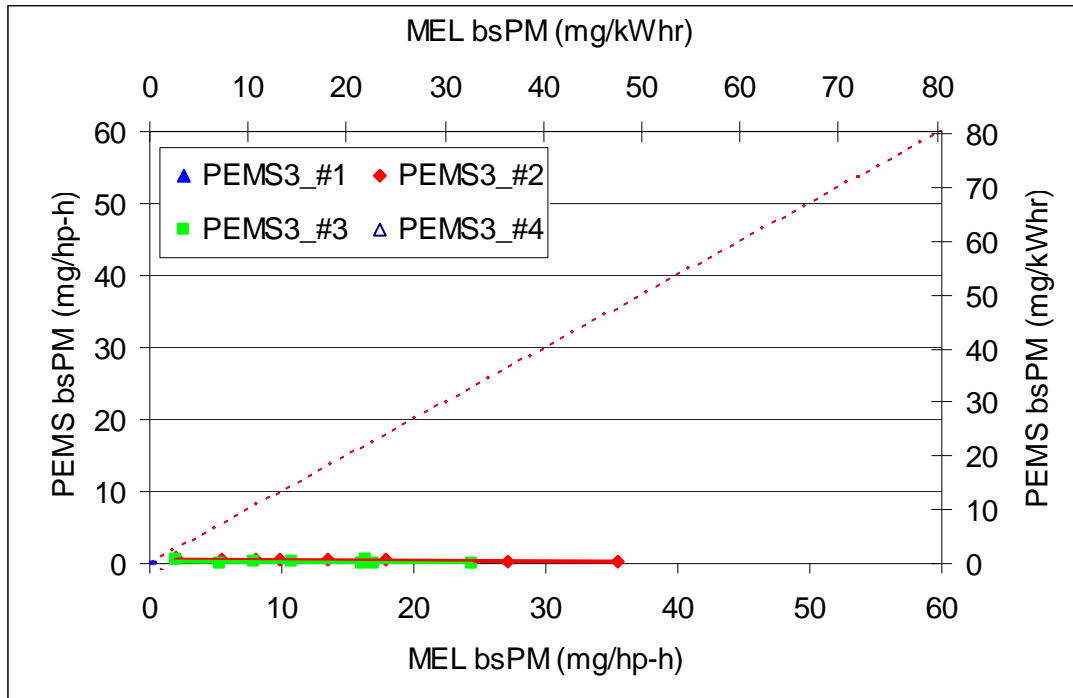
Figure 4-23 PEMS3 bsPM correlation: unit comparison: regenerations

4.4.3 PEMS3 + GFM

At the time of validation testing, the PEMS3 manufacturer assembled a prototype gravimetric module to provide a total PM solution, as explained earlier. The results in this section show the performance of this new prototype system. The reader needs to be cautioned that at the time of this writing the full implementation of the correction factors for this unit is not complete, and thus the data is considered preliminary. The basic idea is to use real-time measurements, such as PM soot, THC concentration, exhaust temperature, and a daily gravimetric filter mass to correct the MSS soot signal to a total PM mass. The results presented here are based on the best available logic for this implementation. Two cases are considered, the data from the main MA study using events that did not contain DPF regeneration and secondly events that are nearly exclusively regenerations are considered. In addition a section on the total PM modeling approach is presented to discuss successes and issues.

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4.4.3.1 Non-Regenerations

Figure 4-24 shows the bsPM correlation results for PEMS3 for the soot sensor only, simple span approach (_f), and with an alpha modeled approach (_a). The regression equations in Figure 4-24 are forced through zero to show the relative difference between the slopes. The PEMS3 MSS only data is based on the Method 1 calculations and the other two are based on the Method 3 calculations. If the Method 1 calculation was used for MSS only data because this is consistent with the rest of the report. If the Method 3 calculation were used instead the red line would move down slightly. Table 4-3 shows the correlation statistics for comparisons between the approaches. The data spread increased with the usage of both the filter and alpha approaches. The alpha approach increased the slope from 0.92 to to 1.00 where the simple filter increased the slope to 1.07. In both cases the SEE increased from 3.0 to 3.3 and 3.8 mg/hp-h respectively.
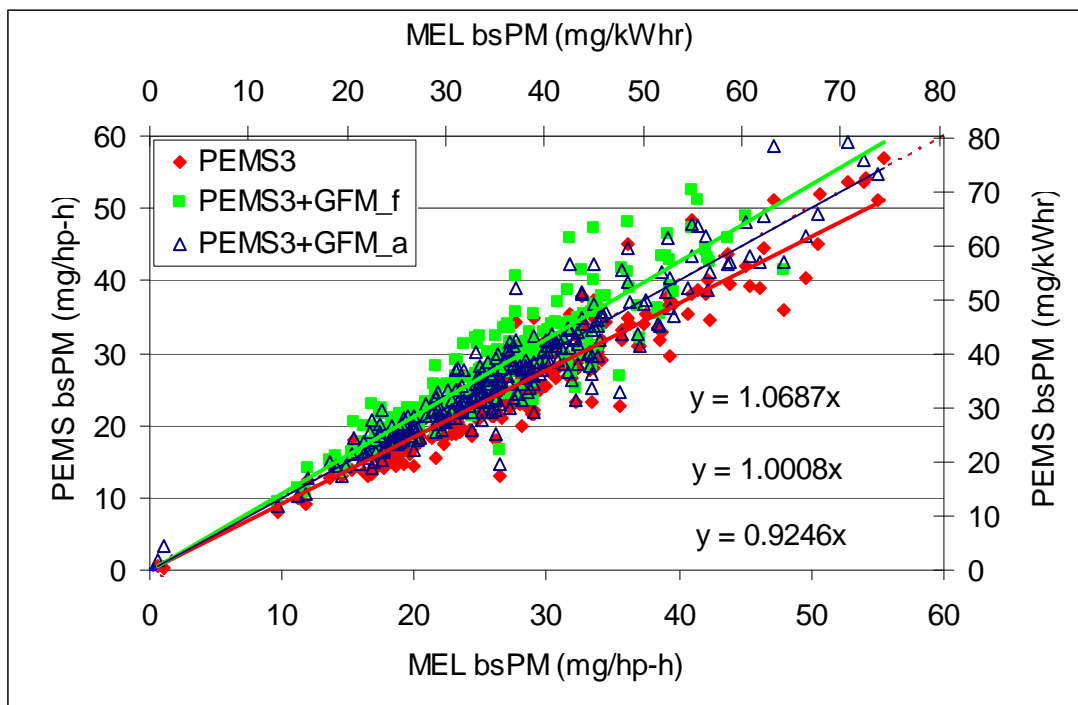
Figure 4-24 PEMS3 + simple filter (_f) and alpha (_a) modeled terms correlation (non-regen)

Table 4-3 PEMS3 + simple filter (_f) and alpha (_a) modeled terms correlation statistics

PEMS	Slope	Intercept	R^2	SEE	t-test
MSS	0.95	-0.7	0.94	3.0	2E-25
GFM_f	1.12	-1.6	0.92	3.8	3E-10
GFM_a	1.04	-1.2	0.94	3.3	6E-01

4.4.3.2 Regenerations

Figure 4-25 shows the bsPM correlation results for PEMS3 for the soot sensor only, simple span approach (_f), and with the alpha modeled approach (_a) for Units #2 and #3. Unit#4 was not

evaluated for regenerations so the data set is limited to about 16 test points. The correlations did not improve for the regeneration case using the simple filter or the alpha approaches. The slopes were all negative and the R^2 was less than 0.1.
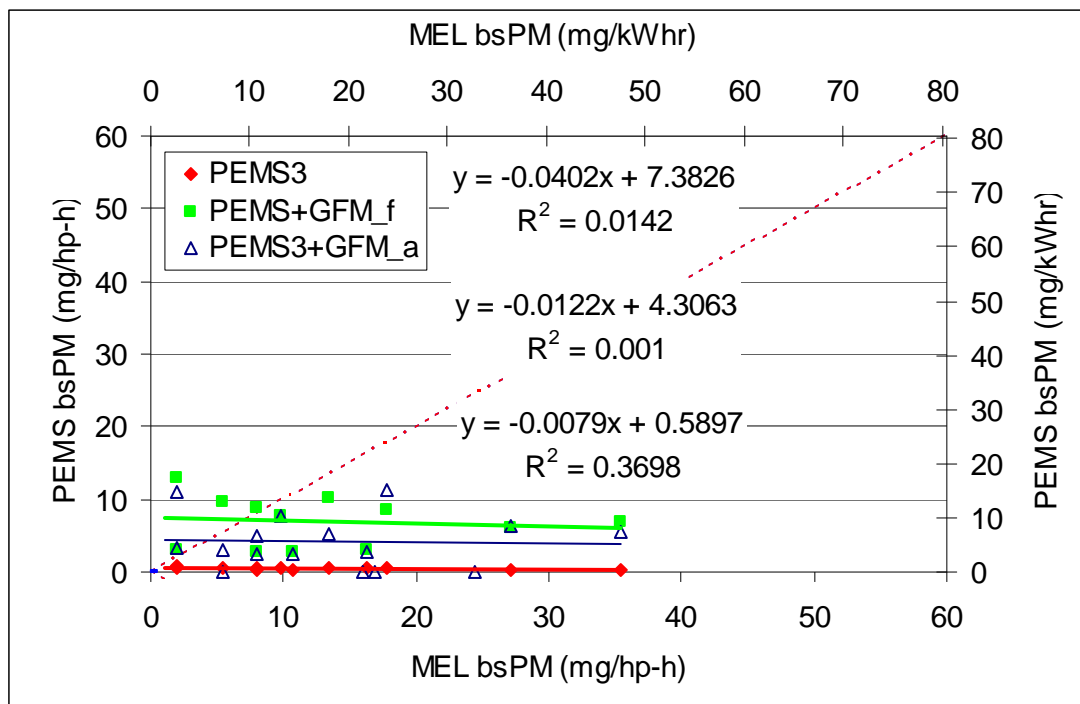
Figure 4-25 PEMS3 + simple filter (_f) and alpha (_a) modeled terms correlation (regen)

The filter weight on the PEMS3 GFM was low relative to the combined MEL filters for both Units tested. The total filter weights should not agree since the MEL is sampling at a higher flow rate, different dilution ratios, and different sample durations. The MEL dilution averaged 6 to 1, but is proportional and the flow rate is 60 slpm where the PEMS is 6 to 1 constant dilution and 4 slpm, thus the MEL filter could be 10-15 times higher. Also the PEMS filter is sampled over the full test route where the MEL is only sampled for relatively short intervals with-in each test sequence. Thus, the PEMS filter samples longer than the MEL. To make the filter weight comparison the MEL filters were added and compared to the PEMS filter. For Unit#2 and #3 there were eight MEL filters and one PEMS filter. The PEMS3 filter for Unit#2 was 47.5 ug where the MEL was 1145 ug and for Unit#3 the PEMS was 48.7 and the MEL was 1400 ug.

Composition analysis showed that most of the MEL filter was sulfate > 95% as will be discussed later in Section 4.7. The PEMS filter measured only about 11 ug of sulfur out of 47 ug or 25% of the total mass. The 11 ug sulfur measurement is near the quantification limits, thus more research is needed to understand the sulfate filter weight differences. Also during these tests some of the THC measurements from the gaseous PEMS were off-scale which may have affected the alpha corrections as will be discussed in the next section. During a previous study by Durbin et al (2009b) the reconstructed modeled approach performed better where the slope increased by a factor of 10 from 0.04 to 0.34 for the high sulfate type PM.

4.4.3.3 Total PM evaluation

The alpha modeling approach requires reliable measurements of THC concentration, exhaust temperature, fuel sulfur and a gravimetric filter mass to reconstruct the total PM. THC is difficult to measuring during high concentration and low load low rpm conditions. Figure 4-26 shows the raw measurement of THC concentration prior to an NTE event. The figure shows a 20 ppm THC hang-up compared to the CVS diluted sample where this hang-up doesn't appear to occur. The THC concentration directly affects the alpha term of the PEMS3 modeled PM approach. This hang-up issue could cause variability on the alpha terms and may be one reason the total PM approach increased the data spread where the SEE changed from 3.0 to 3.3 mg/hp-h, see Table 4-3. It may also affect the regeneration data where large THC is present during low catalyst temperatures where THC hang-up may occur. Nevertheless the Alpha approach did have a lower SEE than the simple filter approach. More analysis and testing are needed to fully characterize and quantify these findings.
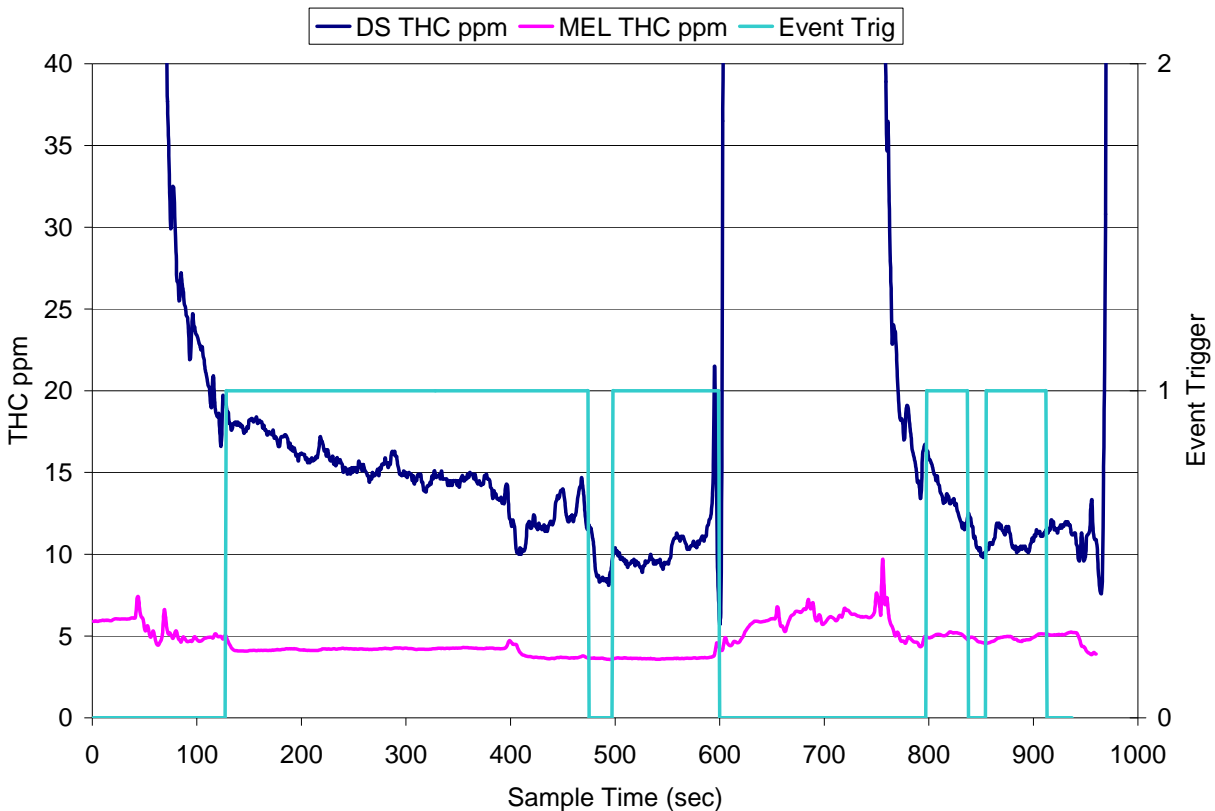
Figure 4-26 PEMS3 + GFM real time tailpipe THC hang up difference to dilute CVS THC.

One example of the true success of the GFM system can be shown from the results presented in Figure 4-27. This data was not included in the main analysis since it includes a regeneration where the bypass was installed. This test case provides an example of what would happen if both the DPF and DOC failed during in-use testing and a regeneration was performed. Figure 4-27 shows the real time measurements of THC and PEMS concentrations for PEMS3, 4, and 5. During the bypass regeneration the PEMS3 and 5 systems responded with very little compared to PEMS4 (light scattering device). For this event the gravimetric bsPM was 60.7 mg/hp-h and

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PEMS4 overestimated it at 87 mg/hp-h and PEMS3 and 5 underestimated at around 21 mg/hp-h. When the PEMS3+GFM alpha approach are used, the reconstructed PEMS3 data increased from 22.0 to 54.7 mg/hp-h. This reduced the error on this point from 60% low to 10% low relative to the MEL. The simple filter approach did not improve the total PM as much and only increased to 27.4 mg/hp-h which is still about 55% low relative to the MEL.
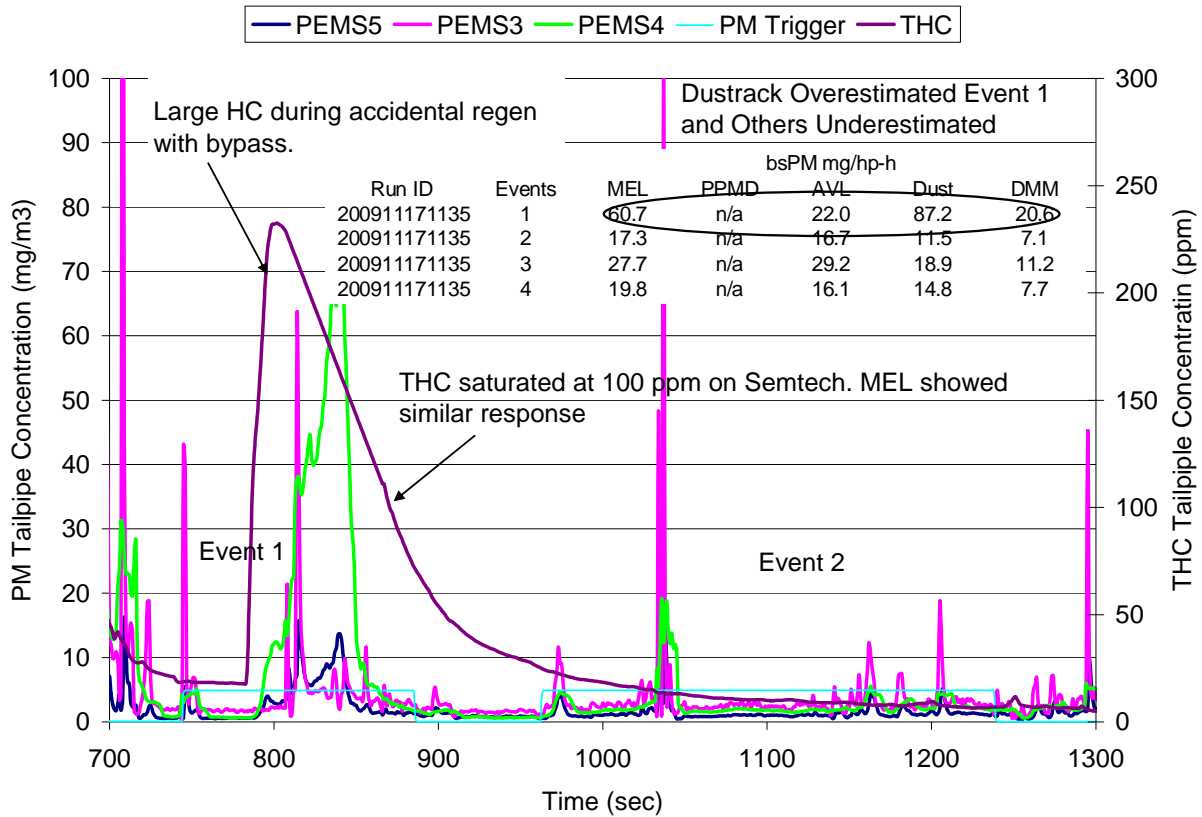
Figure 4-27 PEMS3 + GFM THC spike and reconstructed total PM with PEMS4 and 5.

In general, the PEMS3 total PM approach appears to be mixed. During non-regeneration conditions the alpha approach showed very close correlation and the simple filter approached overestimated the PM mass slightly, although within the accuracy of the two reference laboratories. The events that were nearly all regeneration, without bypass condition, did not show a good correlation with either the simple filter or alpha approaches. The lower performance may be due to THC measurements, filter artifacts, or possibly some filter sampling issues with the GFM. As noted above, filter analyses indicate that there are differences in the capture of sulfates that need further study. The regeneration with bypass where the organic fractions are high showed significant improvements with the alpha approach compared to the simple filter approach. Additional testing is needed to verify that both approaches are valid over the range of expected emissions level and composition expected during in-use testing where there may be repeated regenerations, but it is encouraging to see how well the method can work on dry soot and with high organic PM situations.

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4.4.4   INST 4 and 5 Trends

In addition to the PEMS2 and 3 systems, two other PM instruments were also analyzed to show the relative errors between the current PEMS and other PM measuring instruments. These instruments are called INST4 and 5 as described in Section 3. INST4 and 5 are not PM PEMS and are not considered alternate systems for in-use compliance testing, but they do provide insight for trends between PEMS units and on a composite basis.

INST4 is typically calibrated on Arizona road-dust, but was integrated into the MEL with a MEL gravimetric span calibration performed back in 2005. Thus INST4 measurement is based on a 2005 calibration with the MEL. INST5 utilizes its own internal daily calibrations which does not include a span, but does include a zero check performed daily. INST5 was also corrected for actual sample flow rates, as discussed earlier. Thus, these data are presented briefly here and later in the combined analysis section that follows.

Unit 1 events evaluated
INST4 and 5 showed similar responses for the runs associated with units 2, 3 and 4, but both showed a noticeably higher response for the unit 1 testing, see Figure 4-28 through Figure 4-31. Figure 4-28 and Figure 4-29 are INST4 and 5 bsPM correlation figures, and Figure 4-30 and Figure 4-31 are the PM correlation figures respectively. The slopes for INST4 and 5 changed from 1 and 1.3 (unit 1) to ~ 0.73 and 0.4 for units 2, 3, and 4 testing, respectively. The SEE was also different between the same units were the SEE changed from 5 and 12 mg/hp-h to 3 and 3 mg/hp-h for INST4 and 5, respectively. This suggests that unit 1 test events were slightly different than those for the other unit tests.

Time alignment was evaluated on unit1 for INST4 and 5 to see if this could explain the high slope for unit1 vs the other units. Ideal time alignment for INST4 and5 is 3 seconds based on previous practices. Time alignment was evaluated from no time alignment (0 seconds) to 10 seconds of delay. The results did not vary significantly and at the maximum delay shift of 10 seconds affected the slope on both INST4 and 5 only slightly. The slope did decrease, but the amount was not significant enough to affect the results and is thus not presented.
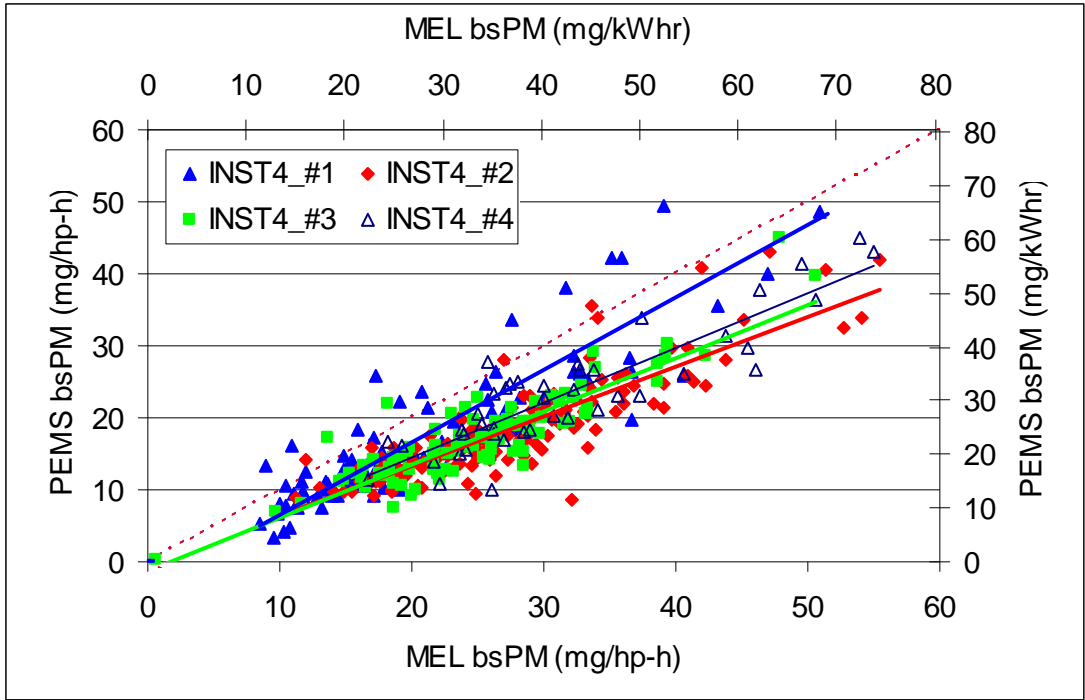
Figure 4-28 INST4 bsPM correlation: unit comparison
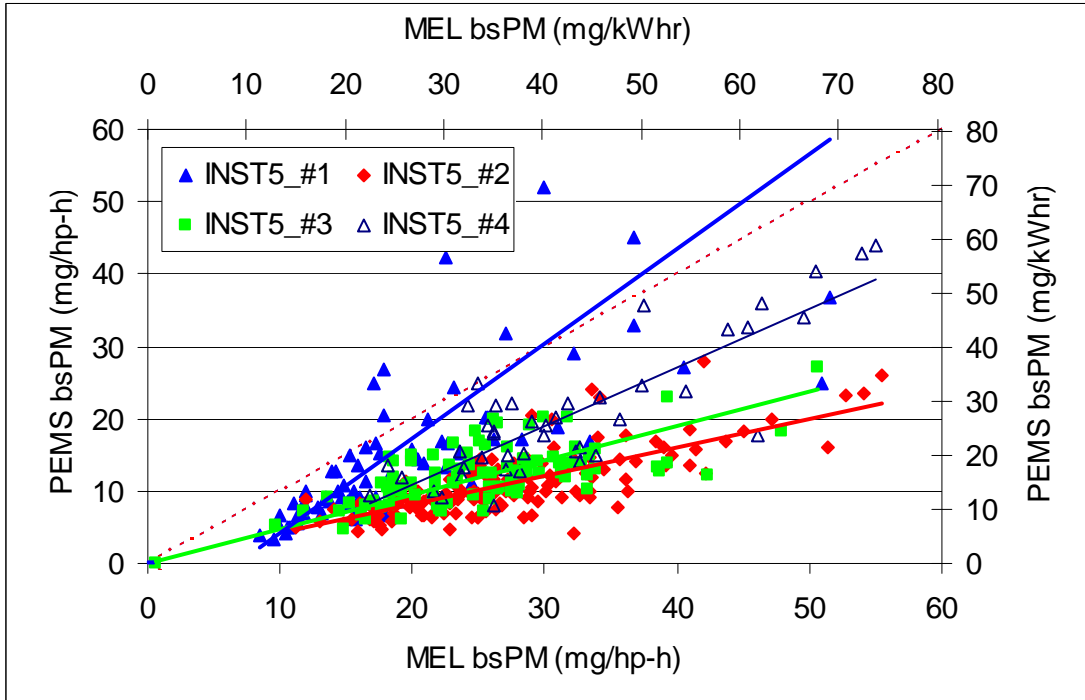
Figure 4-29 INST5 bsPM correlation: unit comparison

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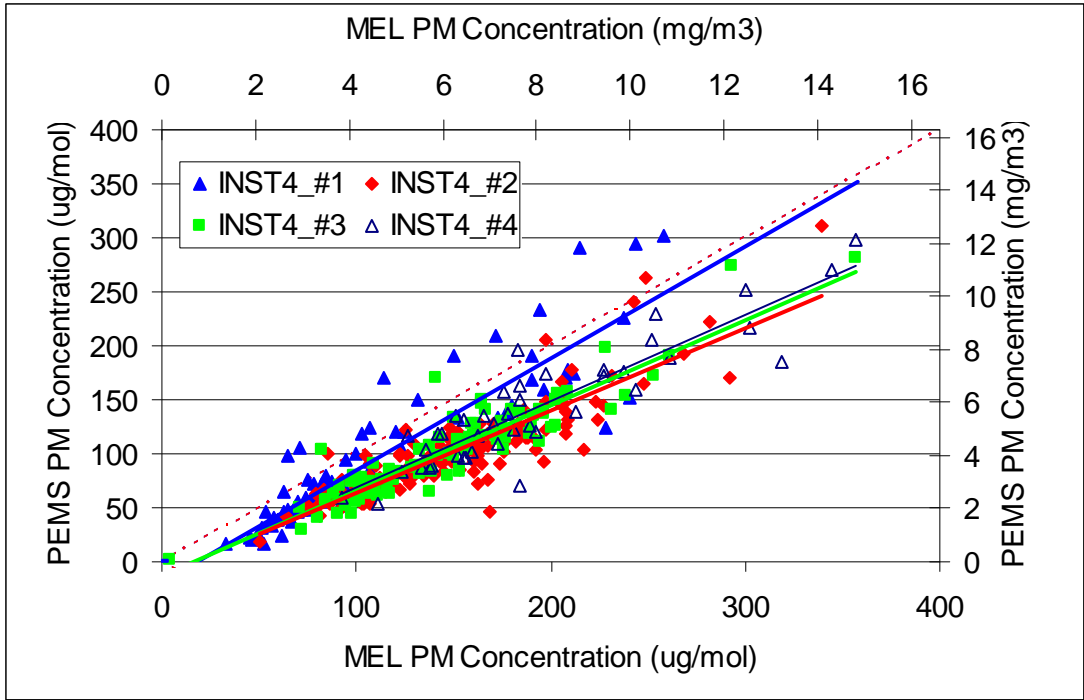
Figure 4-30 INST4 concentration correlation: unit comparison
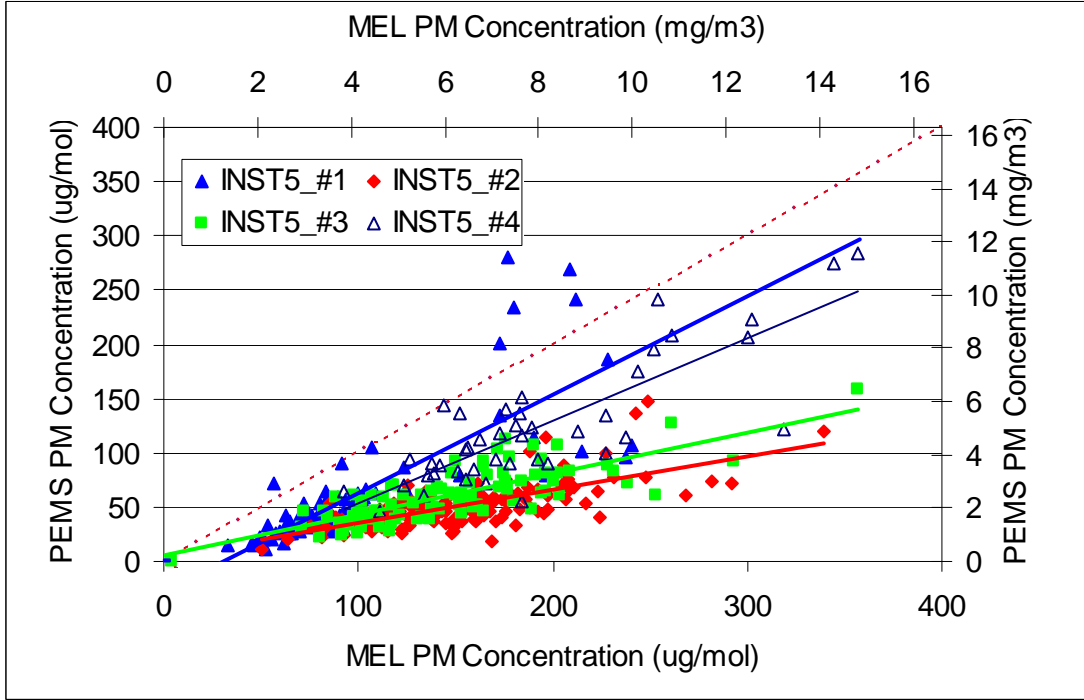
Figure 4-31 INST5 concentration correlation: unit comparison

Affect on PEMS2 and 3

The slight difference on unit 1 was not apparent for either the PEMS2 or PEMS3 data. PEMS3 did not have any valid data for unit 1. PEMS3 variability was large and due to the incorrect

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crystal sensitivity for unit 1, which may mask any differences in testing for unit 1 vs. units 2 and 3.

bsPM versus PM concentration plots
Another observation that became apparent from the INST4 and 5 plotted data was the difference between the bsPM correlation and the PM concentration correlation. The slope of the INST5 changed from over predicting some bsPM values to under predicting some PM concentrations. It appears that the work term tends to move the data points around in the correlation plot causing the correlation to behave in a way that changes the indicated behavior. This suggests that PM concentration correlation plots may be more informative when comparing instrument behavior. Since this study is about instrument measurement errors, the PM concentration plots are probably the more appropriate comparisons figure for understanding trends and causality.

4.4.5 PEMS and INST Correlation Summary Unit Comparisons

The following tables list all the correlation summaries for each unit comparison figure presented in Section 4.4. They are presented in tables for direct comparisons between all PEMS and INST. The non-regeneration results are presented in Table 4-4 through Table 4-8 and the regeneration results are presented in Table 4-9 through Table 4-12.

Table 4-4 Non Regeneration PEMS bsPM Method 1 correlation by unit (mg/hp-h)

PEMS	Slope				Intercept				R^2				Standard Error Estimate			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
PEMS 2	0.30	0.24	0.14		1.5	3.9	8.2		0.52	0.34	0.20		4.8	4.9	5.8	
PEMS 3		0.98	0.87	0.92		-0.5	-0.3	-0.4		0.93	0.96	0.98		3.3	2.1	2.0
INST 4	1.00	0.70	0.74	0.76	-3.4	-0.7	-1.2	-0.7	0.89	0.87	0.89	0.89	5.0	3.4	3.0	3.9
INST 5	1.33	0.39	0.36	0.81	-9.4	0.4	3.2	-5.2	0.75	0.76	0.67	0.85	11.6	2.9	3.1	4.9

Table 4-5 Non Regeneration PEMS PM concentration by unit (ug/mol)

PEMS	Slope				Intercept				R^2				Standard Error Estimate			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
PEMS 2	0.22	0.40	0.36		13.7	21.8	52.0		0.46	0.42	0.32		23.5	42.5	55.1	
PEMS 3		0.95	0.85	0.85		-1.5	-2.9	-2.4		0.90	0.96	0.98		20.4	13.0	11.6
INST 4	1.04	0.76	0.79	0.80	-19.6	-12.9	-13.0	-11.0	0.91	0.88	0.92	0.90	25.8	19.8	17.6	24.0
INST 5	0.91	0.31	0.38	0.76	-29.1	4.8	4.8	-23.1	0.78	0.71	0.79	0.83	35.1	14.3	15.4	32.0

Table 4-6 Non Regeneration PEMS bsPM Method 1 deltas by unit (mg/hp-h)

PEMS	Slope				Intercept				ttest				Standard Error Estimate			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
PEMS 2	-0.70	-0.76	-0.86		1.5	3.9	8.2		4.E-18	9.E-41	6.E-36		4.8	4.9	5.8	
PEMS 3		-0.02	-0.13	-0.08		-0.5	-0.3	-0.4		2.E-70	2.E-51	4.E-24		3.3	2.1	2.0
INST 4	0.00	-0.30	-0.26	-0.24	-3.4	-0.7	-1.2	-0.7	2.E-37	4.E-79	1.E-49	9.E-24	5.0	3.4	3.0	3.9
INST 5	0.33	-0.61	-0.64	-0.19	-9.4	0.4	3.2	-5.2	1.E-25	9.E-77	5.E-46	4.E-25	11.6	2.9	3.1	4.9

Table 4-7 Non Regeneration PEMS PM concentration deltas by unit (ug/mol)

PEMS	Slope				Intercept				ttest				Standard Error Estimate			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
PEMS 2	-0.78	-0.60	-0.64		14.8	21.8	52.0		1.E-16	9.E-36	2.E-29		23.5	42.5	55.1	
PEMS 3		-0.05	-0.15	-0.15		-1.5	-2.9	-2.4		2.E-71	1.E-46	3.E-23		20.4	13.0	11.6
INST 4	0.04	-0.24	-0.21	-0.20	-19.6	-12.9	-13.0	-11.0	5.E-37	6.E-82	3.E-46	3.E-23	25.8	19.8	17.6	24.0
INST 5	-0.09	-0.69	-0.62	-0.24	-29.1	4.8	4.8	-23.1	5.E-32	6.E-77	9.E-44	2.E-23	35.1	14.3	15.4	32.0

Table 4-8 Non Regeneration PEMS bsPM Method 1 deltas percent of point)

PEMS	Slope 1	Slope 2	Slope 3	Slope 4	Intercept 1	Intercept 2	Intercept 3	Intercept 4	Standard Error Estimate 1	Standard Error Estimate 2	Standard Error Estimate 3	Standard Error Estimate 4
PEMS 2	-0.8%	-0.5%	-4.2%		-39%	-49%	62%		45%	17%	57%	
PEMS 3		0.0%	0.1%	0.1%		-4%	-15%	-12%		11%	7%	6%
INST 4	0.5%	0.0%	0.1%	0.0%	-29%	-32%	-34%	-27%	22%	12%	14%	13%
INST 5	1.9%	-0.1%	-0.2%	0.4%	-61%	-56%	-45%	-48%	38%	10%	13%	15%

Table 4-9 Regeneration PEMS bsPM Method 1 correlation results by unit (mg/hp-h)

PEMS	Slope 1	Slope 2	Slope 3	Slope 4	Intercept 1	Intercept 2	Intercept 3	Intercept 4	R^2 1	R^2 2	R^2 3	R^2 4	Standard Error Estimate 1	Standard Error Estimate 2	Standard Error Estimate 3	Standard Error Estimate 4
PEMS 2	-0.01	0.04	0.27		2.9	2.6	3.0		-0.05	0.34	0.74		0.9	1.8	1.9	
PEMS 3		-0.01	-0.02			0.7	0.4			-0.75	-0.53			0.1	0.2	
INST 4	0.05	-0.14	-0.01		0.3	3.6	0.5		0.22	-0.47	-0.21		1.0	3.3	0.4	
INST 5	0.17	0.18	0.36		0.1	-1.0	-1.8		0.73	0.85	0.86		0.8	1.4	2.1	

Table 4-10 Regeneration PEMS PM concentration correlation results by unit (ug/mol)

PEMS	Slope 1	Slope 2	Slope 3	Slope 4	Intercept 1	Intercept 2	Intercept 3	Intercept 4	R^2 1	R^2 2	R^2 3	R^2 4	Standard Error Estimate 1	Standard Error Estimate 2	Standard Error Estimate 3	Standard Error Estimate 4
PEMS 2	0.06	0.06	0.36		11.2	22.0	31.1		0.71	0.33	0.71		3.1	17.0	18.8	
PEMS 3		-0.01	-0.01			3.2	2.5			-0.52	-0.46			1.0	1.4	
INST 4	0.06	-0.13	-0.01		1.2	21.2	3.2		0.37	-0.41	-0.23		6.1	23.2	2.5	
INST 5	0.14	0.16	0.25		-0.1	-4.8	-6.2		0.80	0.90	0.77		3.8	6.5	13.3	

Table 4-11 Regeneration PEMS bsPM Method 1 deltas correlation results by unit (mg/hp-h)

PEMS	Slope 1	Slope 2	Slope 3	Slope 4	Intercept 1	Intercept 2	Intercept 3	Intercept 4	ttest 1	ttest 2	ttest 3	ttest 4	Standard Error Estimate 1	Standard Error Estimate 2	Standard Error Estimate 3	Standard Error Estimate 4
PEMS 2	-1.01	-0.96	-0.73		2.9	2.6	2.9		2.E-01	6.E-02	9.E-03		0.9	1.8	1.7	
PEMS 3		-1.01	-1.02			0.7	0.4			9.E-03	4.E-03			0.1	0.2	
INST 4	-0.95	-1.14	-1.00		0.3	3.6	0.3		3.E-03	1.E-02	4.E-03		1.0	3.3	0.3	
INST 5	-0.83	-0.82	-0.71		0.1	-1.0	-0.7		3.E-03	7.E-03	4.E-02		0.8	1.4	1.6	

Table 4-12 Regeneration PEMS PM concentration deltas correlation results by unit (ug/mol)

PEMS	Slope 1	Slope 2	Slope 3	Slope 4	Intercept 1	Intercept 2	Intercept 3	Intercept 4	ttest 1	ttest 2	ttest 3	ttest 4	Standard Error Estimate 1	Standard Error Estimate 2	Standard Error Estimate 3	Standard Error Estimate 4
PEMS 2	-0.94	-0.94	-0.64		11.2	22.0	30.2		2.E-01	8.E-02	2.E-02		3.1	17.0	16.6	
PEMS 3		-1.01	-1.02			3.2	2.7			1.E-02	4.E-03			1.0	1.2	
INST 4	-0.94	-1.13	-1.00		1.2	21.2	2.2		2.E-02	2.E-02	3.E-03		6.1	23.2	2.3	
INST 5	-0.86	-0.84	-0.78		-0.1	-4.8	-2.6		2.E-02	1.E-02	4.E-02		3.8	6.5	9.5	

4.5   PM PEMS Combined Analysis

The following analysis and results are for all units combined for PEMS2 and 3 to look at the overall picture for the non-regeneration and regeneration cases. The first subsection is for the main non-regeneration case used for the MA validation evaluation and covers all valid results submitted to SwRI. The second subsection covers the same analysis, but for the regeneration non-bypass only case. Both cases utilized the Method 1 calculation.

In addition to the main PM PEMS, two other PM instruments were also added to the comparison to show relative errors between the current PEMS and other the PM measuring instruments, INST4 and 5.

4.5.1.1   Non-Regenerations

This section covers the combined results used for the MA validation for the non-regeneration case. Figure 4-32, Figure 4-34, and Figure 4-36 show the correlation comparisons between PEMS2 and 3 and the MEL. Figure 4-33, Figure 4-35 and Figure 4-37 show the same correlation except with the addition of INST4 and INST5. Table 4-14 through Table 4-17 list the correlation statistics for each of the figures for direct comparisons between PEMS and INST tested. Figure 4-32 and Figure 4-33 are on a brake specific basis, Figure 4-34 and Figure 4-35 are on a delta brake specific basis and Figure 4-36 and Figure 4-37 are on a concentration basis.

bsPM correlation
PEMS3 showed the highest correlation and PEMS2 the lowest correlation at $R^2 = 0.94$ and 0.37. INST4 and 5 had R^2 values of 0.86 and 0.56, respectively. PEMS3 also showed the closest to unity slope and lowest SEE overall at 0.95 and 3 mg/hp-h. PEMS2 slope was the lowest at 0.24 and the SEE was the next to highest at 5.4 g/hp-h. INST4 and INST5 both showed a higher slope (0.76 and 0.59) than PEMS2. INST4 showed a lower SEE at 4.3 mg/hp-h and INST5 higher at 8.3 mg/hp-h compared to PEMS2. INST5 showed a lower SEE compared to PEMS2 for the concentration correlation discussed later.

bsPM delta correlation
The bsPM delta figures, Figure 4-34 and Figure 4-35, provide a similar result as the correlation figures, but visually show the pool of PEMS2 and 3 data relative to 34% (MA proposed reference line) and 100% error lines. The blue dotted line below the x-axis is the -34% error line and the red dotted line below the x-axis is the -100% error line. Figure 4-34 shows PEMS3 is clearly between the x-axis (0% error) and the -34% error where PEMS2 is clearly between the -34% and -100% error lines. Figure 4-35 shows the comparison of INST4 and 5 to PEMS2 and 3. INST4 and PEMS3 were above the - 34% error line where INST5 and PEMS2 were below the -34% error line. The PEMS2 mean bias at the 20 mg/hp-h bsPM emissions is -10 mg/hp-h and at 30 mg/hp-h the mean bias is -18 mg/hp-h. The PEMS3 mean bias at the 20 and 30 mg/hp-h were xx and xx mg/hp-h respectively.

PM concentration

The concentration figures show similar trends to the bsPM correlations with the addition of higher relative SEE and a slight shift in PEMS2 and INST5 correlations. The SEE from the figures appears to have increased for all PEMS and INST. To evaluate the relative variability, the PEMS SEE was compared to the 50th percentile measurement (i.e., SEE/50th percentile). The PEMS2 and 3 concentration SEE% was 50% and 21%, respectively. The corresponding bsPM SEE% was 23% and 13%, respectively. INST 4 and 5 SEE also increased, as listed in Table 4-15.
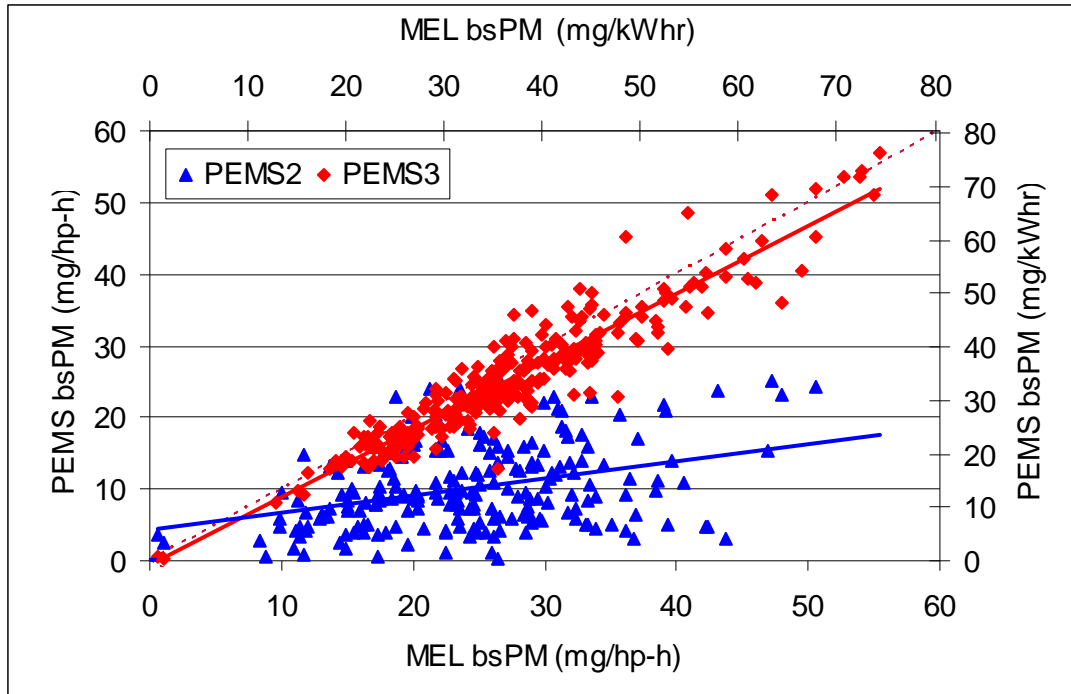
Figure 4-32 PEMS2 and 3 bsPM combined correlation comparison
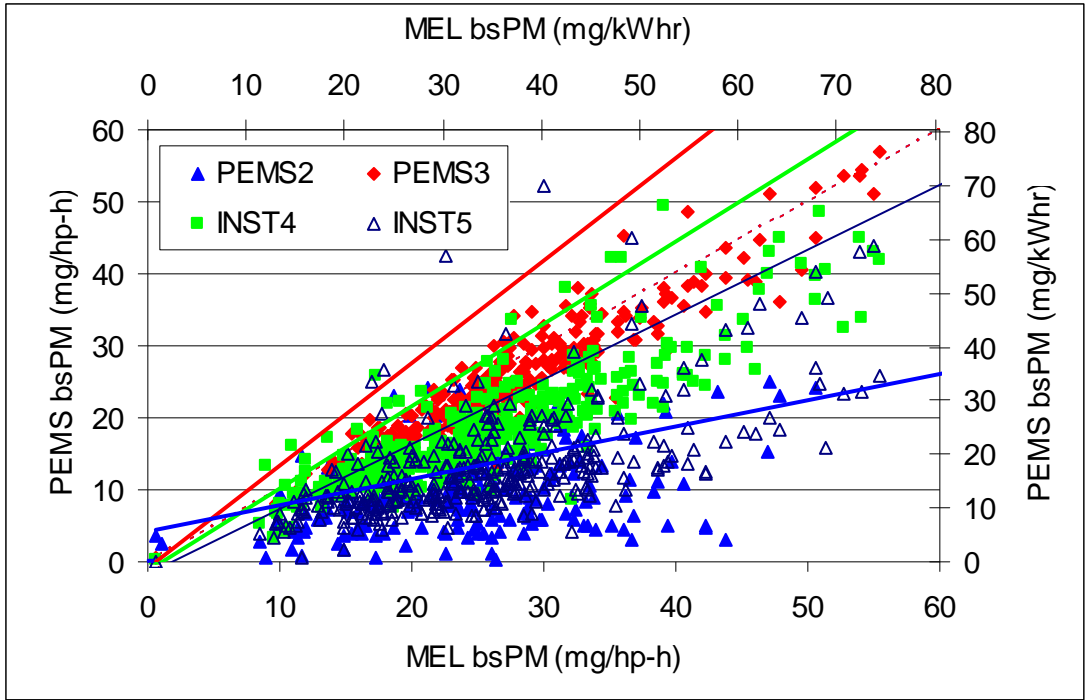
Figure 4-33 PEMS2 and 3 INST 4 and 5 bsPM combined correlation comparison
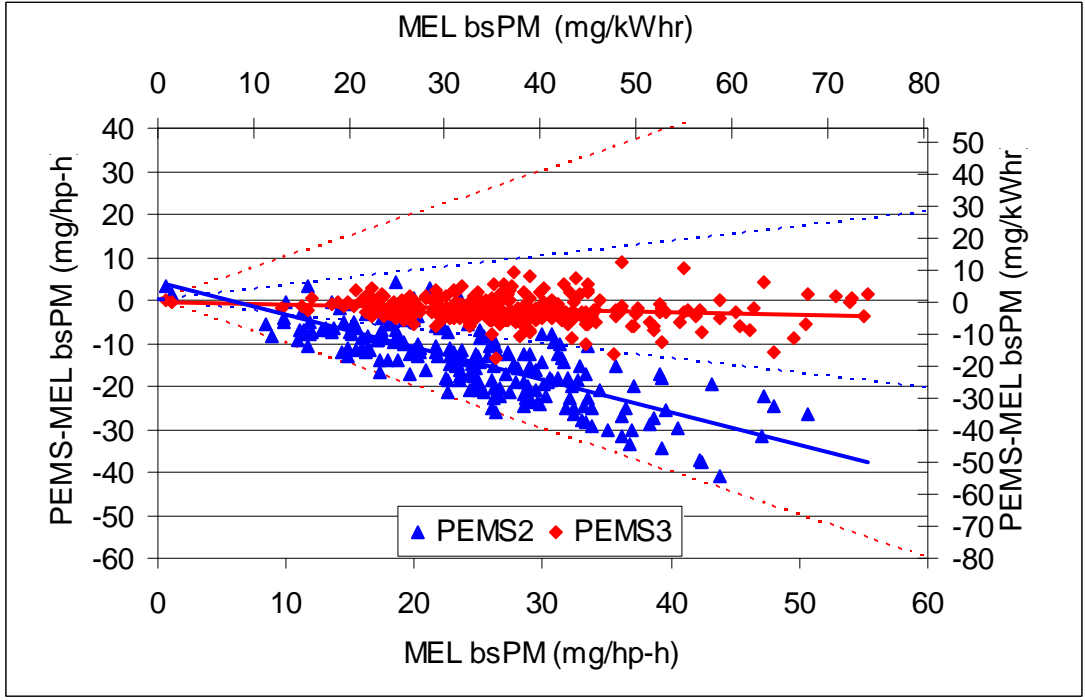
Figure 4-34 PEMS2 and 3 bsPM combined delta correlation comparison
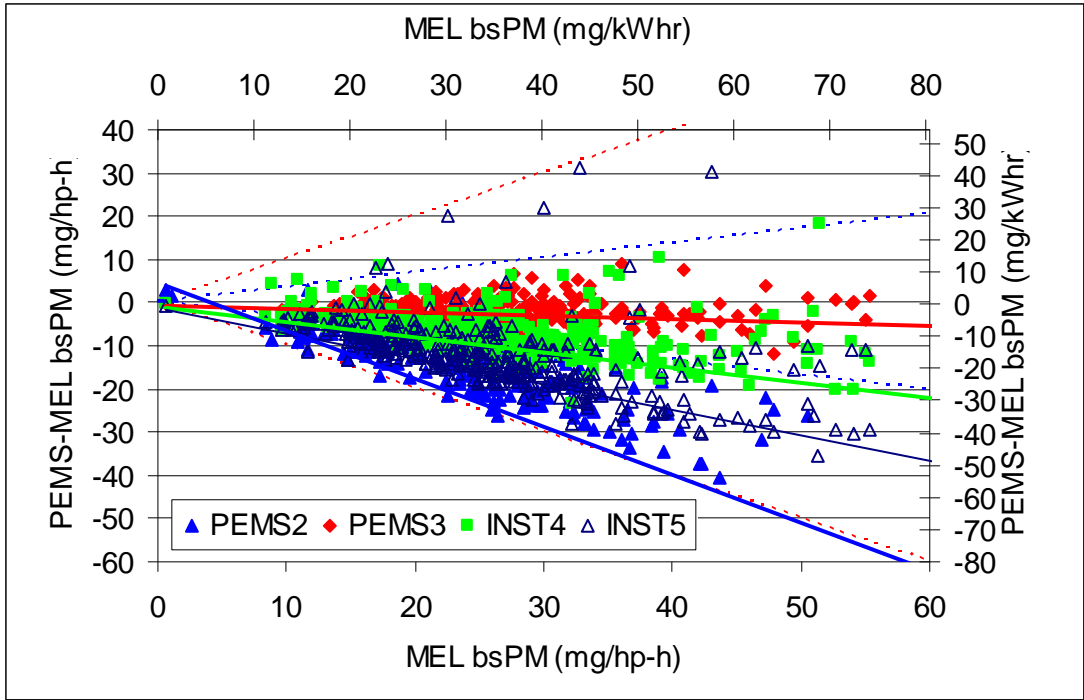
Figure 4-35 PEMS2 and 3 INST 4 and 5 bsPM combined delta correlation comparison
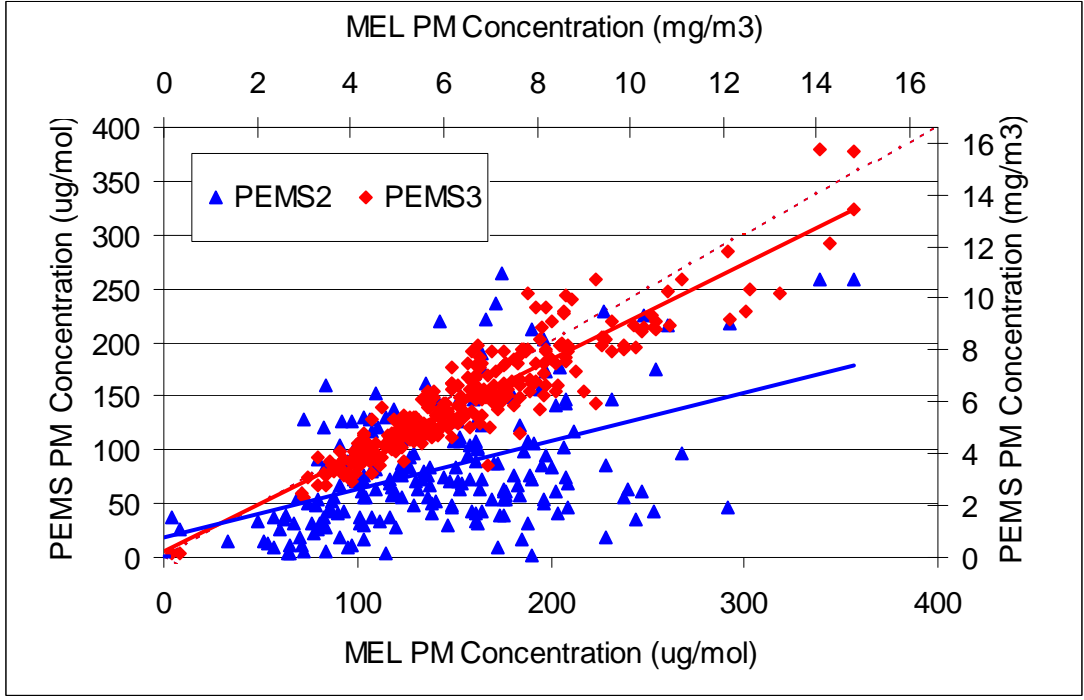
Figure 4-36 PEMS2 and 3 PM concentration correlation comparison
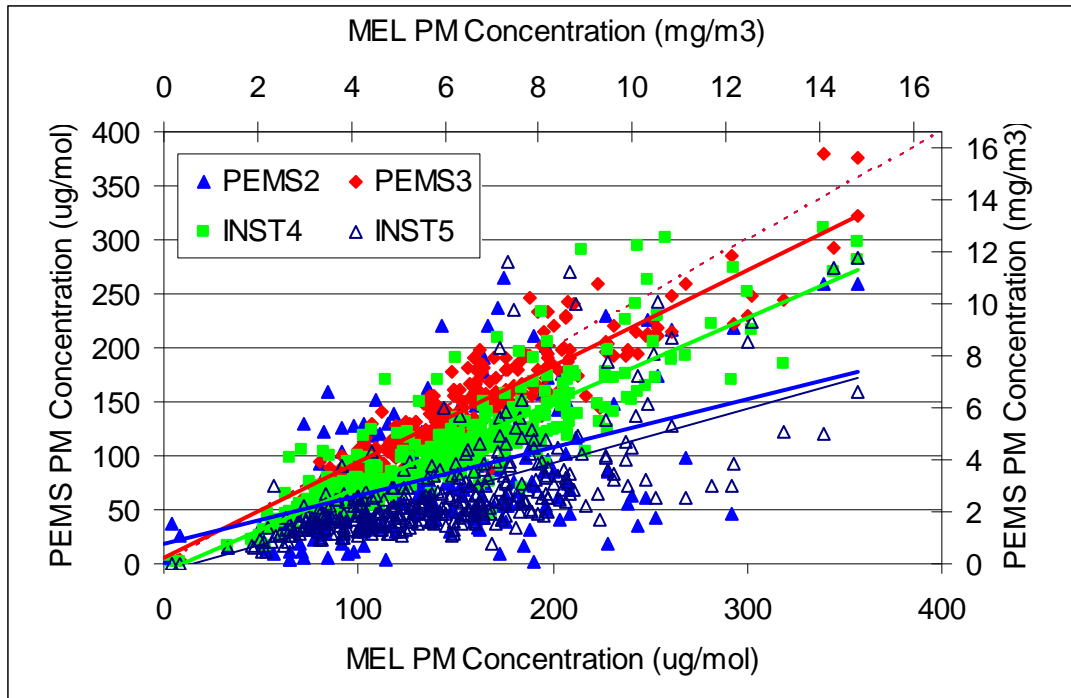
Figure 4-37 PEMS2 and 3 INST 4 and 5 PM concentration correlation comparison

Table 4-13 PEMS PM bsPM correlation results combined (mg/hp-h)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	0.24	4.2	0.37	5.4	2E-63
PEMS 3	0.95	-0.7	0.94	3.0	2E-25
INST 4	0.76	-1.0	0.86	4.3	1E-96
INST 5	0.59	-1.3	0.56	8.3	1E-78
PEMS 3_M2	0.90	-0.8	0.94	2.9	4E-54

Table 4-14 PEMS PM concentration correlation results combined (ug/mol)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	0.45	17.9	0.47	48.4	2E-35
PEMS 3	0.89	5.9	0.92	20.1	6E-18
INST 4	0.78	-8.3	0.88	24.3	6E-95
INST 5	0.50	-8.0	0.67	32.4	2E-117

Table 4-15 PEMS bsPM Method 1 deltas correlation results combined (mg/hp-h)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	-0.76	4.2	-0.78	5.4	5E-89
PEMS 3	-0.05	-0.7	-0.16	3.0	2E-139
INST 4	-0.24	-1.0	-0.47	4.3	1E-171
INST 5	-0.41	-1.3	-0.42	8.3	1E-150

Table 4-16 PEMS PM concentration deltas correlation results combined

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	-0.76	4.2	-0.78	5.4	5E-89
PEMS 3	-0.40	-0.8	-0.17	20.6	1E-78
INST 4	-1.21	-8.3	-0.42	24.8	9E-135
INST 5	-2.35	-18.8	-0.52	37.1	4E-137

Table 4-17 PEMS bsPM Method 1 % deltas correlation results combined

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	-2.0%	-5%	-0.35	46%	5E-102
PEMS 3	0.1%	-12%	0.11	11%	1E-142
INST 4	0.0%	-29%	0.02	17%	7E-178
INST 5	0.1%	-49%	0.04	27%	2E-170

4.5.1.2 Regenerations

This section discussions the regeneration analysis for PEMS2, PEMS3, INST4 and INST5. This analysis is brief given the few points that were collected as part of this program. A more comprehensive analysis of regenerations with and with-out bypass is provided in a separate report by Durbin et al. (2009a).

Figure 4-38 through Figure 4-40 show the regeneration correlations comparing all PEMS and INST to the MEL. Figure 4-38 is the bsPM correlation, Figure 4-39 is the bsPM delta correlation, and Figure 4-40 is the concentration correlation. The summary statistics are listed in Table 4-18 through Table 4-21.
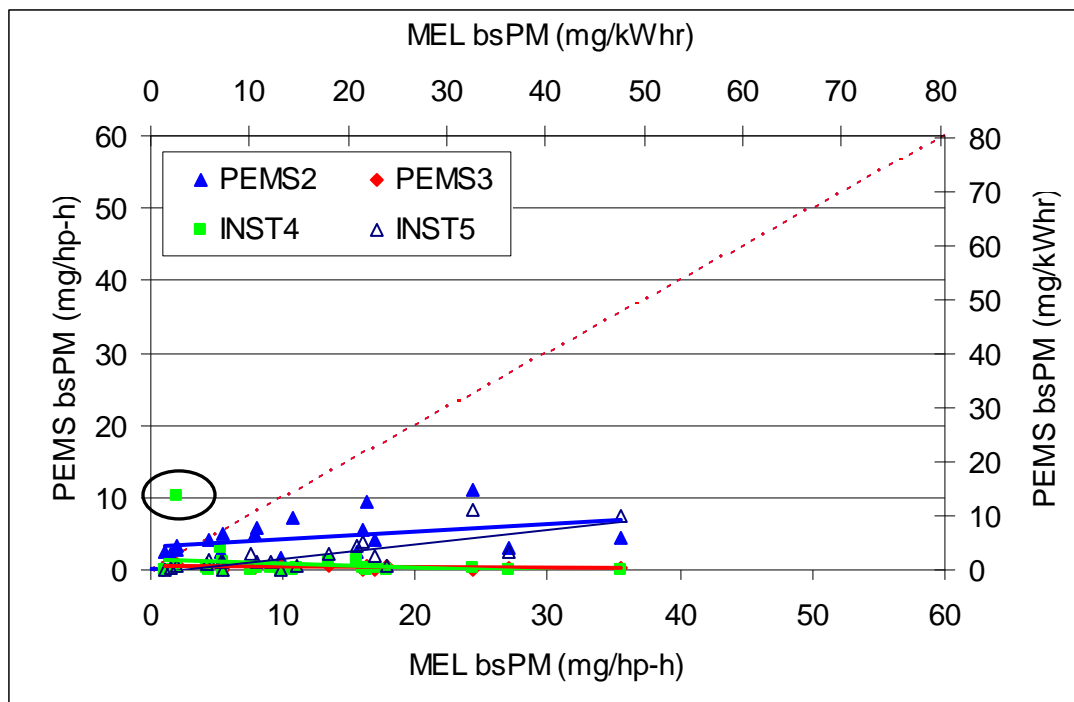
Figure 4-38 Regeneration PEMS2 and 3 INST 4 and 5 bsPM correlation
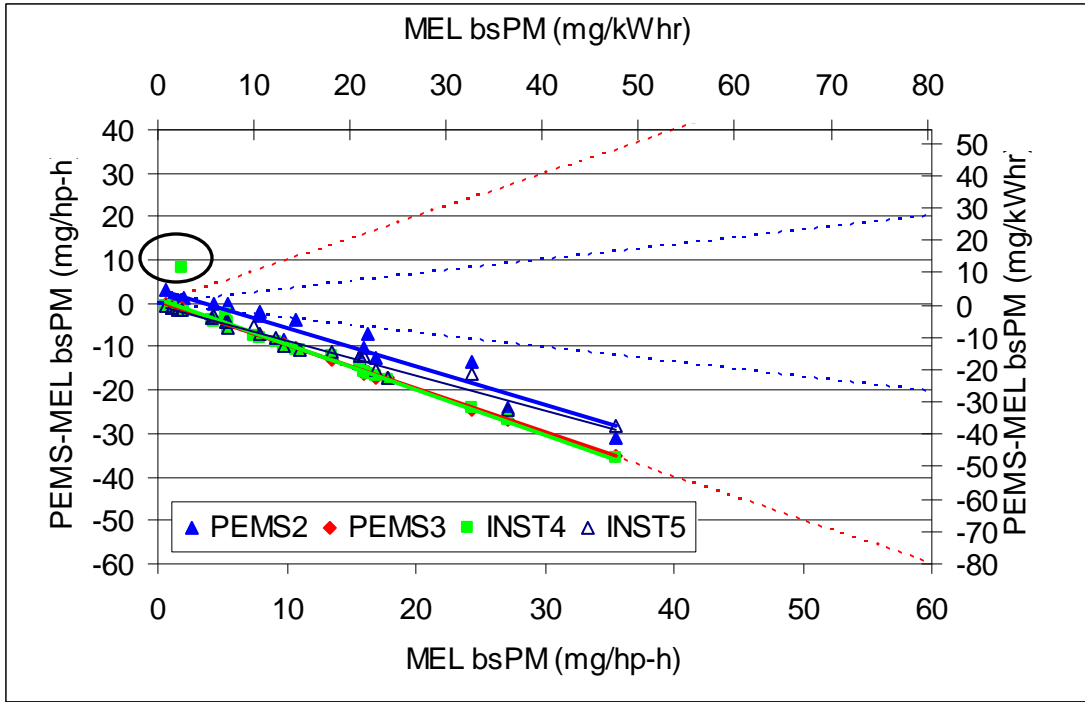
Figure 4-39 Regeneration PEMS2 and 3 INST 4 and 5 bsPM correlation
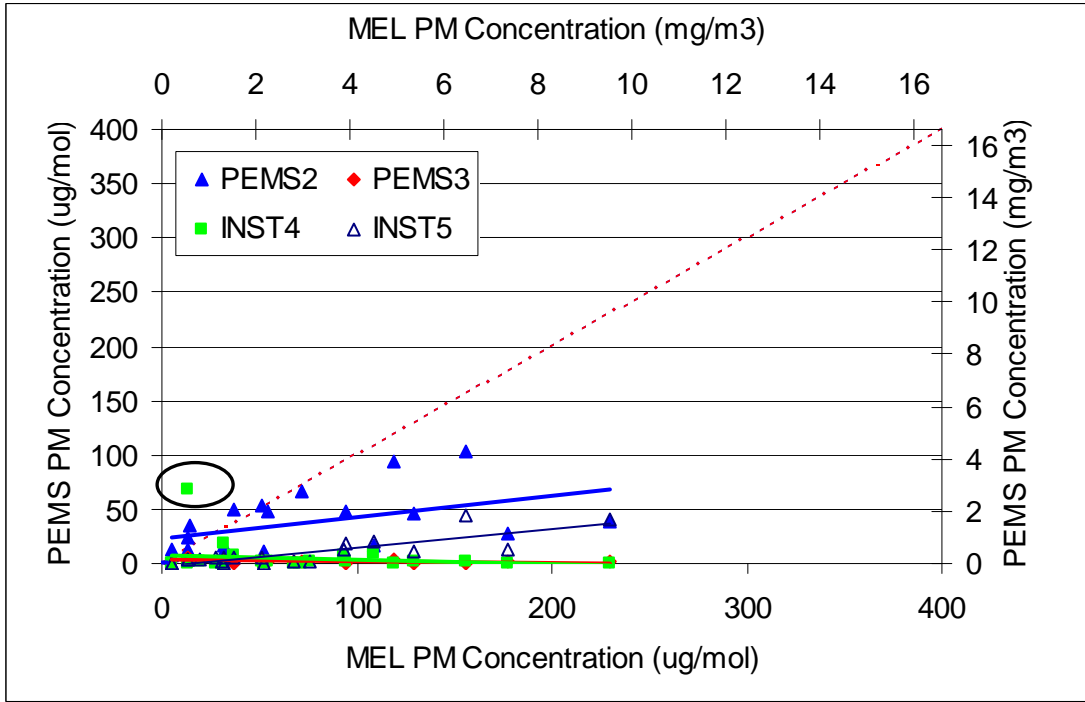
Figure 4-40 Regeneration PEMS2 and 3 INST 4 and 5 PM concentration correlation

Table 4-18 Regeneration PEMS bsPM Method 1 correlation results combined (mg/hp-h)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	0.11	3.2	0.40	2.4	3E-03
PEMS 3	-0.01	0.5	-0.37	0.2	5E-05
INST 4	-0.06	1.4	-0.24	2.0	1E-05
INST 5	0.20	-0.4	0.78	1.4	9E-06

Table 4-19 Regeneration PEMS PM concentration correlation results combined (ug/mol)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	0.20	23.6	0.46	25.2	1E-02
PEMS 3	-0.01	3.2	-0.38	1.6	7E-05
INST 4	-0.05	8.2	-0.19	13.7	4E-05
INST 5	0.17	-2.0	0.83	7.1	4E-05

Table 4-20 Regeneration PEMS bsPM Method 1 deltas correlation results combined (mg/hp-h)

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	-0.89	3.2	-0.97	2.3	6E-04
PEMS 3	-1.01	0.5	-1.00	0.2	7E-05
INST 4	-1.05	1.2	-0.98	2.0	4E-06
INST 5	-0.81	-0.3	-0.98	1.4	1E-05

Table 4-21 Regeneration PEMS PM concentration deltas correlation results combined

PEMS	Slope	Intercept	R^2	SEE	t-test
PEMS 2	-0.89	3.2	-0.97	2.3	6E-04
PEMS 3	-6.45	3.5	-0.98	14.0	1E-04
INST 4	-6.86	12.2	-0.96	17.4	2E-05
INST 5	-5.47	2.9	-0.97	13.2	3E-05

A strange INST4 (Dustrak) spike was found for the circled area. Deeper investigated showed that the PEMS4 system went from 1 to 13 mg/m^3 in 2 seconds and coincided with PEMS3 and INST5 spikes from 1 to 2 mg/m^3. This suggests the event was real, but the response was over reported by INST4. This event shows the measurement difficulties for some of the non-MA PM instruments and why PM measurements are so difficult to make, as their response to PM can dramatically overestimated when their measurement principles are based on surrogates such as light scatter, as opposed to mass.

4.6   PM bsPM Method Comparison

This section compares the different method calculations. PEMS2 is only capable of making calculations via methods 1 and 2 because of the semi-continuous nature of their measurement system. PEMS3 was processed with all three calculation methods. The PEMS2 post processor at the time of this report was not able to calculate Method2, so this calculate was made by UCR. PEMS3 calculated all 3 methods using their standard post processor.

Figure 4-41 shows the PEMS2 Method 1 and 2 calculation methods and Figure 4-42 shows the PEMS3 1, 2 and 3 method calculations. Both figures suggest that the method calculations did not significantly affect the results. Method 1 showed the closest correlation to the MEL system for both PEMS2 and 3. PEMS3 measurement principle is designed to measure soot PM only and thus is expected to underestimate during correlations with gravimetric systems. The soot fraction estimated for these tests was estimated at 90%, suggesting methods 2 and 3 could provide more accurate measurements. For the purposes of this study though, all the regressions were based on Method 1. The choice in method calculation for the work presented here did not affect the overall comparisons for PEMS2 and PEMS3 only show slight differences in slope from 0.95 to 0.90.

bsPM Method 2 and 3 correlation
The Method 2 comparison is evaluated here to show differences between methods on a combined basis. A more detailed unit-to-unit analysis was presented earlier. Method 2 results showed a lower overall slope for PEMS3 and only a slight change for PEMS2. INST4 and 5 were sampled from the CVS and thus could not be used with the Method 2 calculations. PEMS3 slope dropped from 0.95 to 0.9 for Method 2, but the R^2 and SEE remained about the same. PEMS2 slope, R^2 and SEE dropped only slightly to 0.22, 0.35 and 5.2 mg/hp-h, respectively, for the Method 2 calculations.
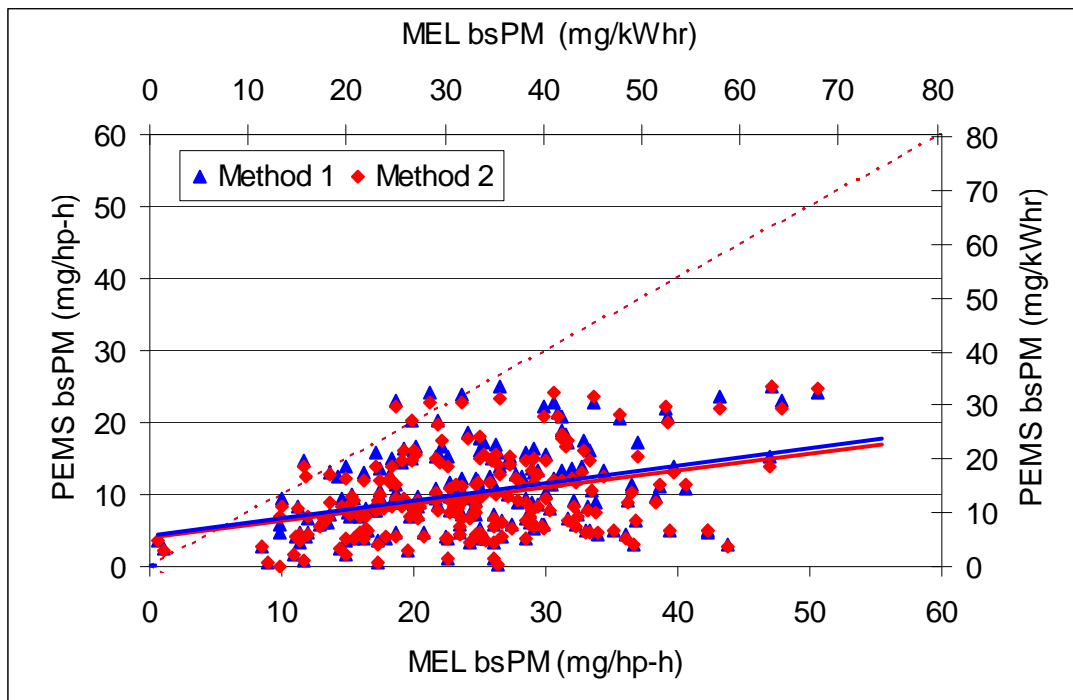
Figure 4-41 PEMS2 bsPM Method 1 and 2 comparison
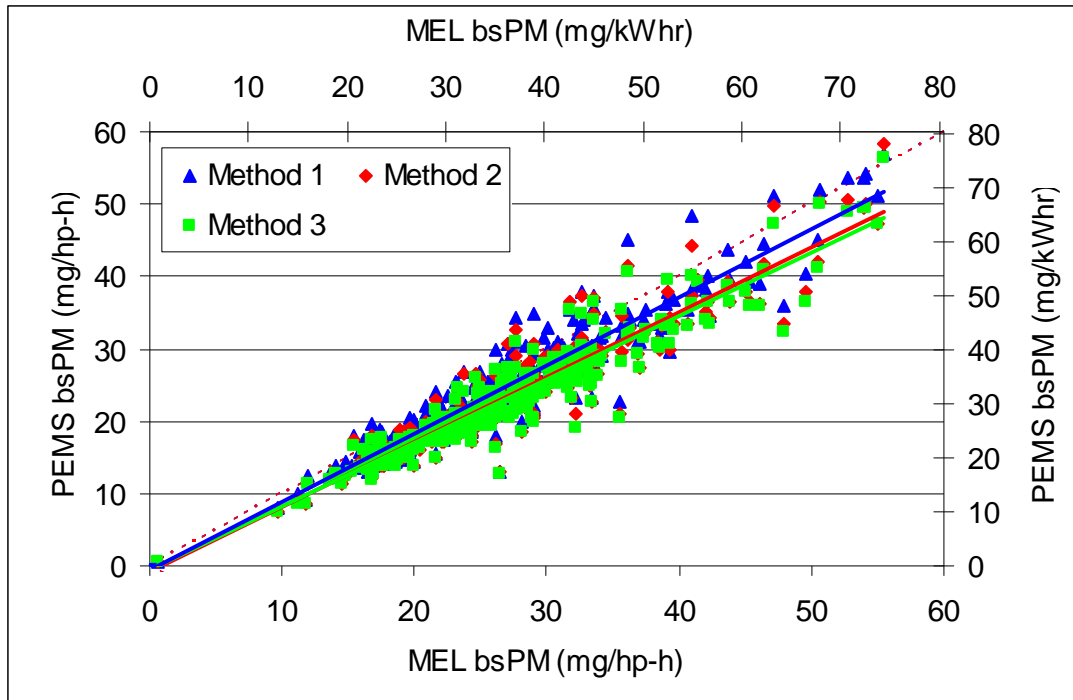
Figure 4-42 PEMS3 bsPM Method 1, 2 and 3 comparison

Table 4-22 PEMS2 bsPM method comparisons combined analysis

Method	Slope	Intercept	R^2	SEE	t-test	
1	0.24	4.2	0.37	5.4	6E-10	M1 vs M2
2	0.22	4.3	0.35	5.2	n/a	
3	n/a	n/a	n/a	n/a	n/a	

Table 4-23 PEMS3 bsPM method comparisons combined analysis

Method	Slope	Intercept	R^2	SEE	t-test	
1	0.95	-0.7	0.94	3.0	6E-62	M1 vs M2
2	0.90	-0.8	0.94	2.9	4E-15	M2 vs M3
3	0.88	-0.6	0.94	2.7	5E-63	M1 vs M3

4.7   PM Composition

This section describes the PM composition during selected events for the non-regeneration cases and regen cases. 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. The assumptions used to compute total PM mass from composition analysis is described in Appendix E. Also included in Appendix E is a description on detection limits for these measurements. The EC and OC were sampled on quartz filters in parallel with the gravimetric measurements. No back up quarts filters were utilized behind the Teflon gravimetric system to asses OC artifact issues, as described in Appendix E. The sulfate was

analyzed direct from the Teflon filters and does not have issues with artifact, but has assumptions about water hydration. The composition PM results are not as accurate as the gravimetric methods, but they do provide a guide on trends.

Non-regeneration
The non-regeneration PM was dominated by EC with small amounts of OC and trace amounts of sulfur. The EC measurements were on the order of 100 to 200 ug, OC around $40 - 100$ ug, and the SO_4^- ions around 1 to 5 ug. EC is a fairly robust and the measurement levels were well above the detection limits. The OC measurements were slightly above detection limits and issues regarding artifact make this measurement difficult and less reliable. The SO_4^- ions are at the detection limits of the instrument which suggests that very little sulfur is present in the non-regeneration PM. Using the assumptions in Appendix E one can estimate that about 90% of the in-use PM mass is from EC and 9% is from OC, and 1% or less is from sulfur species.

Additional analysis was performed by SwRI using a direct filter injection system for gas chromatographs (US Patent # 5109710). During this analysis, SwRI analyzed five selected MEL Teflon filters and 5 from SwRI (during the model development work). This analysis has the benefit of a common platform to better group trends about how dry the soot was or wasn't. The results showed that the CE-CERT filters were between 10 to 20% OC, SwRI steady state filters were 32% to 57% and the SwRI transient filters were between 14% to 16% (Khalek et al 2010). These results suggest that the OC fraction may be closer to 15% for the in-use transient testing, but are on the same order as suggested by the CE-CERT results. Also it suggests that the steady state testing may have a different composition than the transient and in-use testing results, but more analysis is needed.

Regeneration
Regeneration results are typically composed of nucleated sulfuric acid particles. A separate analysis of EC, OC and sulfur measurements were performed for selected regeneration filters. These results showed only trace amounts of EC and OC and a dominate amount of sulfur. Figure 4-43 shows a correlation between sulfur mass and gravimetric mass. The slope is 0.98 and an R^2 of 0.98. This suggests that all the PM mass was sulfur containing species for the regeneration cases. This result agrees with the particle formation process that the regeneration particles are sulfuric acid in nature.
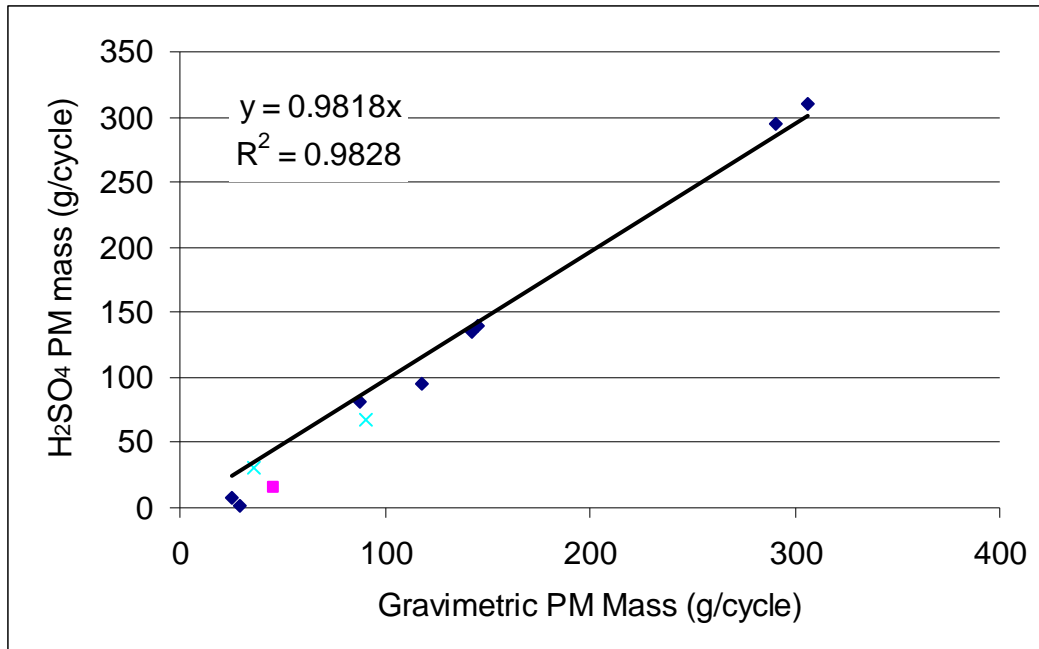
Figure 4-43 Sulfur and gravimetric mass correlation for selected regeneration events

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 an average number diameter of around 60 nm. These diameters vary due to physical processes surrounding the particles during combustion and dilution. Particle number or counting particles depends on dilution methods, but when sampling from similar setups (ie similar dilution ratios) 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) and particle mass is related to diameter to the third power (d^3). 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 3776 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 4-44 and Figure 4-45 show the real time fSMPS number based size distribution for selected forced events for a non-regeneration and regeneration case, respectively. The size distribution in Figure 4-44 shows a small number average particle size (d^0) for the non-regeneration events was 64 nm. The size distribution for the regeneration case in Figure 4-45 shows an averaged number diameter around 15 nm.

Based on the regeneration particle composition being dominated by sulfate and number averaged diameter of 15 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.
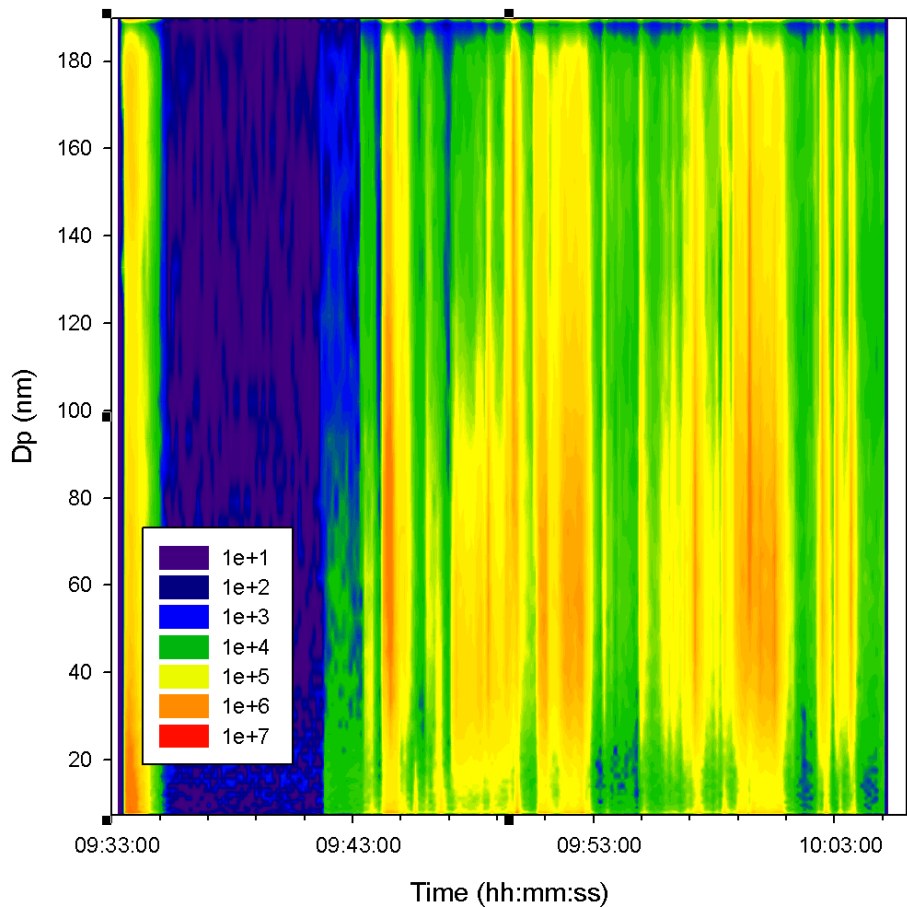
Figure 4-44. PM size distribution dN/dlogDp for a typical non-regeneration event
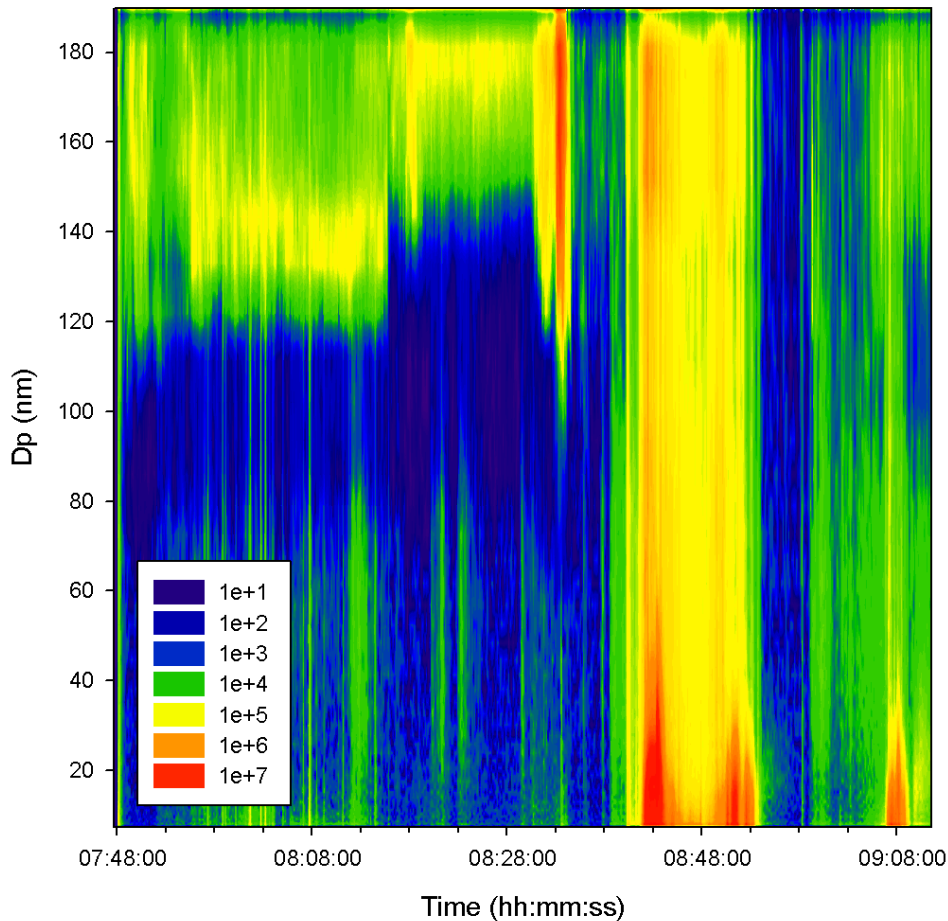
Figure 4-45 . PM size distribution dN/dlogDp for a typical regeneration event

The correlation between the reference and the PEMS was poorest for the regeneration tests compared to the non-regeneration tests. Based on the size distribution data presented, the particle size was much smaller for the regeneration tests compared to the non-regeneration as expected. Thus, it is unclear if the reason for the poor correlation for all PEMS and INST is due to the composition, particle size, or both. In either case it is obvious that all tested PEMS performed poorly on the regeneration PM composition and/or particle size distributions (i.e. PEMS1 was not tested).

Small particle size can contribute to a low signal response for several PM PEMS instruments. Small particles do not scatter light well thus affecting INST4. Small particles affect the ability for INST5 to use its assumption for a log normal distribution being centered at 100 nm the center of their impactor electrometers. Shifting this size distribution for INST5 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 regeneration test at relatively large filter mass loading levels. PEMS3 should

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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. 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 during this program.

4.9   Deeper Look at Selected Forced Events

PM 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 and INST 4 and 5. PEMS2 is not considered here since its data reporting is on an integrated basis (i.e., it is not continuous).

Two significant findings were discovered during this testing program that require a deeper look at the real-time data to understand these differences. One is with event timing, and the other is with possible passive regenerations during conditions with no DPF-byass (i.e., DPF-out conditions). Event timing for PEMS3 is a problem with identifying when to start the event due to large PM spikes at the beginning of the events. Event timing for PEMS2 is problem with starting and stopping the valve switching for PM deposition. The passive regeneration results suggest that the true in-use behavior may include passive regenerations where the PEMS3 system did not measurement the event. Although additional analysis is required to quantify the affects, the results are presented here to show the potential impact.

4.9.1   Event Timing

Event timing is different than time alignment, where event timing is defined as the time at which to start and stop sampling/quantifying PM for a particular event. The PEMS2 system is batch operated so the valve switching and transport delays are part of the event timing measurement difference. For the PEMS3 system, the event timing is the identification of when to start quantifying the PM for the NTE event. For PEMS3 more language is needed in the regulations to define what part of the PM should be included.

PM over long integrated cycles like the FTP and UDDS are fairly well behaved and event timing is usually not an issue for real-time or gravimetric batched PM measurement methods. One reason is the cycles typically start at a steady state low PM concentration. With the introduction of the in-use regulation, where events as short as 30 seconds are regulated, PM event timing becomes very important. Figure 4-46 shows a real-time response of the PEMS3 measurement system. The PM spikes from the steady state value of 0.25 mg/m^3 to around 20 mg/m3 which is a factor of 80 times. Typical entry into an NTE starts with a PM spike, as was discovered with the in-use testing program. The level of spiking will vary depending on several factors such as grade, vehicle weight, congestion and others. For three of the events in Figure 4-46 the PEMS PM mass was within 13% of the MEL, but the last one only captured 50% of the MEL PM mass. It turns out on the last event the NTE entrance occurred exactly at the PM spike. As events approach 30 seconds, the weighting of the initial spike becomes critical and event timing needs to be addressed in order to properly handle in-use PM emissions.

PEMS2 event timing may have caused some of its negative bias. The PM PEMS sample duration delta compared to the MEL duration was explained in Section 6 and is shown in Figure 6-2 and Figure 6-1 where the 50th percentile duration delta was -0.5 with a 5th of -3 and a 95th of 1.5 seconds. Unit#3 showed some outliers at -7 seconds for sample duration. A similar analysis was performed comparing the MEL sample times to the Semtech DS and it was found that the MEL and PEMS were identically matched. It is unclear with out more analysis what affect this has on the start and stop times, but it is clear there are timing issues with the PM part of PEMS2 on the order of seconds. This timing difference could be contributing to the overall PEMS2 negative bias. More analysis is necessary to understand this impact.
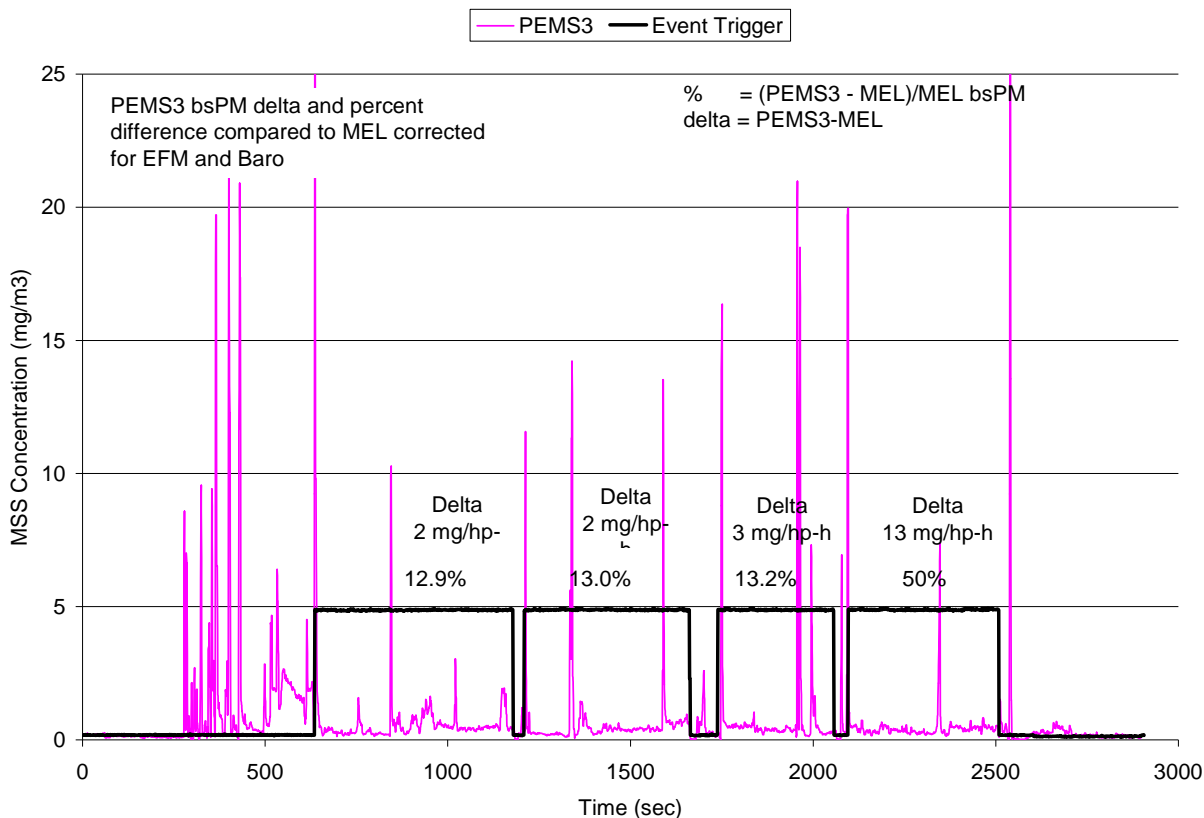
Figure 4-46 PM concentration event timing on a selected events for Unit2 PEMS3

4.9.2 DPF-out conditions

DPF-out conditions are expected to be typical under in-use regulatory situations. PEMS behavior under these conditions was not part of the focus for this study, but is important to understand. Two events were sampled during DFP-out conditions and are presented here. These events were described earlier during the PEMS2 and 3 results sections. PEMS3 showed a -20% and -60% (negative) bias and PEMS2 showed a +124 and +500% (positive) bias on these events.

Figure 4-47 through Figure 4-50 show real-time results for two consecutive DPF-out events. The PM events are identified in the figures by the label "event trigger" shown by the pink lines. The bsPM, sample duration, and filter loading are also listed in each respective event. During these

events the MEL measured 0.6 and 1.1 mg/hp-h, respectively. Figure 4-47 shows that the PEMS3, INST4 and INST5 show no significant difference between the events. It was thought that possible PM from the transfer line was causing the higher MEL loadings which were not seen by PEMS3, INST 4, and 5. Figure 4-48 shows the same data but with both the main stack PEMS3 measurement and the PEMS3 located at the CVS entry (two PEMS3 systems measuring in series). There is no noticeable measurement response difference between locations suggesting the PM is not coming from the transfer line.

Figure 4-49 then shows the response of UCR's particle counter (CPC 3776 D50 3nm), which shows a two times higher particle count for the second DPF-out condition compared to the first. The average particle count increased from 7,000 #/cc to 14,000 #/cc from the 1st event to the second. Particle increase is typically associated with regenerations where sulfate PM increased which is undetected by PEMS3, but is detected by the reference. This can explain the difference in PEMS3 response between these two points. The filter weights were around 50 ug and thus there would not be enough total mass to perform compositional analysis between the two events. In general though, the magnitude of the negative bias for PEMS2 was high when the non measured PM was on the order of 0.5 mg/hp-h. It is unclear with out more testing if this trend is consistent for most DPF-out conditions.

The PEMS2 positive bias for these two cannot be explained by the real-time figures and may be associated with lower detection capabilities, variability, and multiple crystal usages, as explained earlier.
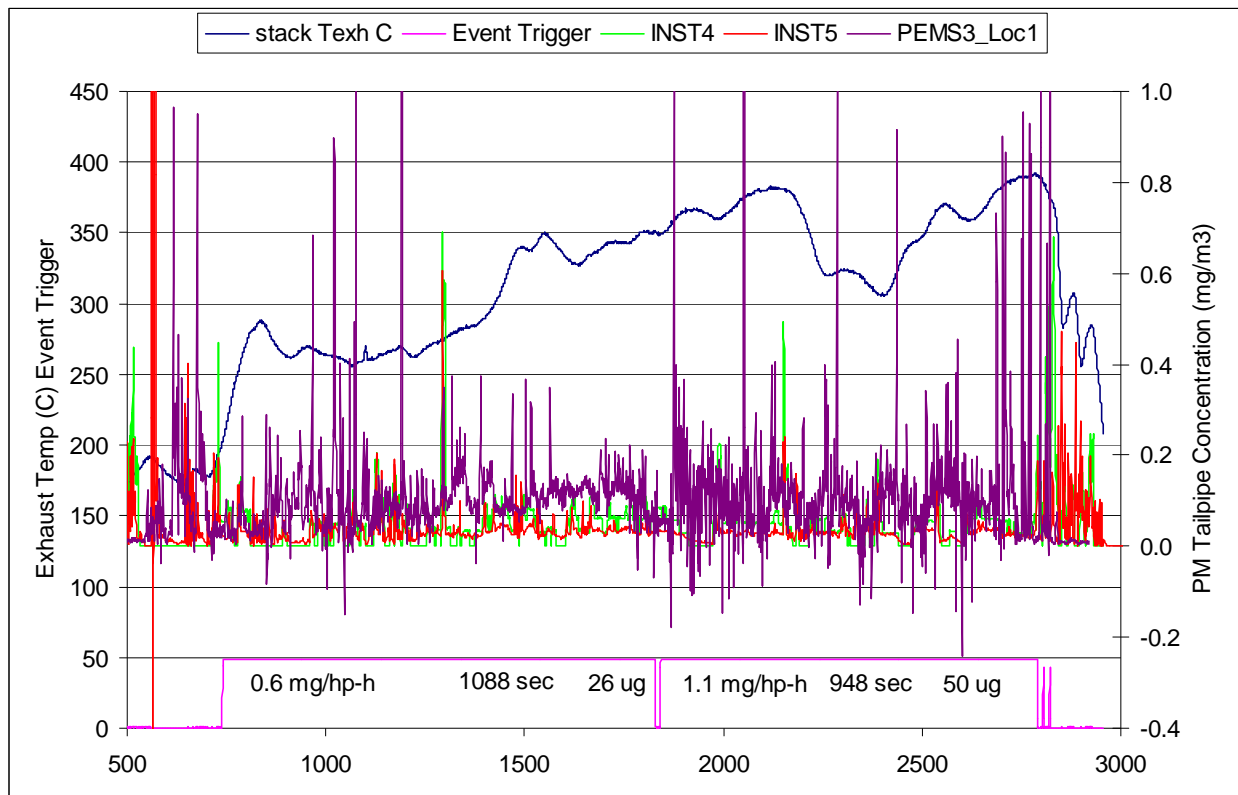

Figure 4-47 DPF-out conditions PM concentration PEMS3 and INST's
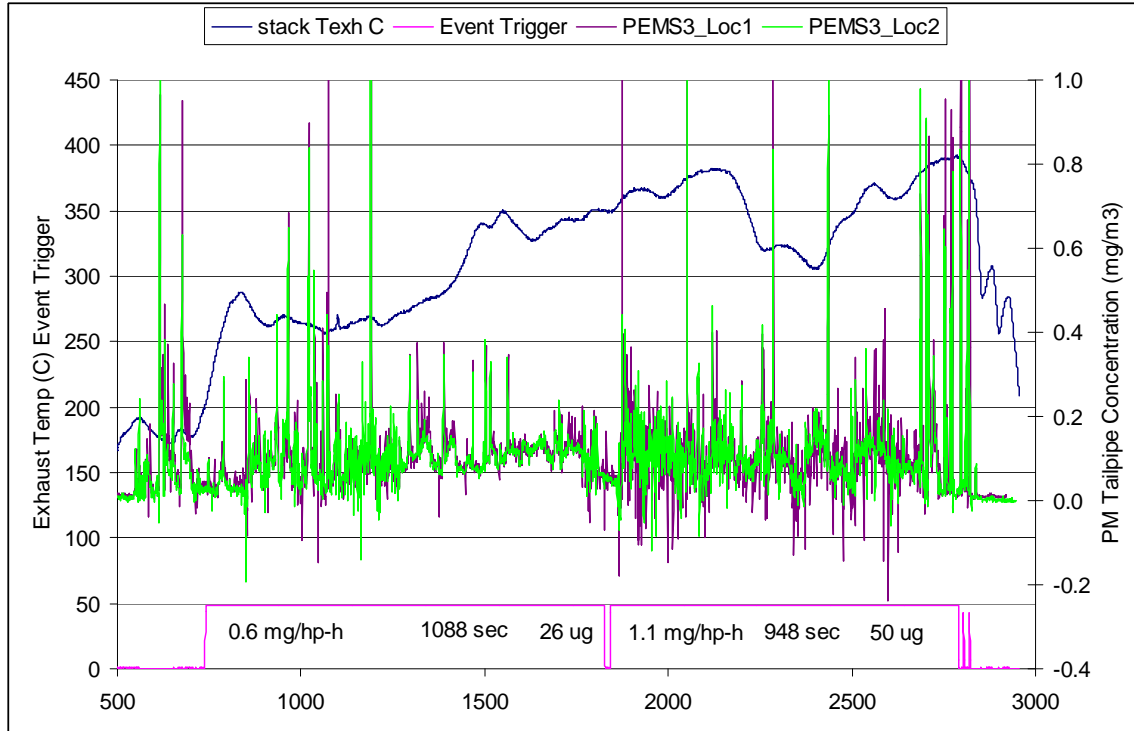
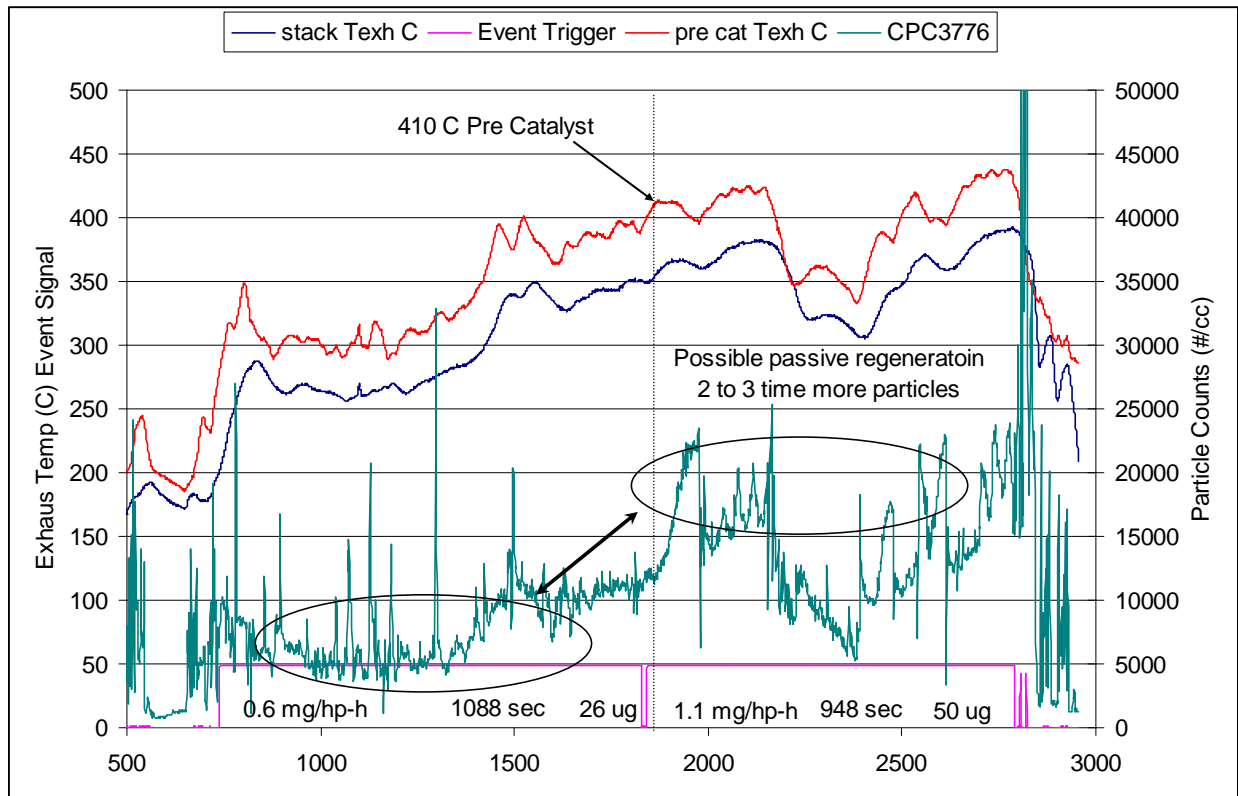**Figure 4-48 DPF-out conditions PM concentration PEMS3 Loc1 and Loc2**

Figure 4-49 DPF-out conditions PM number concentration and pre catalyst temperature
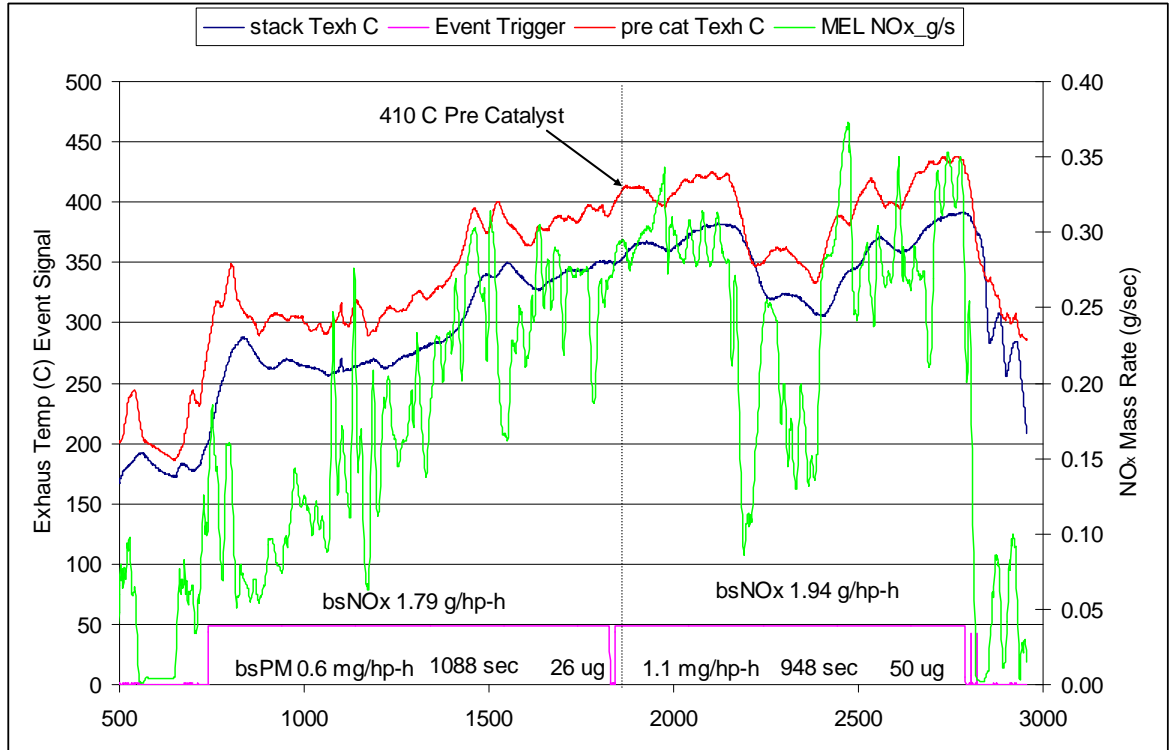
Figure 4-50 DPF-out conditions integrated bsNO$_x$ and real time NO$_x$

5   In-Use Testing –Gaseous Experimental Results

Gaseous emissions data was measured, audited and calibrated for all MA test data in series with the PM measurement allowance testing. CO_2 measurements were needed for Methods 2 and 3 calculations. NO_x, CO, and THC (NMHC) were also desired to provide additional comparisons to the MEL and to help trouble shoot deviations noticed with the PM PEMS data.

In addition to the gaseous emissions data analysis, broadcast J1939 work, carbon balance and exhaust flow were also analyzed to help show differences between the PEMS and MEL. The quality of the entire program rests with the ability of the PEMS and the MEL to be sampling the same point. This is evaluated with quality checks between the ECM, PEMS and MEL measurement systems.

The gaseous data were collected over the same forced events examined for the PM results. The gaseous comparisons are based on in-use NTE calculation method one, as described in CFR40 Part 1065. Additional calculations and analysis are presented to compare between methods 2 and 3. The method calculations provide the basis for understanding the differences between method calculations to support the PM results presented earlier.

5.1   Work Comparison

The work is estimated from the ECM broadcast J1939 actual, friction, and reference torques in combination with engine RPM. There are errors associated with the broadcast torque and are on the order of 5%, as reported by Khalek et al. (2010). For the purposes of this study, the associated errors from work are eliminated since both the PEMS and the MEL are using the same broadcast signals, as discussed in next.

Figure 5-1 shows the correlation between the work calculated by the MEL and the gaseous PEMS2 system for all four units. The figure shows that the gaseous PEMS2 and the MEL work data agree well for each unit with an R^2 greater than 0.99 and a slope ranging from 0.99 to 1.001. PEMS3 utilized the same ECM data collected by gaseous PEMS2 to calculate their work term for bsPM emissions. The data shown in Figure 5-1 represents data from PEMS3 and the gaseous part of PEMS2. In general, the high R^2 and near 1.00 slope provide a reasonable metric that the work data between the MEL, PEMS3, and the gaseous PEMS2 is not contributing to any significant errors.
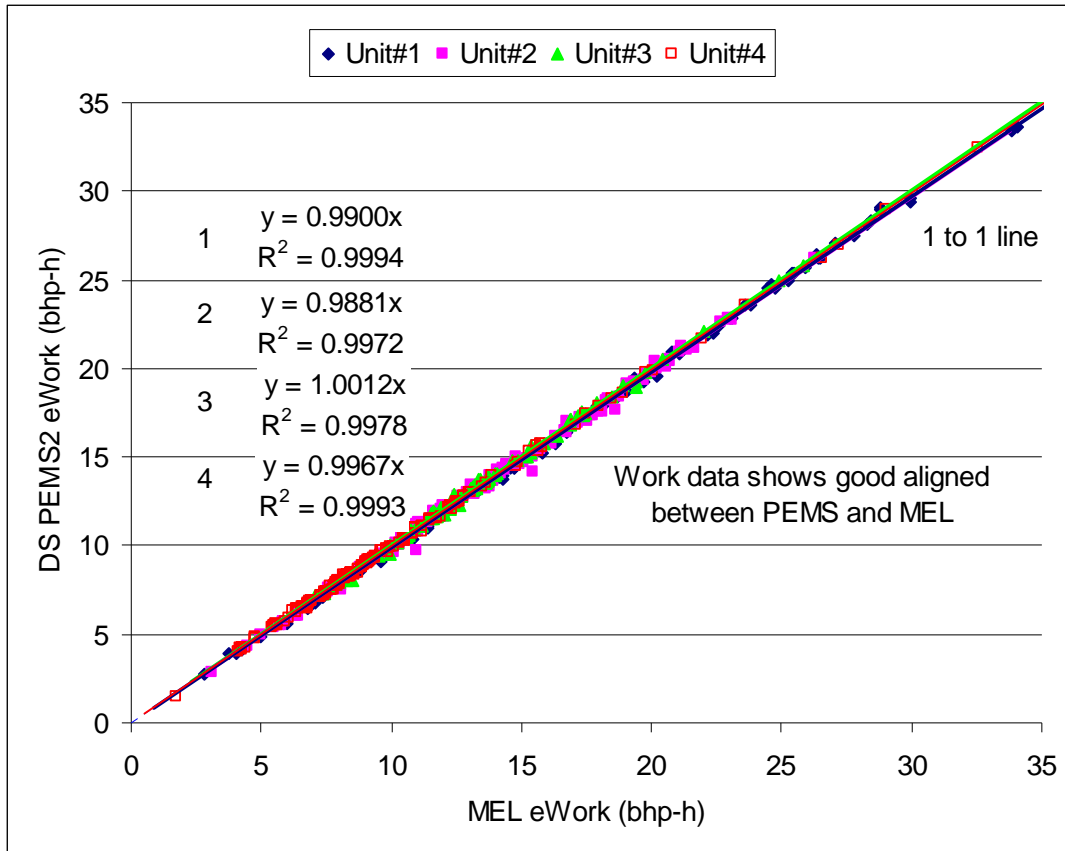
Figure 5-1 Gaseous PEMS2 work correlation compared with MEL

PEMS2 has two independent systems that process and manipulate ECM data due to the integrating window of the PM mass system. The ECM signals are sampled by the gaseous part of PEMS2, but the integration of work is done by the PM parts of the PEMS2 in conjunction with their PM system. As a result there are two outputs of the same results, one from the PM part and one from the gaseous part of PEMS2. Figure 5-2 shows the same correlation results as Figure 5-1 except using the PM PEMS integrated work term. The R^2 values are slightly lower, but the slopes dropped significantly from near unity to 0.94, 0.90, and 0.98 for units 1, 2, and 3 (unit 4 data was not available), respectively. There also appears to be more variability in the measurement as noted visually with the data spread.

During a previous PEMS2 evaluation by Durbin et al. (2009b), a similar difference in the correlation slope was observed between the work for the gaseous and PM parts of PEMS2 compared to the MEL. In general, the lower slope suggests the PEMS had lower integrated work compared to the MEL and PEMS3. It is uncertain what impact this has on PEMS2 bsPM correlation.
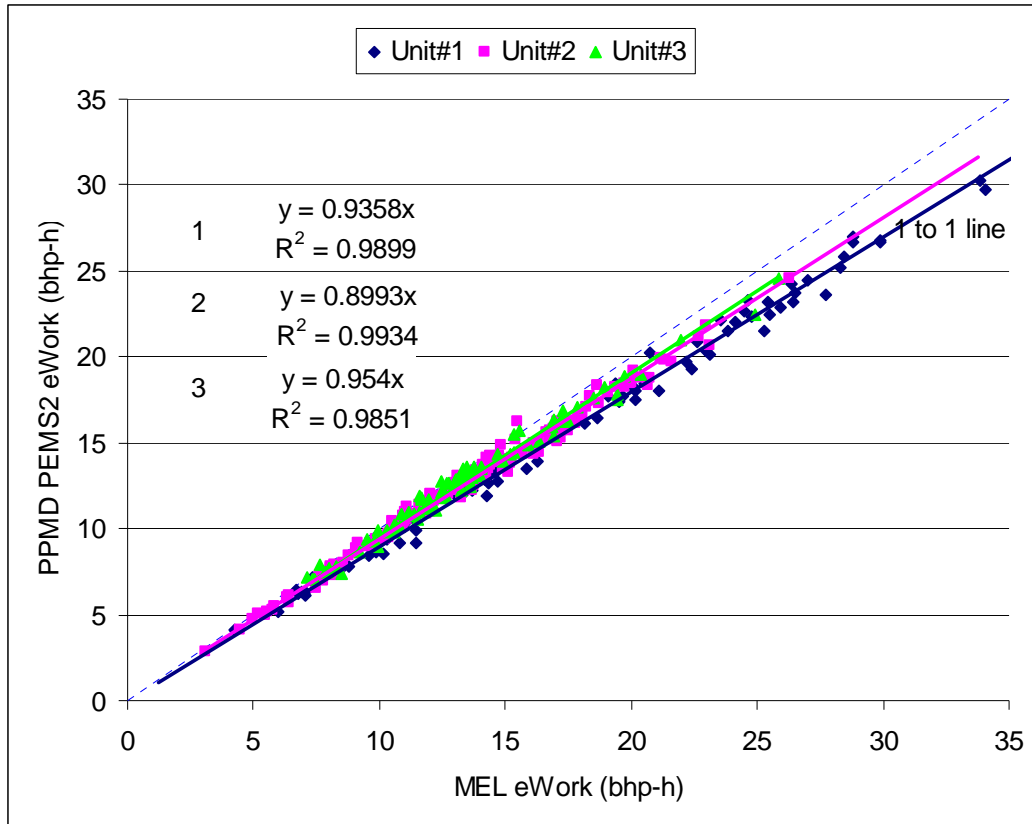
Figure 5-2 PM PEMS2 work correlation compared with MEL

5.2   Fuel Consumption

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 broadcast fuel consumption is accurate to within about 5% during NTE zone operation (Kahlek et al., 2010). The MEL and gaseous PEMS 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. Figure 5-3 shows the MEL comparison and Figure 5-4 shows the PEMS comparison.

Figure 5-3 shows a good correlation between engine fuel consumption and the MEL emissions carbon balance. The R^2 was more than 0.99 for all units and the slope ranged from 0.99 to 1.004. In general, the high R^2 and near 1.00 slopes provide a reasonable metric that the MEL emissions, exhaust flow, and ECM measurements are not contributing to any significant errors. Thus, this suggests the MEL PM results presented should be reliable accurate.
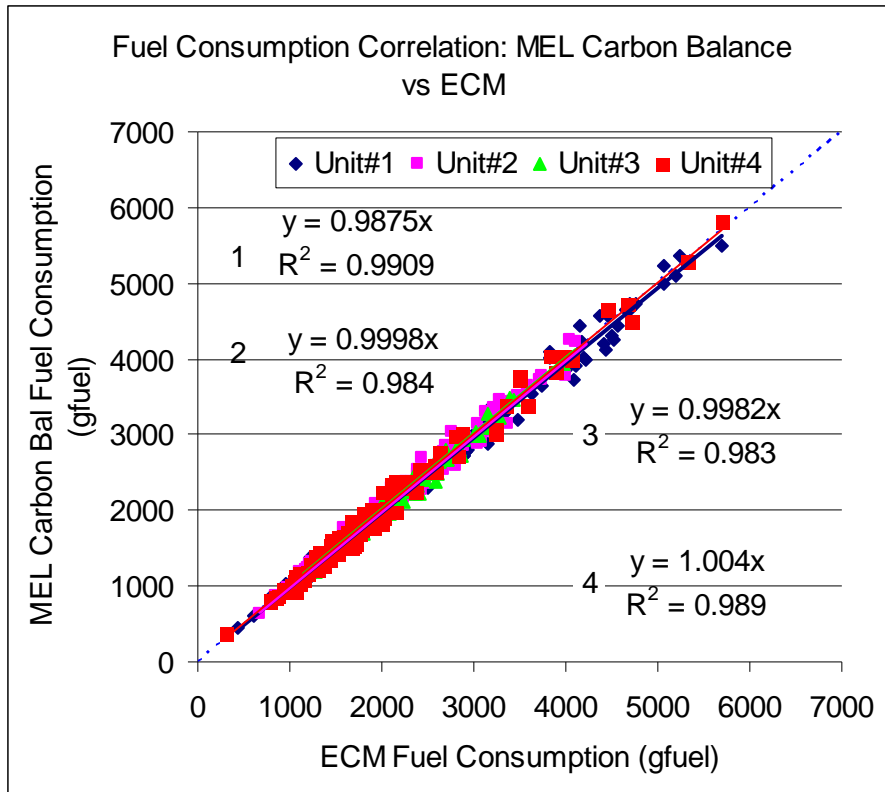
Figure 5-3 Fuel consumption correlation between the MEL and ECM.

Figure 5-4 shows the PEMS also had a good correlation between engine fuel consumption and the emissions carbon balance. The R^2 value was about the same except for a low value on unit 1 of 0.87 which resulted from a few points that were clearly outliers. With these points removed, the R^2 for all units was similar and better than 0.99. The slope was a little further than unity and ranged from +0.99 to 1.08. Note these PEMS carbon balance numbers are after corrections have been made to the PEMS exhaust flow metric. The positive slope of 1.08 suggests the unit 2 exhaust flow is biased high by about 8%, if we assume all the error is associated with the exhaust flow. Method2 and 3 bsCO_2 calculations will show similar trends, as described later. In general, the high R^2 and near unity slopes provide a reasonable metric that the PEMS emissions, exhaust flow, and ECM measurements are not contributing to any significant errors (<10%). Thus, this suggests the PEMS2 and 3 PM results presented should be reliably accurate to within 10%.
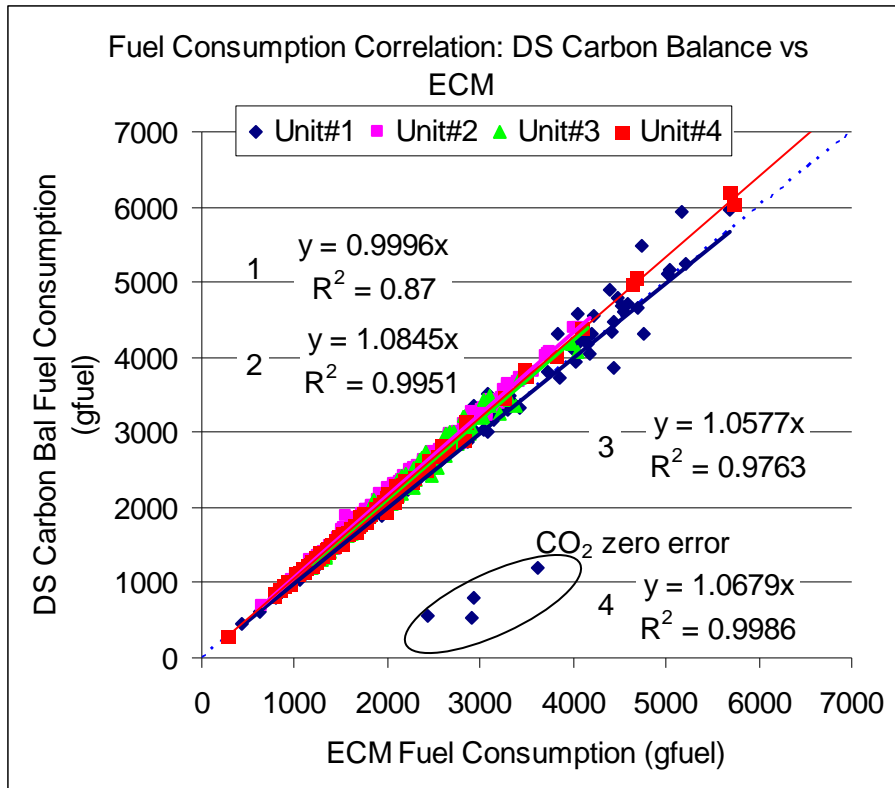
Figure 5-4. Fuel consumption correlation between the PEMS and ECM

5.3 Exhaust flow

The PEMS exhaust flow measurement was an issue for units2 and 3 due to some incorrect tubing connections internal to the PEMS2 system. See Section 6 for a detailed discussion. The exhaust flow is used to compute total mass of PM for all PEMS using Method1 calculation. The exhaust flow was found to be one of the main reasons for the large negative biases between PEMS2, 3 and the MEL. As a result of the need to understand exhaust flow, UCR evaluated the MEL exhaust flow compared to the PEMS exhaust flow as a direct comparison of the correction factors applied to the PEMS exhaust flow measurement for units 2 and 3.

The MEL does not have an integrated exhaust flow measurement system, but it can estimate exhaust flow from the difference of the MEL's total and dilute flow smooth approach orifices (SAO's). One SAO measures total flow and the other measures dilute flow. The difference in the SAO measurements is exhaust flow.

UCR routinely checks the precision between the two SAO's by capping the exhaust inlet where the total and the dilute measure the same flows (assuming there are no leaks). This procedure is shown in Figure 5-5, where the correlation of total and dilute flow is on the primary y-axis with the total – dilute differences are on the secondary y-axis. The figure shows that the difference between the total and dilute is on the order of 10 scfm over the range of flows measured during the PEMS in-use testing. This amounts to about 1-2% of the actual measured exhaust flows.
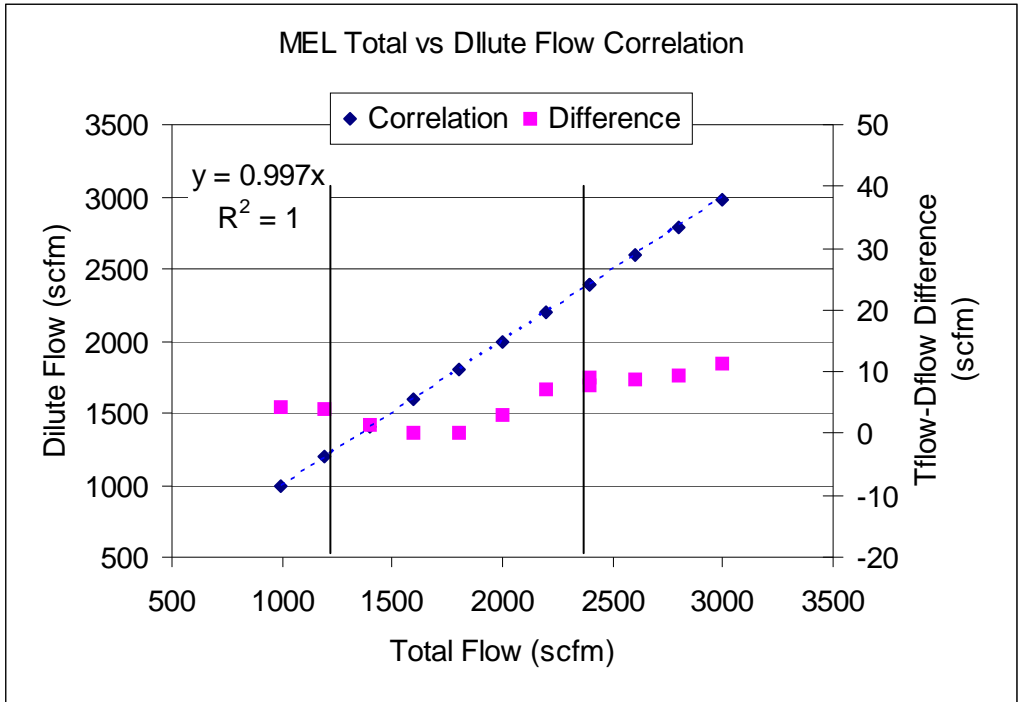
Figure 5-5 UCR's MEL total and dilute SAO venturi's precision test

Figure 5-6 shows the comparison between the MEL exhaust flow and the PEMS exhaust flow after all the corrections were applied. The slopes varied from 0.99 to 1.03 for units 1 and unit 2 respectively. Unit4 did not need any calibration or barometric pressure correction and showed a slightly high slope relative to the MEL's with a slope of 1.04. The R^2 was around 0.9 for all correlations suggesting the correlation was good. These slightly positive slopes of 2-3% agree with the carbon balance where slopes of 5-10% existed. This suggests that some of the bias may be a result of the exhaust flow measurement and some due to CO_2.
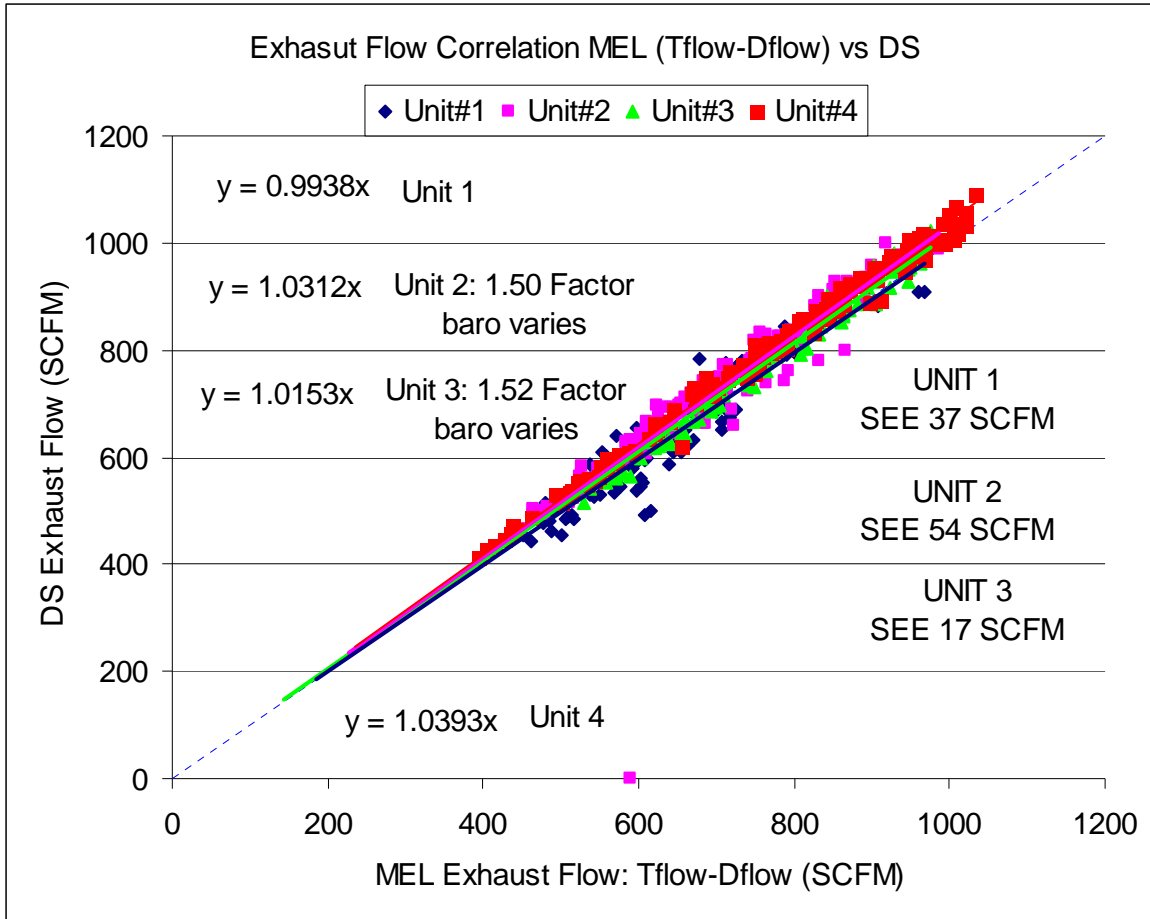
Figure 5-6 Exhaust flow correlation between the MEL and the PEMS system

5.4 Brake Specific Emissions

This section covers the gaseous brake specific emissions during the same forced events presented earlier for PM. 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 5-7 through Figure 5-22 show the correlation of the PEMS2 gaseous results with the MEL's gaseous results.

5.4.1 Brake Specific CO_2

The bsCO_2 correlation results are shown in Figure 5-7 through Figure 5-9 for the Method 1, 2, and 3 calculations. The correlation improved from Method 1 to 2 and 3 with very little difference between Method 2 and 3. The unit 2 slope changed from 1.07 to 1.01 between Method 1 and 2 thus supporting the fact that the unit 2 exhaust flow was high, as shown in the exhaust flow analysis.
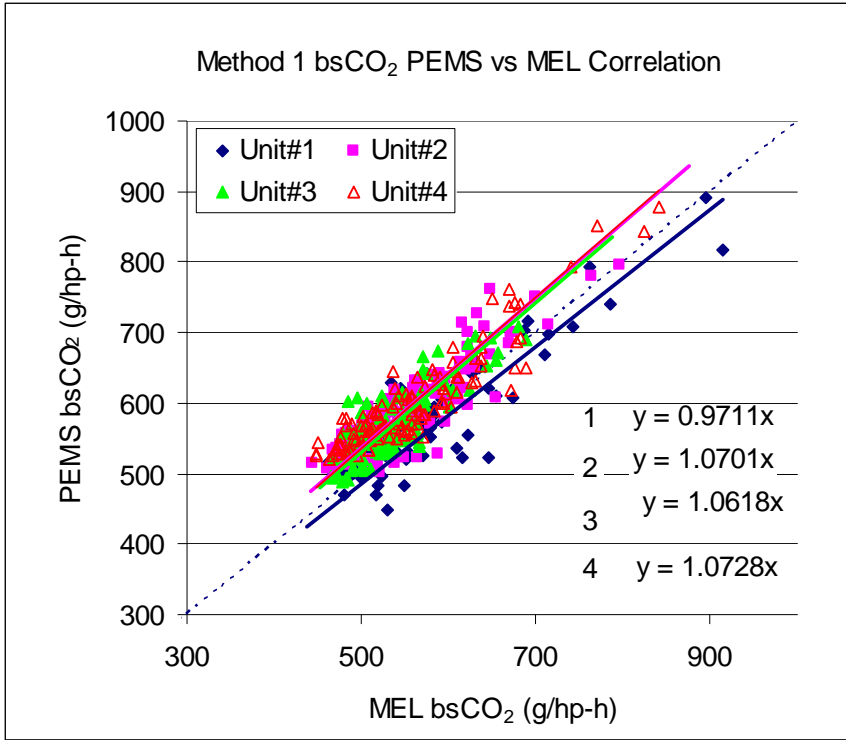
Figure 5-7 bsCO$_2$ Method 1 correlation between PEMS and MEL

Figure 5-8 bsCO$_2$ Method 2 correlation between PEMS and MEL

Figure 5-9 bsCO$_2$ Method 3 correlation between PEMS and MEL

Figure 5-10 and Figure 5-11 show the comparison between Method 1 and Method 2 for the gaseous PEMS2 system. Figure 5-10 show the same trend where Method 1 has a high bias for units 2, 3, and 4, and a slightly low bias for unit 1. Figure 5-11 shows that Method 2 and 3 are very similar and that there appears to be no significant difference between the two methods during this testing program.
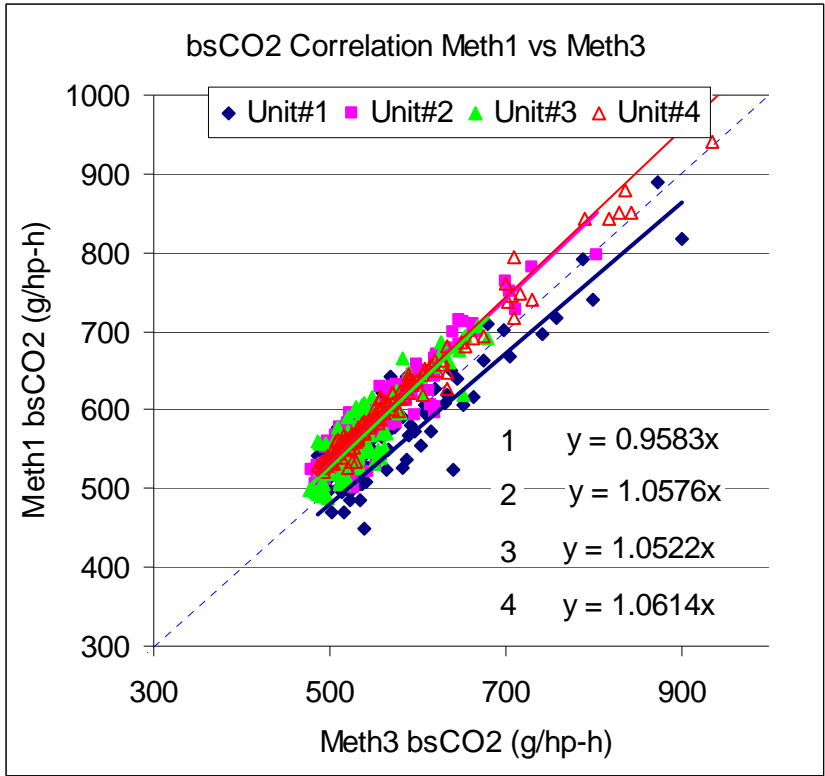
Figure 5-10 bsCO$_2$ Method 1 versus Method 3 correlation
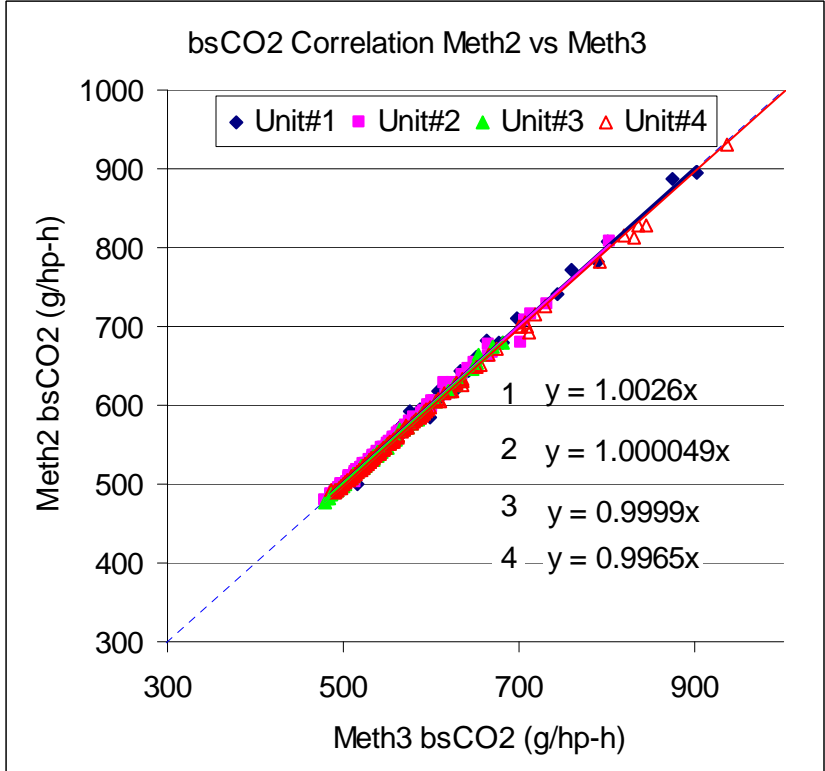
Figure 5-11 bsCO$_2$ Method 2 versus Method 3 correlation

The delta correlation plots are shown in Figure 5-12 through Figure 5-14 and show the same basic trend where unit 1 was biased low and units 2, 3, and 4 were biased high from the exhaust flow. The near zero slopes suggest there are no variations that occur with measurement level.
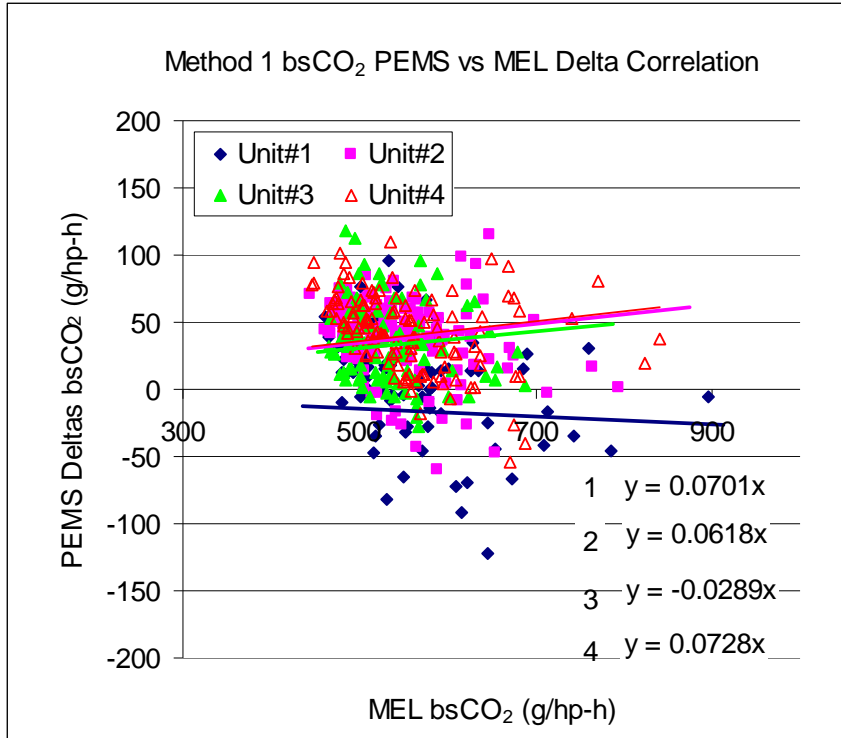
Figure 5-12 bsCO$_2$ Method 1 unit comparisons PEMS versus MEL
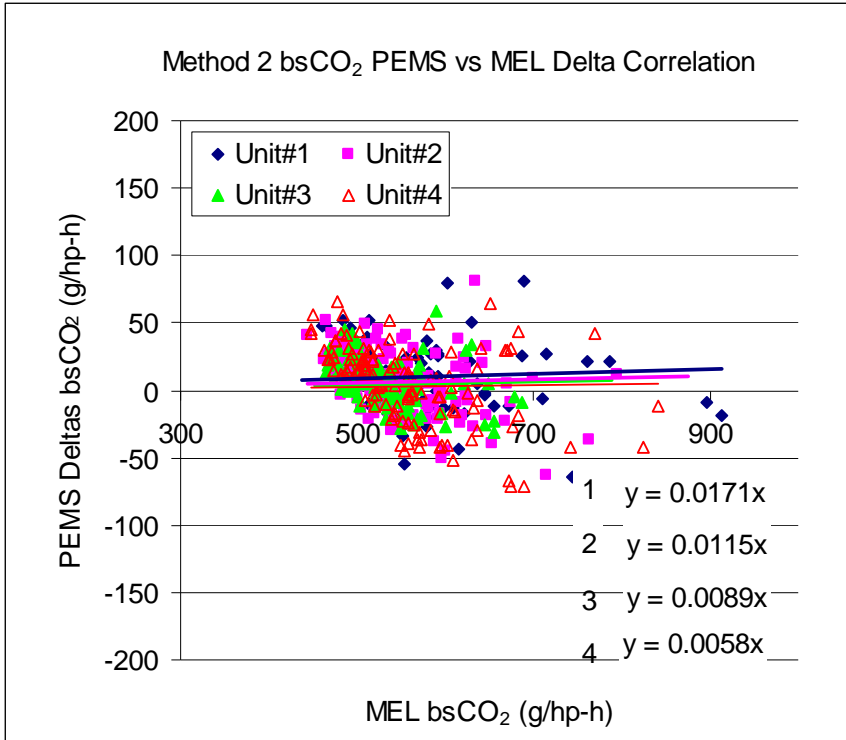
Figure 5-13 bsCO$_2$ Method 1 unit comparisons PEMS versus MEL
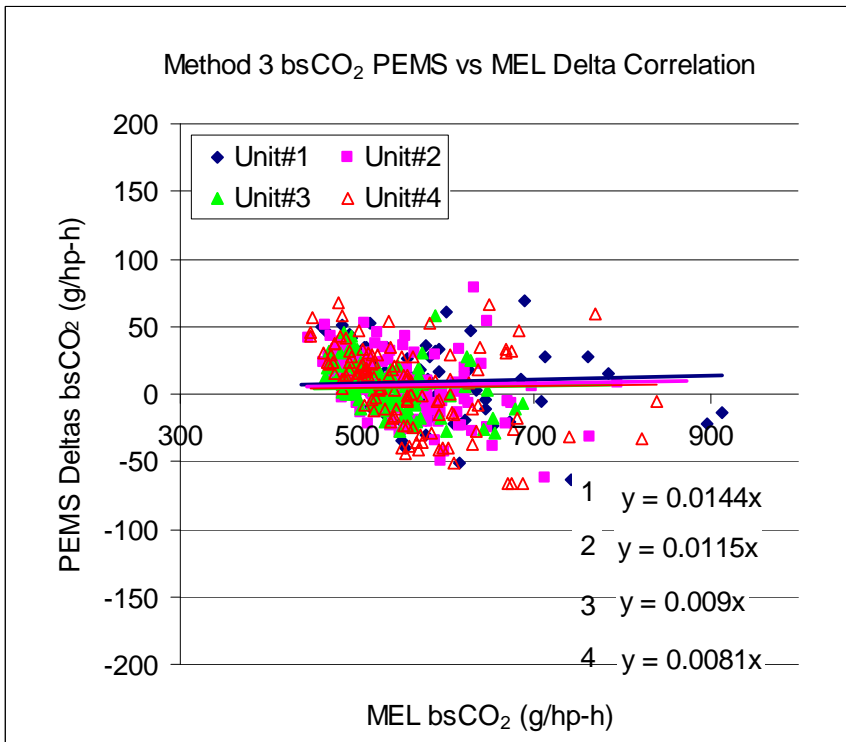
Figure 5-14 bsCO$_2$ Method 1 unit comparisons PEMS versus MEL

5.4.2   Brake Specific NO_x

Figure 5-15 through Figure 5-20 show the $bsNO_x$ correlation results between the PEMS2 gaseous system and the MEL. Figure 5-15 through Figure 5-17 show the correlation for methods 1, 2, and 3 and Figure 5-18 show the same information but using the delta bsPM comparisons.

The correlation appeared to be closest for Method 1, with Methods 2 and 3 underreporting the $bsNO_x$ results compared to the MEL. The Method2 and 3 calculations removed the positive bias in the exhaust flow which caused the $bsNO_x$ correlation to decrease. During the PEMS gaseous validation exercise the $bsNO_x$ data was higher than the MEL. The delta figures show there is a correlation to MEL bsPM emissions level, but with R^2 at 0.1 suggesting there is only a 10 % correlation. The slope appears to be steeper with the Method 2 and 3 calculations.

Also added to these figures are the 2007 and proposed 2010 $bsNO_x$ measurement allowance thresholds. Notice how it appears the data may converge below the 2010 $bsNO_x$ measurement allowance. Also, the data presented easily meets the current measurement allowance of 0.45 g/hp-h. It is important that the data presented here is not based on true NTE operation where shorter events are common and event timing may cause additional biases where the allowances may not look as well behaved as the ones in Figure 5-15 through Figure 5-17.

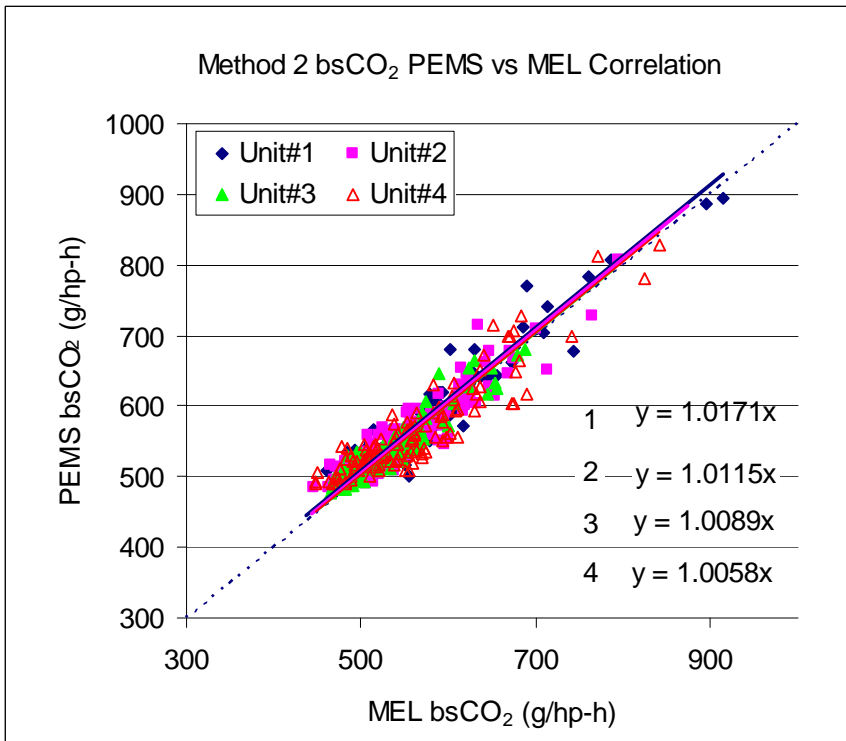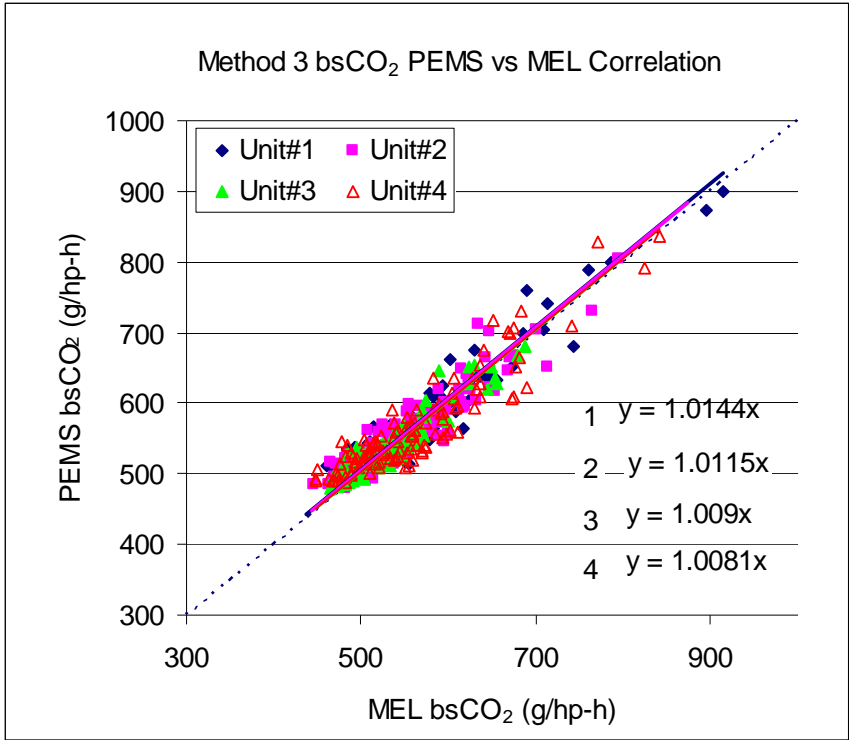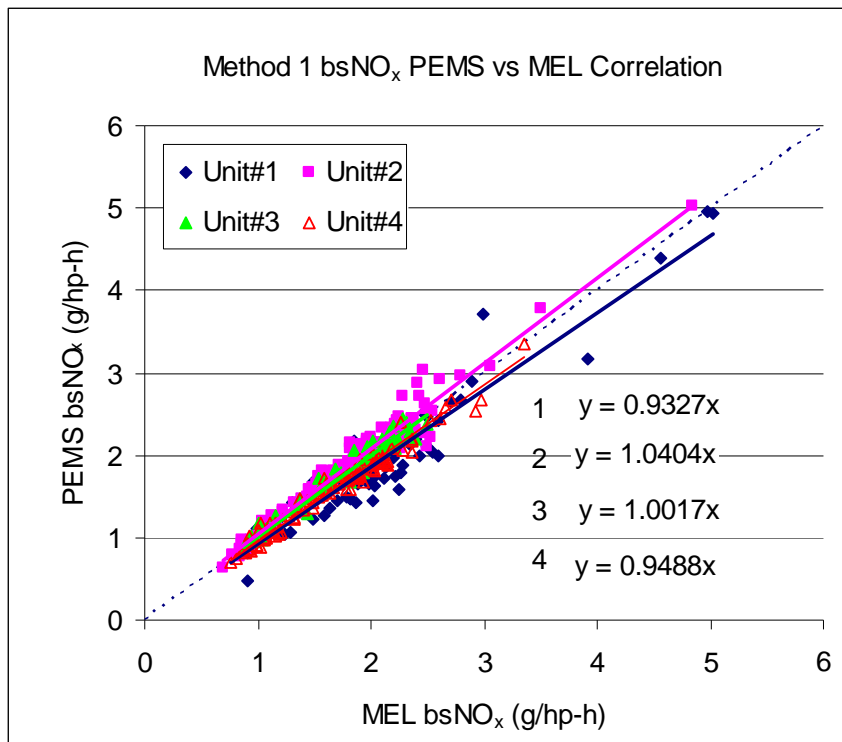**Figure 5-15 $bsNO_x$ Method 1 correlation between PEMS and MEL**
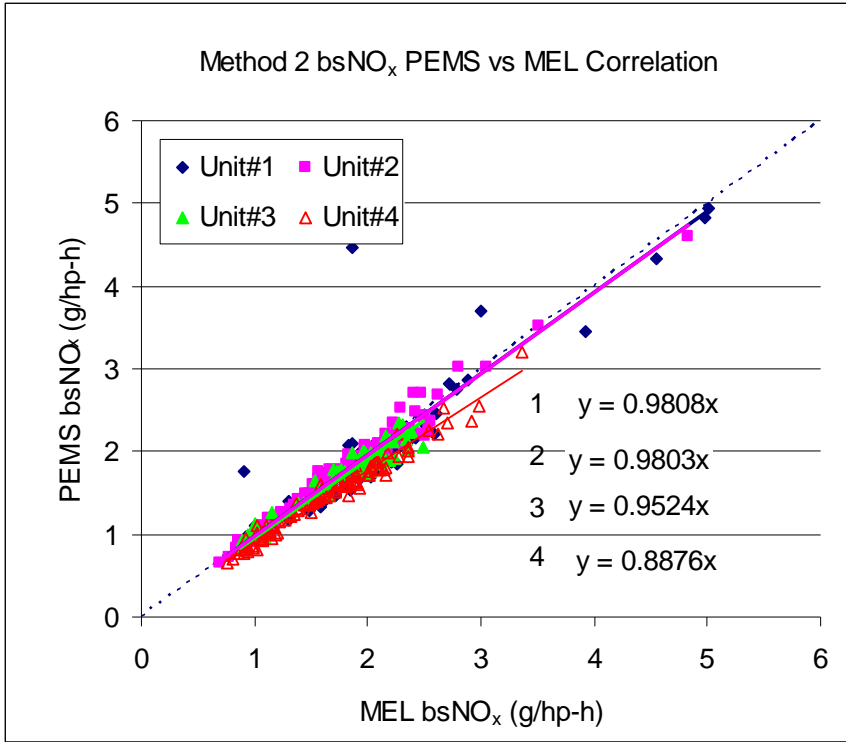
Figure 5-16 bsNO$_x$ Method 2 correlation between PEMS and MEL
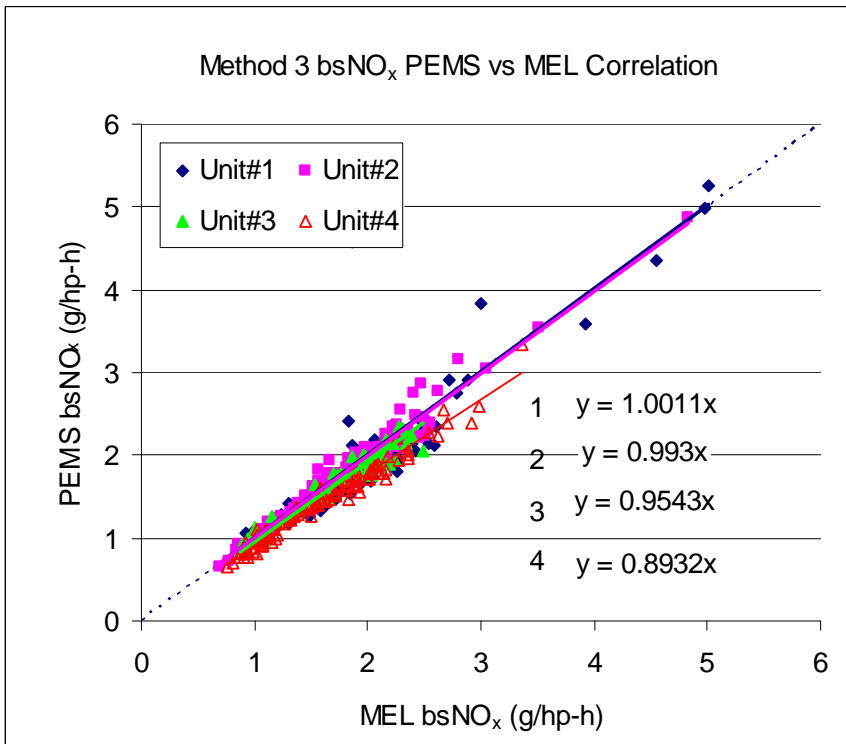
Figure 5-17 bsNO$_x$ Method 3 correlation between PEMS and MEL

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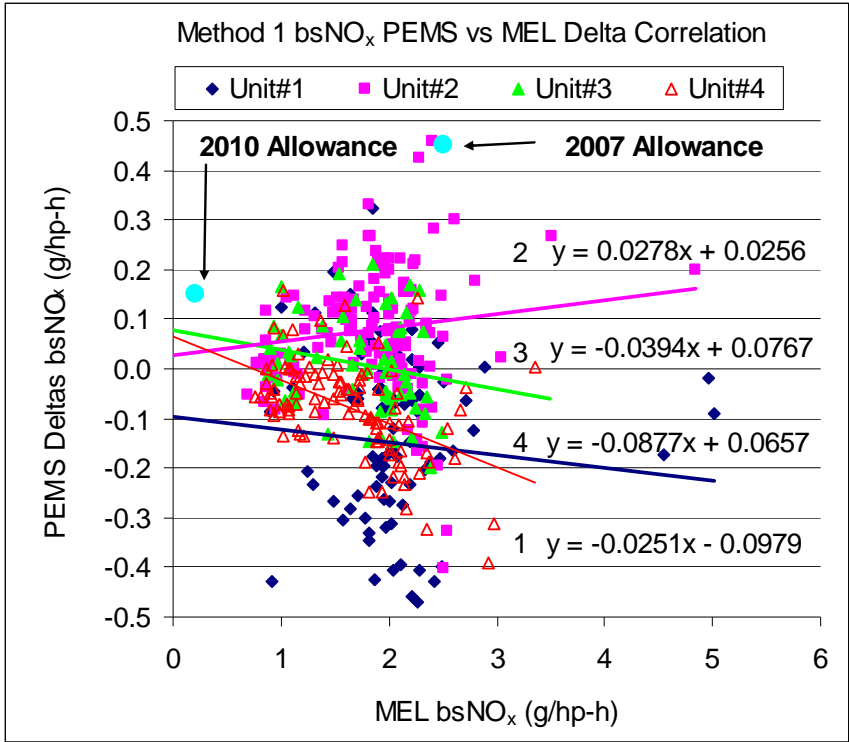
Figure 5-18 bsNO$_x$ Method 1 delta correlation between PEMS and MEL
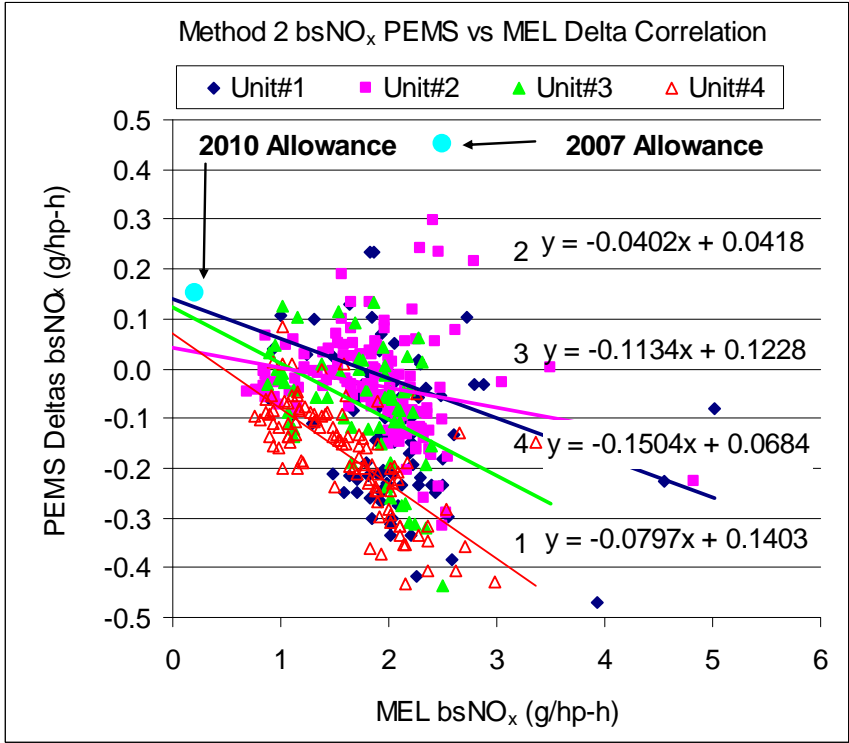
Figure 5-19 bsNO$_x$ Method 2 delta correlation between PEMS and MEL
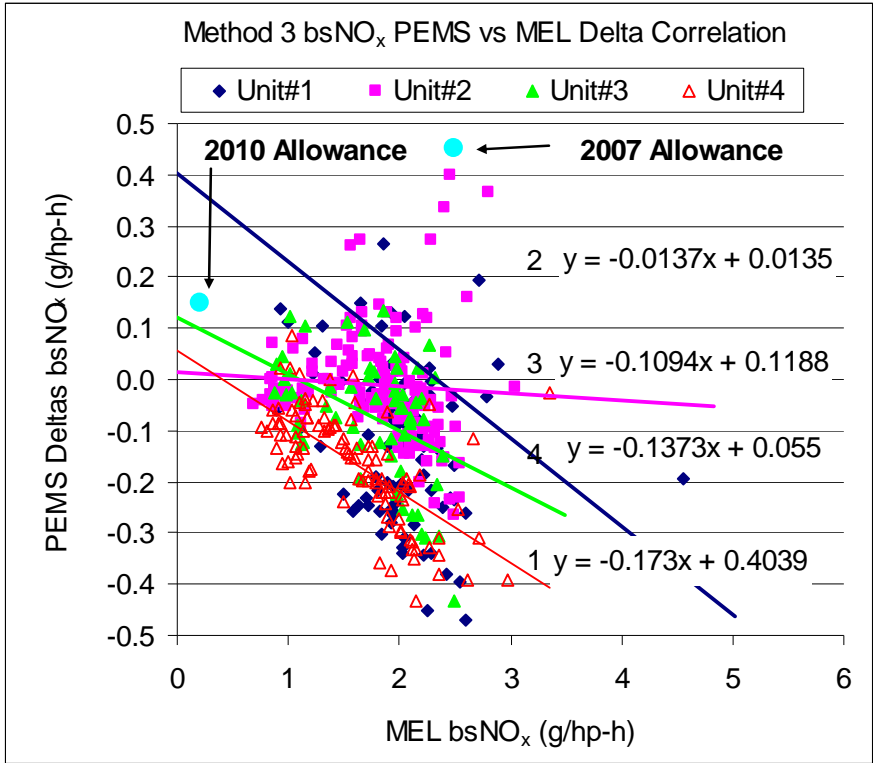
Figure 5-20 bsNO$_x$ Method 3 delta correlation between PEMS and MEL

5.4.3 Brake Specific NMHC

Figure 5-21 shows the NMHC emissions correlation data between the PEMS and the MEL. The correlation between the PEMS and the MEL was poor. One reason for the poor correlation is most likely the low mean concentrations measured by the PEMS and the MEL, as shown in Table 5-1 and Table 5-2. The PEMS and MEL mean THC concentrations were 10 and 2 ppm, respectively. The PEMS typically failed audit checks due to the low level span selected, suggesting it's low end measurement capability has difficulty measuring at levels seem for DPF-equipped engines. The MEL values were above the detection limits, but were at the same level as the ambient concentrations of 2.3 ppm thus making its measurements also diffulct. Overall, the bsNMHC emissions were low and near the lower end of the measurement capabilities of the MEL and PEMS.
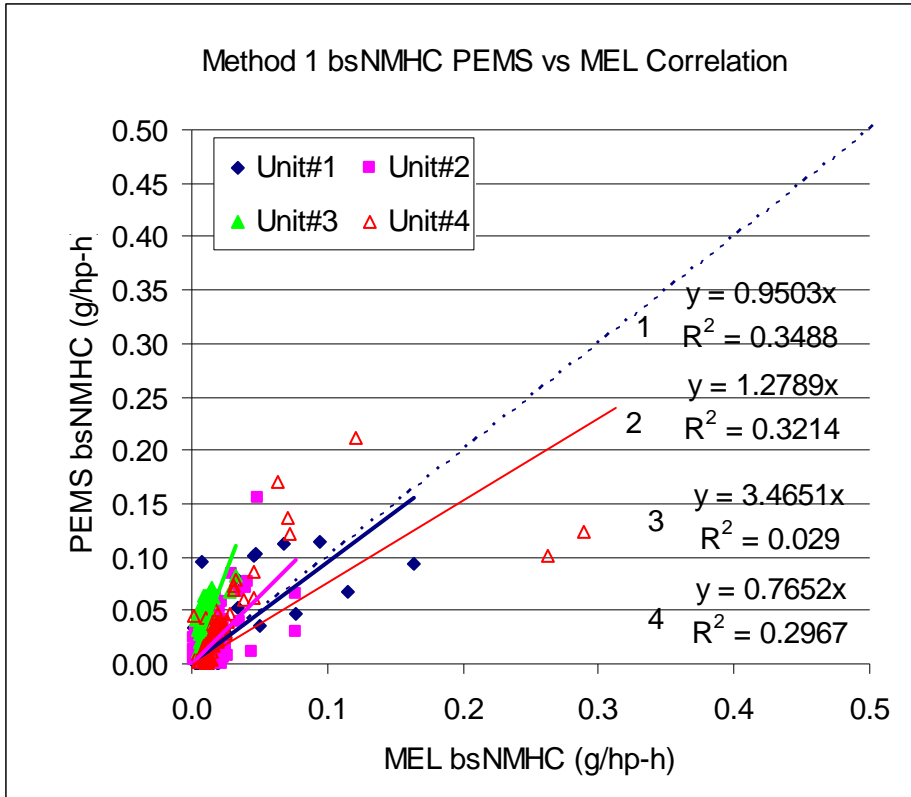
Figure 5-21 bsNMHC Method 1 delta correlation between PEMS and MEL

Table 5-1 PEMS and MEL average event concentrations measured

Unit	NO_x (ppm)		CO_2 (%)		CO (ppm)		NMHC (ppm)	
	MEL	PEMS[1]	MEL	PEMS	MEL	PEMS	MEL	PEMS
1	68.94	247.1	1.89	6.84	3.06	51.63	1.13	6.81
2	80.26	278.7	2.22	7.78	4.54	54.45	1.04	6.10
3	82.66	262.5	2.39	8.03	4.88	42.68	0.80	15.96
4	75.51	240.0	2.57	8.00	8.43	47.09	3.35	10.16

[1] combined NO and NO_2 measurmetns

Table 5-2 PEMS and MEL average event concentrations % of span

Unit	NOx (ppm)		CO2 (%)		CO (ppm)		THC (ppm)	
	MEL	PEMS[1]	MEL	PEMS	MEL	PEMS	MEL	PEMS
1	20%	22%	47%	57%	3%	1%	1%	8%
2	23%	25%	56%	65%	5%	1%	1%	7%
3	24%	24%	60%	67%	5%	1%	1%	18%
4	22%	22%	64%	67%	8%	1%	3%	11%
Overall	22%	23%	57%	64%	5%	1%	2%	11%
SPAN	350	1112	4	12	100	4500	100	89.97

5.4.4 Brake Specific CO

Figure 5-22 shows the CO emissions correlation data between the PEMS and the MEL. The correlation between the PEMS and the MEL was also poor. One reason for the poor correlation is most likely the low mean concentrations measured by the PEMS and the MEL, as shown in Table 5-1 and Table 5-2. The PEMS and MEL mean CO concentrations were 49 and 5 ppm, respectively. The PEMS span is 4500 ppm and the MEL span is 100 ppm. The PEMS average measurement is at 1% of the span value and the MEL is at 5% of its span value. Because the measurements are below 10% of both the PEMS and MEL span levels, both instruments had measurement difficulties leading to a poor correlation. Overall, the bsCO emissions were low and near the lower end of the measurement capabilities of the MEL and PEMS.
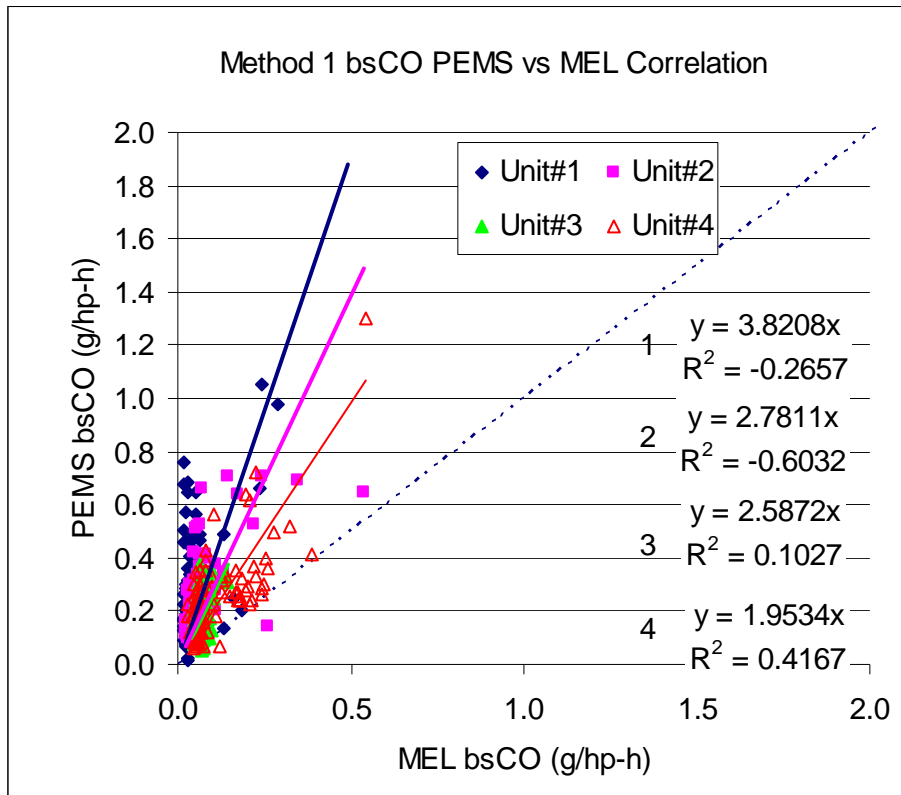
Figure 5-22 bsCO Method 1 delta correlation between PEMS and MEL

6   Lessons Learned and Issues

In this section the PM PEMS problems are discussed. This section is a critical component of the MA study because the state of commercial availability can be evaluated based on PEMS performance. Many of these PM PEMS are still evolving where this section give the reader a snapshot of the PEMS capabilities at the time of this research. Future comparison studies can use this section to characterize PEMS improvements.

The PEMS were tested following manufacturers recommended practices utilizing each PEMS manual as discussed in Section 3. Each PEMS was provided to UCR after being inspected and calibrated by the manufacturers. As such, this section is written from the perspective that the PEMS were shipped ready to go as would be during in-use testing.

In some instances deviations from the manuals were necessary due to the comparison nature of this program. The MEL CVS did create a slight negative pressure for PEMS2 which is not typical for in-use installations. As such, a special installation as discussed earlier was employed which did cause PEMS2 bypass flow system to not work ideally at UCR. Although the author aggress with this assessment, the sensitivity of this parameter on in-use testing should be documented in the manual. It is recognized though that the current version of the post processor does set a fault if not set correctly where the old version did not. In either case the current manual does not discuss this proper installation and its impact on the measurements. It is suggested that all important PEMS parameters, including bypass flow, should be well documented for users to use good engineering judgment for improving operation and providing a common results between users of the same equipment.

Another significant lesson learned is in data post processing and data interpretation. For the MA program the definition of valid data was based on iteration with the manufacturer, good engineering judgment, and the MASC decisions. The operational manual is not clear on data processing and it is expected that user manual should provide the understanding to interpret the data from these PEMS post processors. The manual should be clear on what issues are sensitive and need to be followed strictly and which ones can be loosened. Many of these PEMS are being used for regulatory testing and as such the manuals need to be specific on the requirements for high quality results and data filtering. The choice of data filtering for some PEMS can significantly affect their results.

Previous lessons learned
Previous reports on PEMS2 and 3 show similar issues and others that have been fixed or did not reoccur (Durbin et al 2009a, b). PEMS2 previously showed problems with crystal stability, valve switching delays, startup issues, and other operational specific details. Many of these problems reoccurred, but due to limited time were not quantified to see if they were reduced such as valve timing. During pre model testing at SwRI, UCR did evaluate improvements to the PEMS2 valve timing where it was found that the timing issues were limited to 2 seconds, there were some tests found during validation testing that showed duration deviations on the order of 5-6 seconds suggesting the problem may still exist, but at a lower level of significance. More analysis is needed to characterize fully though.

PEMS2 system had several problems that affected their bsPM emissions comparison and as such it was recommended by the MASC that PEMS2 be retested to confirm that the issues have been resolved. These retest results will be reported as a separate document to this report. A specific analysis that shows a reducing in data spread and a reducing in the negative bias was proposed and is the basis for the PEMS system being of suitable quality for in-use regulatory work.

PEMS 3 showed two previous issues from the in-use testing performed by UCR. One issue was with signal noise and the other was due to overheating (Durbin et al 2009a, b). Neither of these issues reoccurred during this study, but a new issue with an electrical connections was found. Other issues with the prototype GFM will also be discussed.

INST 4 and 5 were not evaluated for problems given they were not subjected to the same harsh environments and thus the comparison would not be comparable. INST 4 and 5 operated with no obvious issues except for the occasional loss of charger voltage and contaminated charger circuit for INST4 due to a need for additional daily cleaning. No issues for INST5 were encountered.

Overview

This section is broken down into three main sections that discuss the issues relative to in-use, startup, and post processing type issues. These categories became distinct between the PM PEMS during the course of the testing program. The reader will be able to get a feel for the complexity, commercial availability and reliability of each PEMS tested based on this section. In each sub section you have PEMS 2, 3, and 3F where each PEMS issues covers three different serial numbers except for PEMS 3F which represents the GFM system.

6.1 In-Use Issues

This section focuses on in-use issues. These issues ranged from electrical and mechanical connections, crystal usage from short NTE's, valve switching, measurement signals, and crystal behaviors. In general PEMS2 had several in-use issues where PEMS3 was isolated to an electrical connection on the MSS and some leaking filters on the GFB.

6.1.1 PEMS2

The PEMS2 issues ranged from fundamental issues to systematic issues such as crystal overloading and electrical connections. Some of the issues could cause bias to the PEMS measurement methods were others cause loss of operation. This section covers issues experienced by the PEMS2 system during in-use operation.

6.1.1.1 Crystal usage

A unique aspect of PEMS2 PM measurement system is the crystal usage for each of its eight crystals. The usage is defined here as the maximum loading and repeated usage prior to regreasing. The maximum loading on a crystal prior to being automatically locked out is defined in the manual at 1 ug (Sensors 2009). There is not a requirement on crystal usage given the variability of in-use testing. During model development and validation testing the maximum

loading was set at 1 ug as per the manual. Crystal usage was controlled by the number of usages needed to achieve the maximum loading. For model development the crystals were typically used two times, but for the validation testing the usage varied from two to around five times due to in-use operation.

Maximum loading proved to be difficult because after further analysis of the data showed that the decay rate of some test runs was negative where mass loss occurred over time. In this situation the maximum loading would never be achieved. Thus, UCR had to estimate the true loading with all these variables in real time while operating the PEMS systems. Overloading the crystals is also not an absolute threshold, but a function of the PM composition, in-use conditions, and reference crystal status. For example elemental carbon, or "dry soot", will show signs of overloading before organic carbon type PM, or "wet" PM. The test article used at UCR did show a similar transient elemental carbon PM compared to SwRI, but possibly a dryer PM than the steady state generated data where the molded error surfaces were more dominate.

Some reasons for the higher crystal usage for the validation testing compared to the model development was due to real NTE operation and issues with QCM mass loss over time. The real in-use NTE operation includes invalid events less than 30 seconds and valid events longer than or equal to 30 seconds. The short invalid NTE events would use numerous crystals with a variety of mass loading. In some cases two crystal events would occur prior to a valid NTE event. In these cases the number of events would not be a reasonable metric for controlling usage, but max loading would be.

In general the PEMS2 system did appear to have more crystal usage and thus more overloading issues than the model development data. The PEMS2 manufacturer recommended lowering the upper limit from 1 ug to 0.75 ug (Booker 2010). Additional analysis and testing are required in order to fully understand the impact of crystal loading and PM measurements for the PEMS2 system at these lower limits.

6.1.1.2   Timing delays and valve switching

Valve timing and valve switching delays can affect PEMS2 bsPM correlation with the reference as discussed in Section 4.9.1. During the previous study by Durbin et al (2009b) valve start and stop timing was found to very by several seconds. The timing was found with slow start times and slow end times. No analysis though was performed to quantify the bsPM affect of the problem, but it was believed that valve timing and PM agreement are important as discussed in Section 4.9.1.

The timing delays and valve switching times were analyzed in this study by looking at the sample duration. Sample duration and event timing are not the same since it is unknown with sample durations where the deviation occurs. A deviation of three seconds could occur as a result of different start and/or end times. More analysis is needed to characterize this, but due to time additional analysis was not performed.

The duration data are shown in Figure 6-1 and quantified using Figure 6-2. All tested units appear to have about the same behavior where unit1 showed a slightly lower 50th (-1 second)

compared to units 2 and 3 (-0.3 seconds). The average 5th and 95th percentile timing differences were -3 and 1.5 seconds respectively. Outliers as much as -7 seconds and +3 seconds were experienced. The larger differences agree with some of the findings from the study by Durbin et al (2009b). No analysis was performed to quantify the effect of the time on the bsPM results.
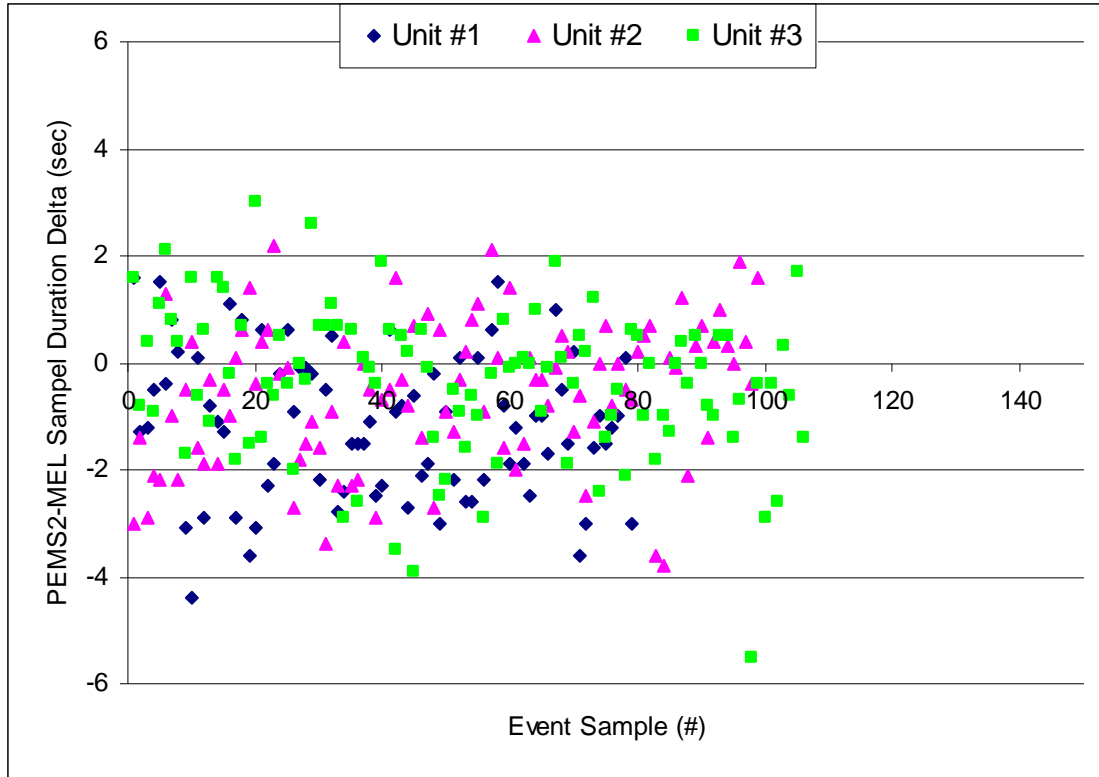
Figure 6-1 PEMS2 sample duration deltas compared to the MEL
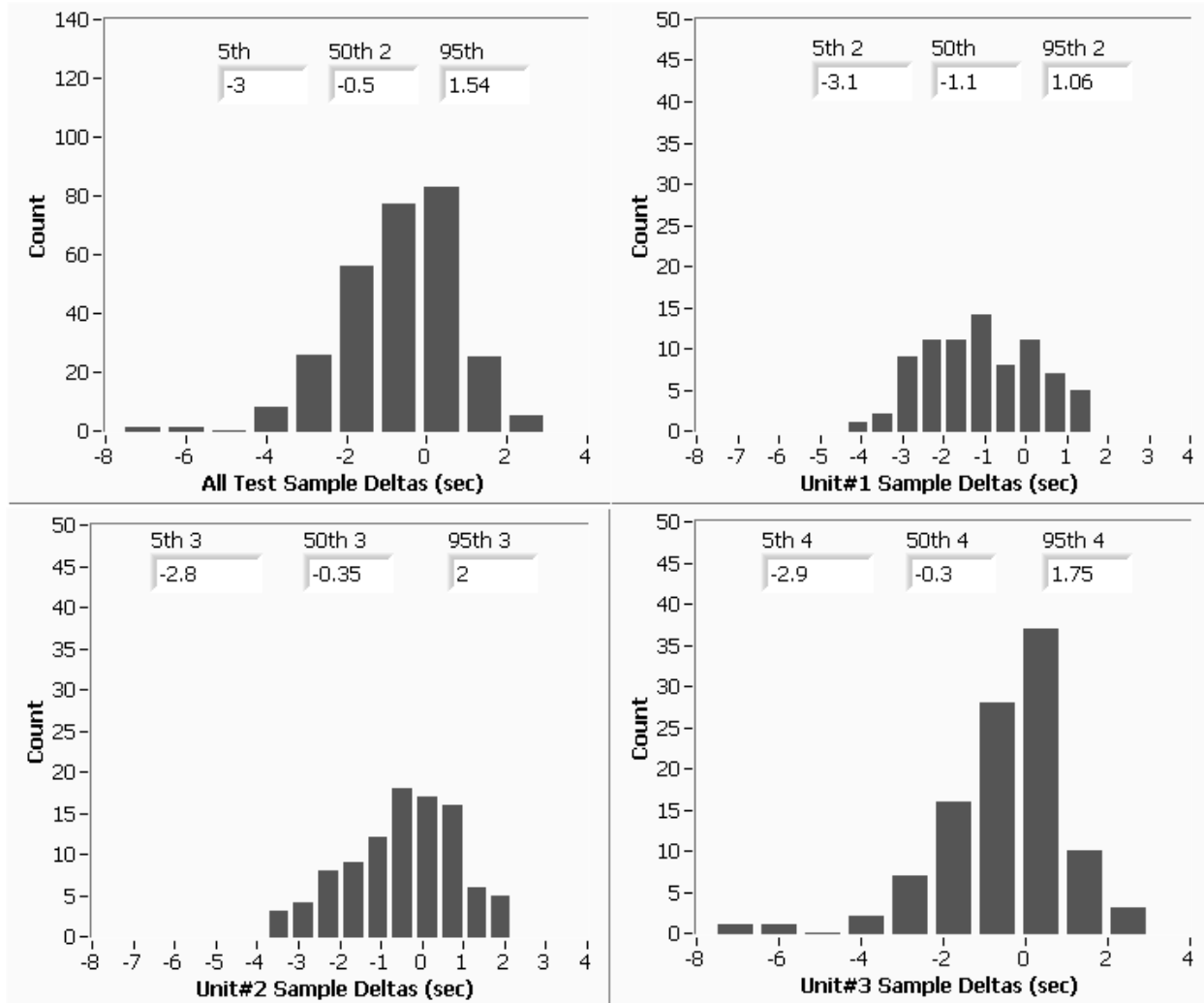
Figure 6-2 PEMS2 sample duration deltas histograms relative to the MEL

6.1.1.3   Barometric pressure measurement

Barometric pressure is used by PEMS2 for the calculation of its exhaust flow. Any error in the measurement of this pressure affects the exhaust flow and thus the Method1 bsPM resutls by the square root of the deviation. UCR found that the PM PEMS2 barometric pressure signal varied significantly from the MEL. UCR also found that the gaseous part of PEMS2 barometric pressure signal agreed with-in 1% of the MEL's, thus suggesting the problem is with the PEMS2 barometric pressure sensor. The good MEL carbon balance agreement also supports that the MEL barometric pressure was correct.

Given the PM PEMS2 barometric pressure is used for all their bsPM calculations, it was decided to reprocess all PEMS2 PM data using a correction factor from the gaseous part of PEMS2 systems. Figure 6-3 shows a plot of the barometric pressure error factor as a function of event tested. The equation for the factor is also shown in the figure. The error factor appears to have a trend with events which makes sense since the events were captured while changing in elevation. The error factor is also near unity at the start of each day suggesting that the barometric pressure

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was reasonable at the UCR starting elevation. It also is interesting that all three units had a similar trend.
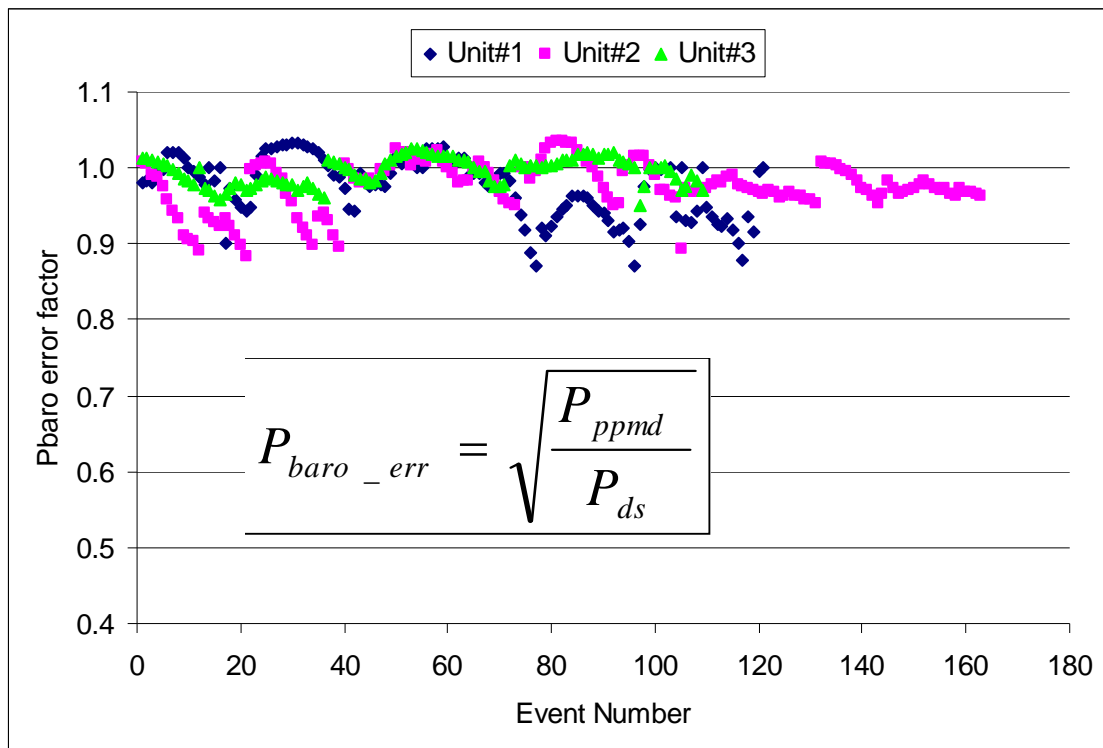
Figure 6-3 PEMS2 barometric pressure factor applied to the exhaust flow

All PEMS2 PM data was corrected on an event basis for the factors shown in Figure 6-3 utilizing the PEMS2 gaseous barometric pressure measurements.

$$Q_{est} = Q_{meas} * \sqrt{\frac{\Delta P_{ppmd}}{\Delta P_{DS}}}$$ **Equation 6**

6.1.1.4 Sample flow: temperature ratio

PEMS2 system depends on its sample flow for the transfer of particles to the PM detection surfaces and for its proportionality to the transient exhaust flow. Thus, it is important that the sample flow requirements be followed. One unique feature of the PEMS2 system is the sample system uses a bypass flow to keep the sample path at elevated temperatures. A prescribed bypass flow is necessary to keep the sample flow environment at a near-uniform temperature in order to correct the measured volumetric flow rate to a mass flow rate (Booker 2010). With-out proper bypass, it is expected that up to 10-15% negative bias can be expected in the measurement of the sample mass flow.

During the UCR validation testing it was found that the temperature ratio was low compared to the manufacturer's expectation and what was seen at SwRI. The temperature ratio at SwRI was 80% and the manufacturer recommends a ratio of 90%. UCR's temperature ratio was typically less than 50% according to Booker (2010). UCR did not quantify the low temperature ratio, but did confirm that several runs do show a low ratio on the order of 50%.

UCR operated and installed the PEMS2 system according to the manufacturers recommendations as per the manual (Sensors 2009). There is no mention in the current version of the manual about proper bypass setup, but based on UCR's experience with two different PEMS2 testing programs and previous discussions, UCR installed the PEMS2 system by connecting the bypass port to a location down stream of the sample port due to the CVS connection. The installation shown in the manual will provide a sufficient bypass where the bypass setup requirements would not be necessary, but other setups may require its importance and provide some magnitude of its compliance. PEMS2 latest version of the post processor, as discussed in Section xx, did provide a new flag that identifies issues with the temperature ratio. It is unfortunate that this processor version was not available at the time of testing or other interested parties did not see the deviation prior to the completion of the testing campaign.

It is interesting though that the SwRI bypass was greater than at UCR where both laboratories performed comparisons studies with CVS systems. Some reasons may be differences between the CVS setups, location of the bypass port, and differences between ambient test cell conditions versus in-use ambient conditions. In general the overall affect of no bypass has been suggested to be on the order of a negative 10-15% bsPM bias according to the manufacturer. Further analysis is needed to quantify the true affect of the low MPS temperature ratio experienced by UCR.

6.1.1.5   Sample flow: proportionality (SEE/mean)

Proportionality is another critical factor for proper PM detection for batched type systems like PEMS2 (also used by PEMS1). Proportionality is needed in order to sample the PM from the exhaust proportional to the amount of total exhaust flow. During hard accelerations there can be a high PM concentrations "puffs" where it is important to have a larger sample flow (ie increasing the sample flow in proportion to the exhaust flow) to capture these "puffs".

One statistic for determination proportionality is based on the SEE divided by the mean sample flow or SEE/mean. The manufacturer recommends a value of less than 5 and 1065.545 recommends a value less than 3.5. Figure 6-4 shows a figure of the PEMS2 SEE/mean proportionality for all events and for each unit. A significant fraction of the proportionality results are greater than 5 as shown in Figure 6-4. Unit2 required additional tuning after some in-use operation had been completed, as seen by the two circled areas in Figure 6-5. There was no obvious reason for the loss of proportionality for unit2. Also there was no evaluation of the effect this may have on the bsPM results presented. In summary the proportionality did not meat 1065, but was determined to be sufficient for the validation study.
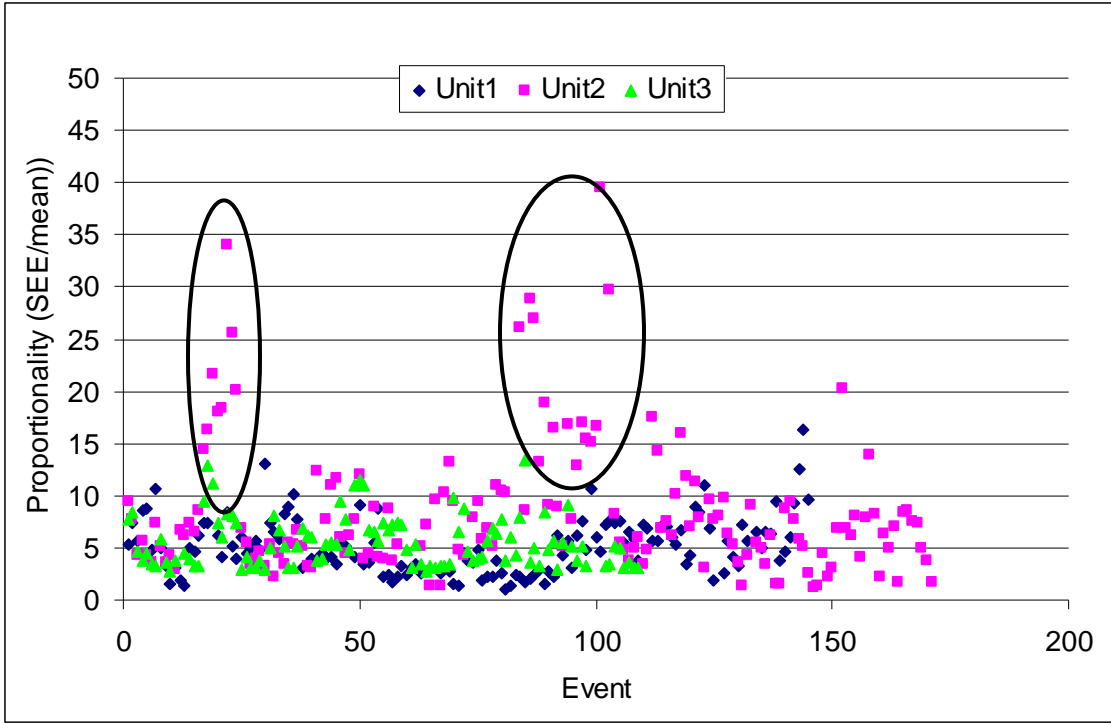
Figure 6-4 PEMS2 proportionally for all events and for each unit tested

There is some suspect that CVS systems could cause some loss of proportionality and as such UCR took steps to minimize the affect of the MEL CVS. Each unit was tuned prior to starting each new unit. Tuning involved interactive approach where CE-CERT and the manufacturer agreed on the acceptability of the proportionality. Figure 6-5 shows a typical startup proportionality trend that would be used as the basis for proceeding. Some preliminary results were shared with the MASC that showed the high SEE/mean statistics in Figure 6-4 where it was agreed that UCR should continue with testing and try to reduce deviations as much as possible.
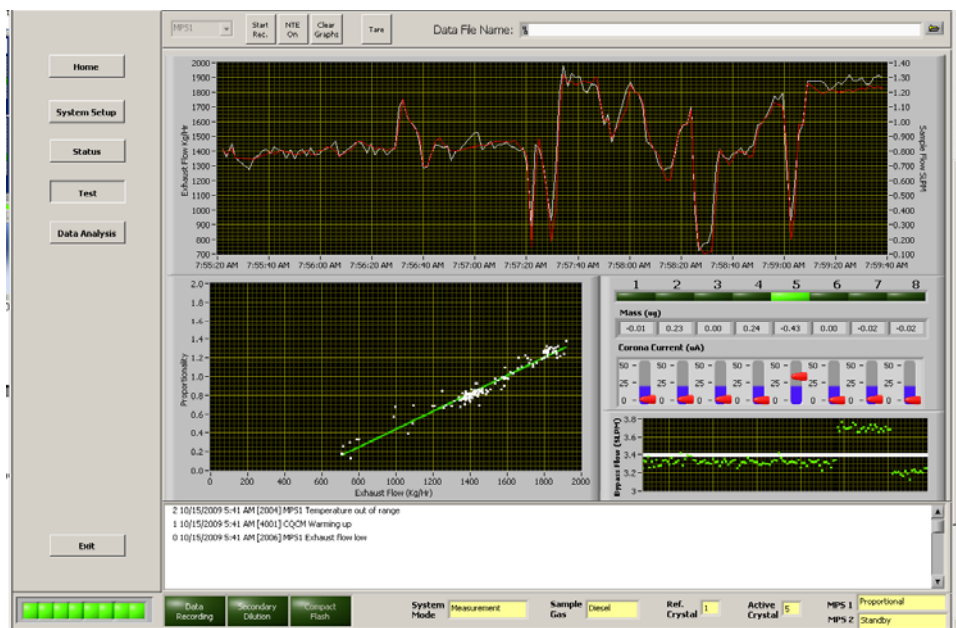
Figure 6-5 PEMS2 typical startup proportionality

6.1.1.6 QCM flow

The PEMS2 targeted QCM flow is a critical setting for proper PM quantification. The QCM flow is the flow that passes over the QCM crystal surface and its rate affects the amount of PM deposition. The manufacturer found that flows of 0.4 to 0.5 slpm provided optimum performance and is the recommended sample flow (Sensors 2009). During a previous study by Durbin et al (2009a) various operational conditions, including QCM flows, caused significant biases between the gravimetric reference and PEMS2.

During this study the QCM flow was targeted to 0.45 with a range of 0.4 to 0.5. Figure 6-6 shows the average sample flow as a function of each unit. Most of the data is bounded by the desired flow of 0.4 to 0.5 slpm for units2 and 3 where unit1 had a significant amount of flow below 0.4. The low flow for unit 1 occurred when the PEMS2 system drifted due to in-use operation. Readjustment of the QCM flows was required to correct the problem. A description of the flow control is described later to help the reader understand why the PEMS2 system would drift with in-use operation. The near zero flows for unit2 was the result of loss of communication with PEMS2 TSI flow meter as described later in this section. Both circled cases required pulling over and resolving the communication issue in the field. With-out continuous monitoring of the PEMS2 systems, the communication error would not have been caught. As such, additional data would have been lost if continuous supervision of the PEMS2 flows was not performed.

Before we explain how the large unit1 flow deviation could have occurred, we need to first understand how the flows are reported and controlled. The reported QCM flows are calculated from a difference of flows and the flow is set by eight different needle valves. Figure 6-7 shows the physical layout of the needle valves and Figure 6-8 shows a schematic of the QCM flow with the needle valves identified. Each needle valve controls the flow through a specific crystal. During non-NTE event operation the maximum flow goes through the TSI meter (Q_{ref}) and in

NTE sample mode one crystals worth of flow diverts to the crystal surface and Q_{ref} drops by 0.4 to 0.5 slpm depending on the setting of that QCM's needle valve. Thus, the needle valve settings control the flow through each crystal and the difference in Q_{ref} determines the reported QCM flow. Thus, the QCM flows will vary by the settings of each needle valve which is one reason for the flow variability in Figure 6-6. Also the needle valve flow will vary with elevation slightly and is expected to be small relative to short NTE events and possibly noticeable for long events with continuous grade.

One reason for large QCM flow deviations could be due to vibrations or shock on the needle valve settings, since the needle valves control the QCM flow. Unit1 showed good QCM flow for the first two days with some deviation on day three and significant deviations on day four. Day five flows were good due to making readjustments to the needle valves. Vibration or shock could change the position of the needle valve thus cause the flow to change. Physical readjustment will be necessary for future problems of this nature and the problem may not be easy to identify during startup or during in-use operation.
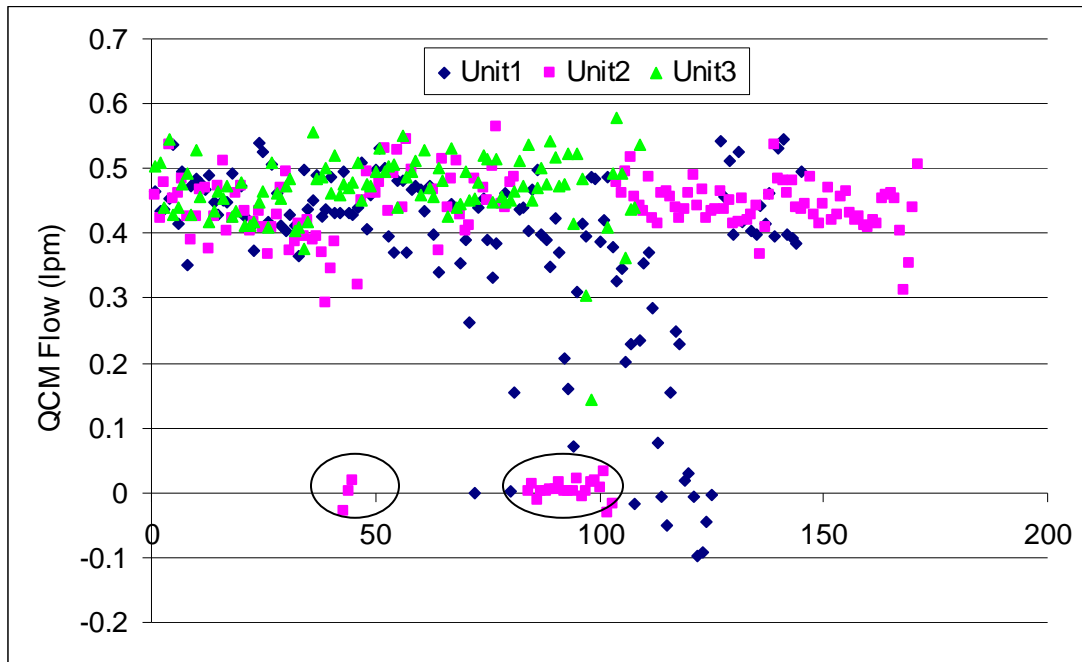
Figure 6-6 PEMS2 sample flow variations by unit

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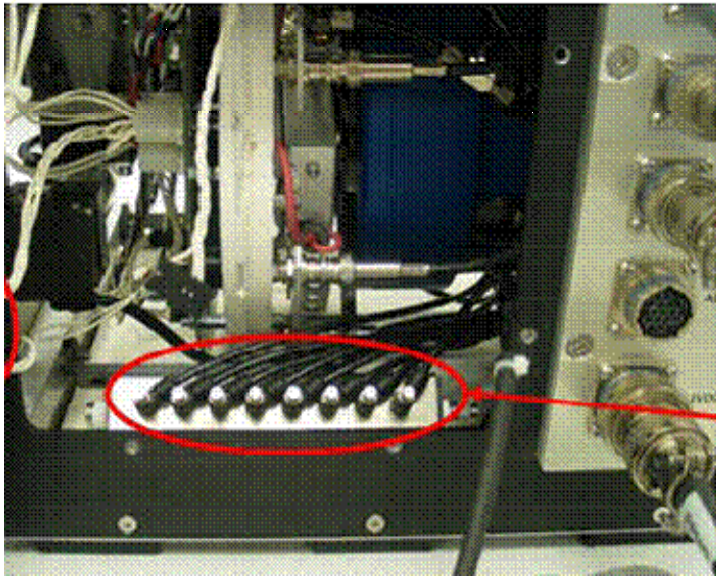
Figure 6-7 PEMS2 micro-needle valves for QCM flow adjustment
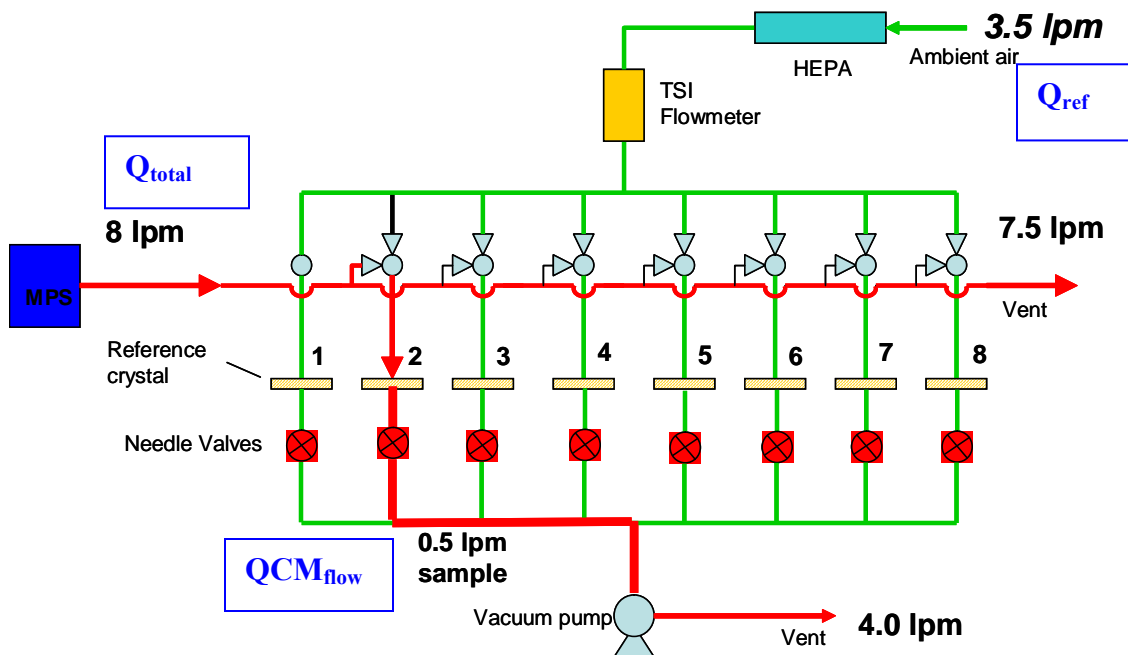
Figure 6-8 PEMS2 QCM flow schematic for contributing systems

6.1.1.7 Corona current mode

Important to PEMS2 operation is a parameter dependent on the operational mode of the corona current that is used to charge the particles to ensure deposition on the QCM surface. One mode is constant current and the other is constant voltage. The manufacturer has shown that constant voltage (ie varying current) is the optimum method for particle deposition. Figure 6-9 shows the corona current for units 1, 2, and 3. Units 1 and 2 were operated in constant voltage mode where

unit 3 started in constant voltage then shifted to constant current. It is not clear what caused the change from constant voltage to constant current.
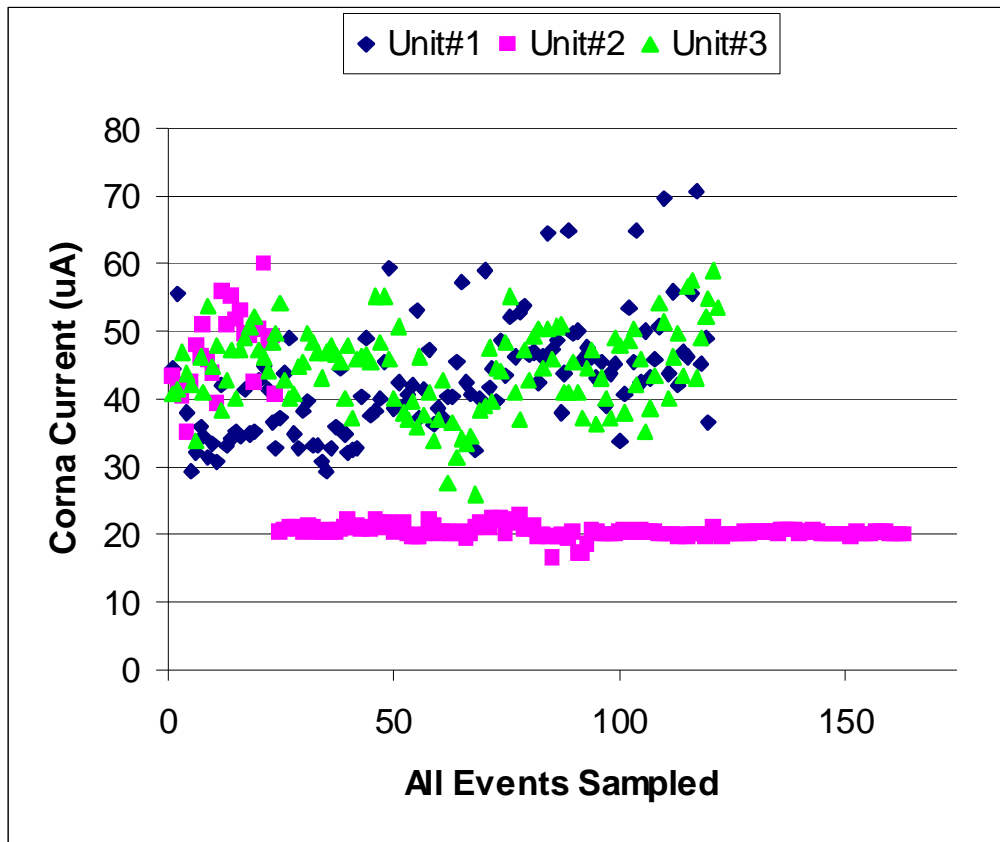
Figure 6-9 PEMS2 corona current mode units1, 2, and 3

The effect corona current mode has on the PEMS bsPM is not obvious from some results on unit#3. Figure 6-10 shows the bsPM delta's for all units (blue dots) and data in constant current mode (pink circles). The SwRI model development was performed with the PEMS2 system in constant voltage mode. More analysis is needed to understand the impact of the corona mode of operation.
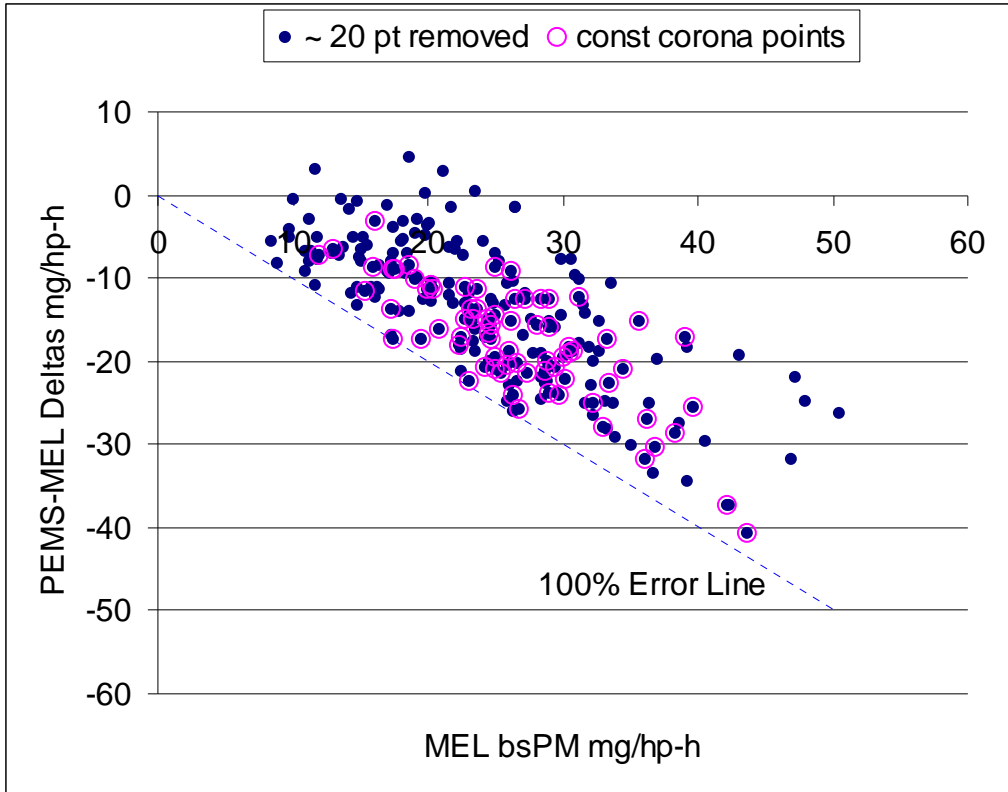
Figure 6-10 PEMS2 corona mode issue in terms of the bsPM delta plot

6.1.1.8 Total flow

The total flow is the diluted sample flow coming from the exhaust and MPS1 dilution system (MPS2 was not used in this study). The total flow is identified in Figure 6-8 as Q_{total}. The total flow is set based on manufacturers specifications.

Figure 6-11 shows the mean total flow measured for each event for units 1, 2 and 3. Unit 1 varied from 8 to 9 slpm, unit 2 varied from 7.5 to 8.5 and unit 3 remained relatively constant at 10 slpm. Unit1 and 2 total flows were targeted to 8 slpm and unit 3 was changed to 10 slpm as a result of an increase in diameter of the sample capillary system from units 1 and 2 to unit 3. It is unclear what impact the variability of the total flow has on the PEMS2 system, but these were the deviations noted for the validation testing.
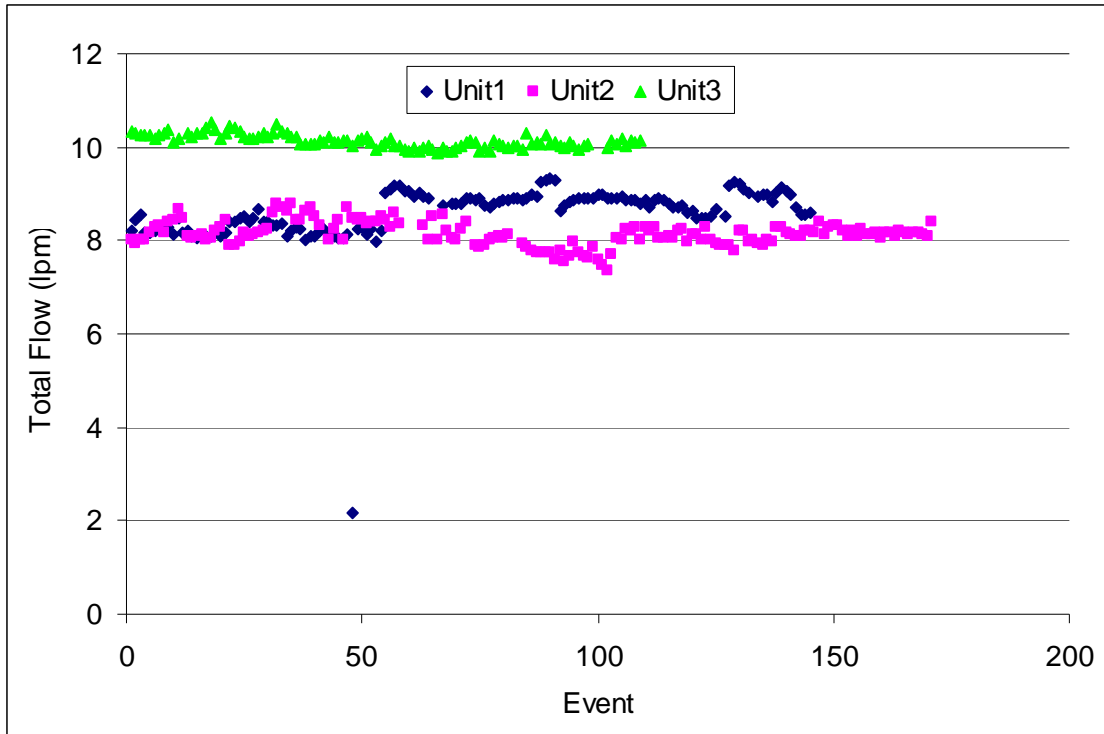
Figure 6-11 PEMS2 mean total flow for each unit

6.1.1.9   Crystal stability

Data filtering for PEMS2 is an integral part of their PM system since data removal is common. One of the steps to removing PEMS2 data is to look at crystal stability and remove data points where the stability is above some threshold. Figure 6-12 shows the crystal stability results for each event tested. The stability threshold used for the validation testing was 0.01 ug as shown by the dark line in Figure 6-12. Units 3 showed the most points above the 0.01 ug where units1 and 2 were fewer, but still significant. During discussions with the MA committee the threshold was decided to be increased from 0.01 to 0.02 to increase data yield on unit 3, but units 1 and 2 used the 0.01 ug threshold as designed.
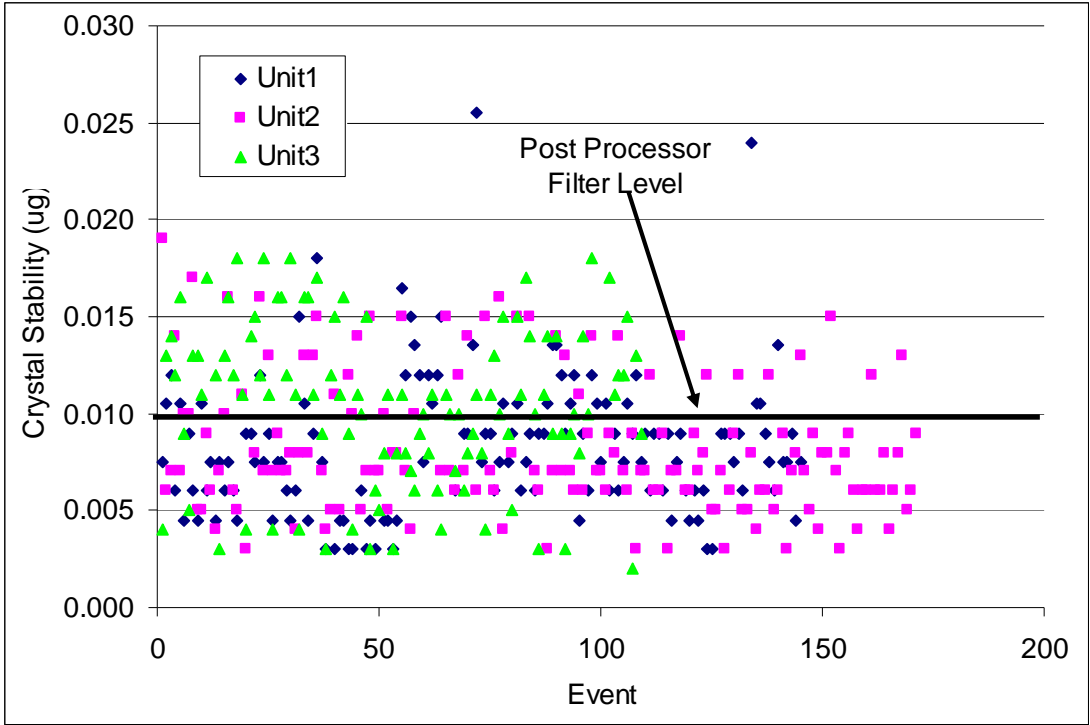
Figure 6-12 PEMS2 crystal stability unit by unit with post processor thresholds used

6.1.1.10   Electrical connections

Electrical connections were a problem experienced on several of the units tested. Figure 6-13 through Figure 6-16 show some examples of the different electrical connection issues experienced. Figure 6-13 shows a bad connection on the TSI meter to the main mother board, Figure 6-14 shows a problem with a damaged TSI serial communication to CAN interface circuit, Figure 6-15 shows a problem where a connection between the TSI flow meter failed, Figure 6-16 shows a figure where the MPS1 mother board deflects under different loads and becomes a bad connection. Rubber spacers were used to create enough pressure for this connection to be inserted all the way. Other issues encountered with electrical connections included the motor drives, QCM and MPS displays systems to mention a few.
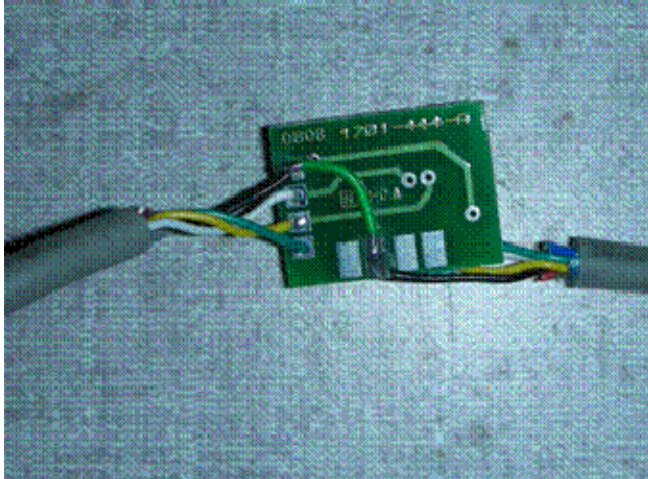
Figure 6-13 PEMS2 electrical connection on TSI flow meter serial to can interface
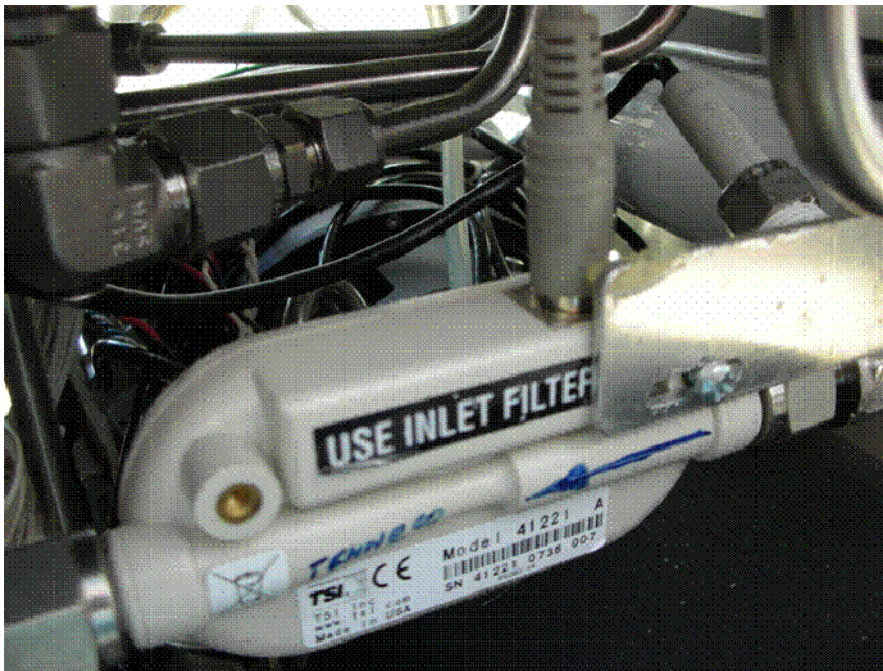
Figure 6-14 PEMS2 electrical connection on TSI flow meter assembly
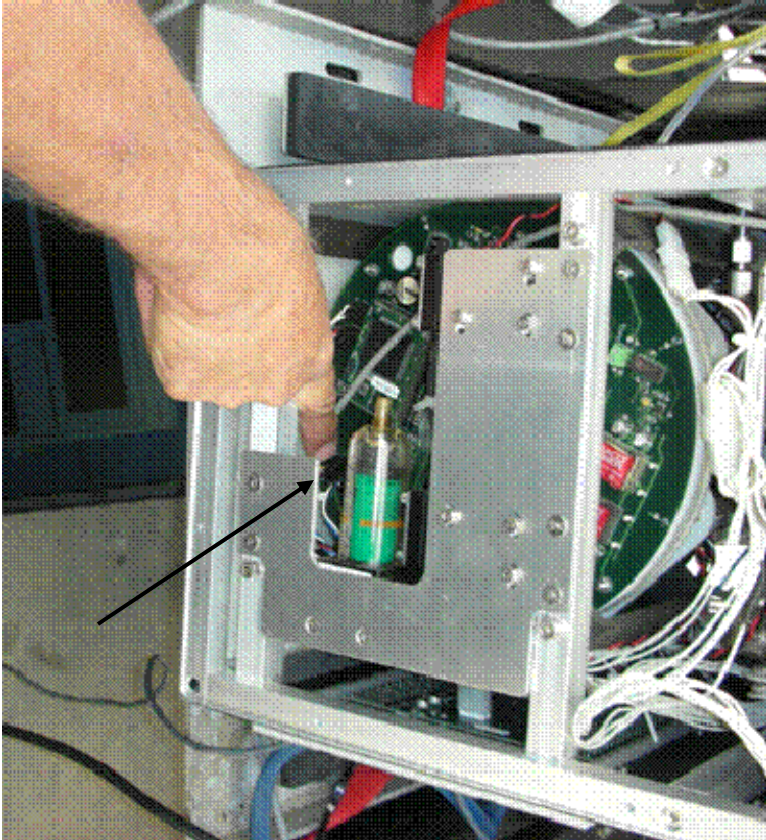
Figure 6-15 PESM2 main board connector for bypass flow
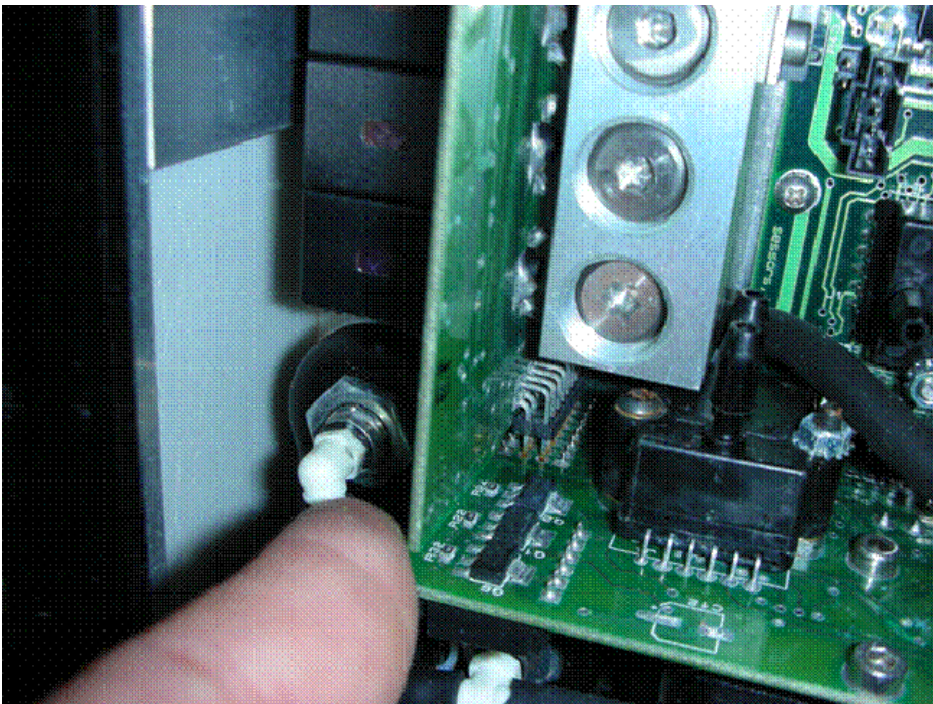
Figure 6-16 PEMS2 MPS1 electrical connection causing data loss for proportional system

6.1.1.11 Moisture contamination

During validation testing there were a few days where rain prevented the MEL from testing. UCR used tarps to cover the PEMS equipment to prevent direct rain damage. All the PEMS equipment was thus exposed to possible condensation depending on their ruggedness to handle this type of coming in-use situation. The PEMS2 system did experience some condensation film was noticed on several components. In some cases this film caused communication issues and operational problems. Corrective solutions required removing and reconnecting and some times cleaning the electrical components and connections to get proper operation.

6.1.1.12 Electrical spikes and surges

PEMS reliability is a critical part of in-use testing where unattended operation is expected for a typical 8 hour shift. During some Unit2 testing the PEMS2 system was operating as expected, but as the vehicle drove away (possibly due to cranking the truck engine) all the exhaust flow parameters were lost from the PEMS2 system. Loosing the exhaust flow signal caused incorrect proportionality and UCR had to return back home. It turned out some of the EFM microprocessor parameters were reseat to default values the prevented the system from operating. The exhaust flow meter and proportionality systems produced strange results and were non operational. It was unclear what caused the problem, but the solution was to reload the default coefficients for one of the microprocessors in the PEMS2 system from a file that was e-mailed to UCR from the manufacturer.

6.1.2 PEMS3 MSS

During the previous studies by Durbin et al (2009a, b) PEMS3 experienced in-use issues with temperature and vibrations. One reason for the temperature issue was a result of its proximity to the exhaust and engine heat. During this testing there were no vibration or temperature issues reported. The main issue with PEMS3 was a result of a CO_2 connector and the GFM module as described in the next section.

6.1.2.1 CO_2 connector

PEMS2 system measures CO_2 concentration as a diagnostic for operational performance with its soot measurement system. During unit2 testing the connector dislodged itself and the error code put the instrument in a standby mode preventing the collection of two runs of data. Figure 6-17 shows a picture of the CO_2 sensors and the connector. The problem was fixed by using hot glue and preventing the connector from coming at the request of the manufacturer.
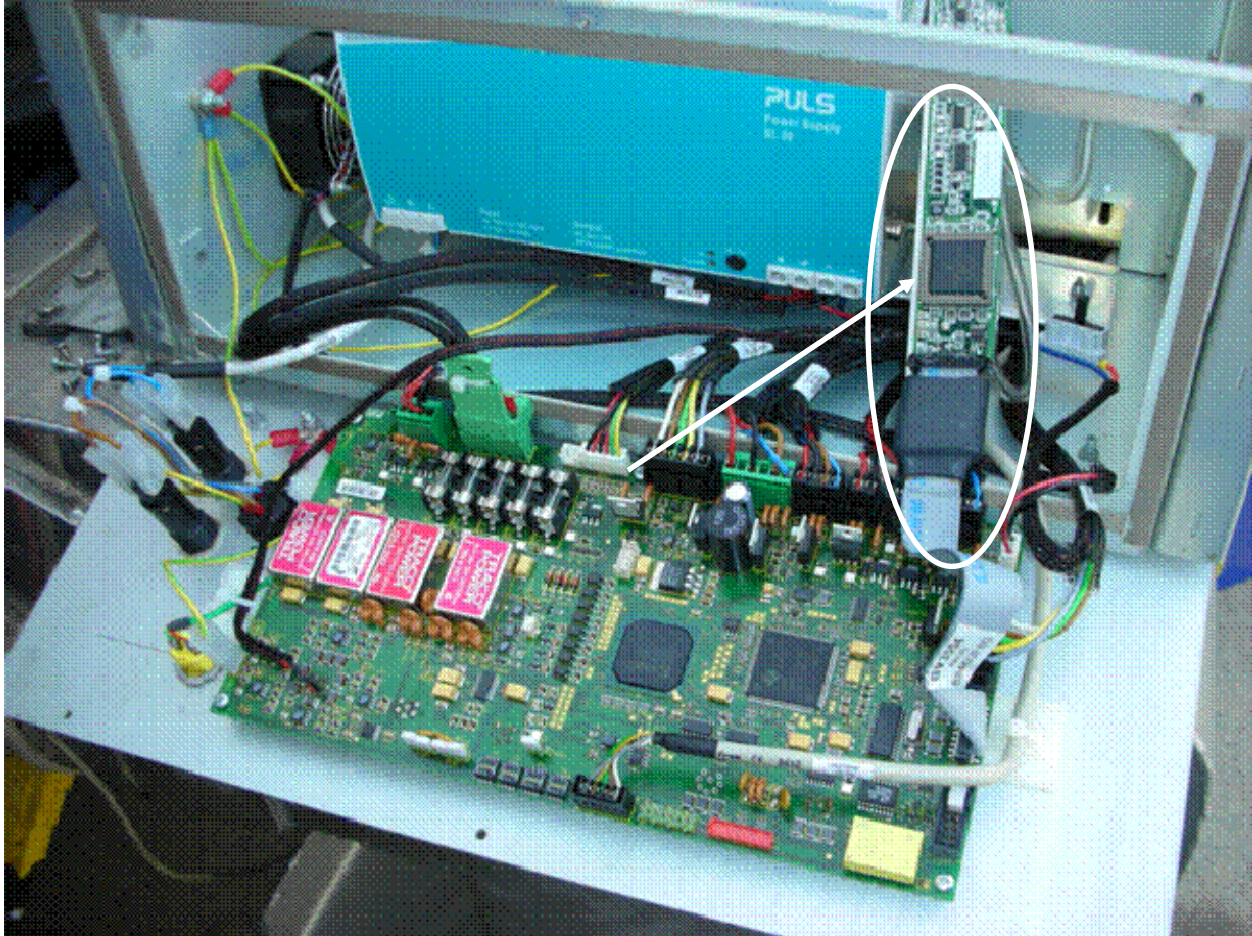
Figure 6-17 PEMS3 CO2 electrical connector caused system inoperable

6.1.3 PEMS3 MSS + GFM

The commissioning issues with the PEMS3 with the GFM option were a result of the level of development this instrument had which was on the order of a few months. In fact the validation test was the first time this prototype was evaluated in the field and by UCR not manufacturers representatives. The ability for PEMS3 manufacturer to release a prototype product for use without onsite manufacturer operation shows the level of simplicity and robustness their design has and thus needs to be stressed prior to talking about some of the lessons learned which would be expected on any new prototype research instrument. Below are the issues learned during operation commencing of the integrated PEMS3 GFM system.

6.1.3.1 Unit1 GFM system leak

Leak checks are performed as routine startups for most systems to ensure data integrity. PEMS3 MSS system pass its system leak check, but the procedure for a filter box leak check were not complete and were found to not be sufficient. During unit 1 testing a leak formed between the bypass sample filter on the GFM system. The leak was the result of possible vibrations or tight tolerances on the filter holder assembly. Once the leak was identified corrective action required

significant effort to tighten the filter holder. An improved leak check method was employed that prevented this problem on units2, 3 and 4.

6.2   Operational issues

Operational issues focus on problems associated with startup, commissioning and systems prior to testing in-use. Typical issues include incorrect system configurations, procedures that don't work, startup software, and other recommended practices that didn't function according to the manual. This section provides the reader a sense of readiness and inconsistencies according to manuals.

6.2.1   PEMS2

PEMS2 had several issues require a significant amount of commissioning and startup time. In addition it was typical that consecutive testing could not be performed due to repairs or results suggesting some type of tuning, tweaking or repairs were needed. This section covers the PEMS2 operational issues

6.2.1.1   Mass sensitivity

PEMS2 uses several parameters stored in microprocessors for the control and accuracy of its measurement system. One of these parameters is called mass sensitivity. The mass sensitivity is used to covert crystal oscillations changes with mass loading and has units of ug/Hz. After completion of unit1 testing, a significantly low bias was found between the PEMS2 and the MEL. It was discovered that the mass sensitivity loaded into the PEMS2 system was incorrect. The mass sensitivity was changed from 100 ug/Hz to 150 ug/Hz. The bsPM data presented in this report was corrected for this mass sensitivity. The correction was straight forward and required a direct multiplier of 1.5 times all bsPM and concentration numbers presented for unit 1 PEMS2.

6.2.1.2   Exhaust flow tubing

Exhaust flow is a critical part for both gaseous and PM measurements using Method 1 calculation. The exhaust flows was found to be reasonable for unit1, but low for units2 and 3 relative to the MEL. The MEL does not directly measure exhaust flow and uses the difference of its total and dilute CVS venturi flows as described in Section 5.3. Figure 6-18 shows the PEMS2 exhaust flow measurement compared with the MEL exhaust flow estimation. Unit 1 agrees well, but units 2 and 3 are off by factors of 1.5 compared to the MEL. Figure 6-19 shows the PEMS exhaust flow real time signal for three selected routes where the unit 1 data is noticeably higher at idle and at full load compared to units2 and 3. The real time figure also shows the transient nature of the data was present for all units and only the magnitude of units 2 and 3 were affected.

After further investigation, using carbon balance, Method 2 and Method 3 calculations, it was confirmed that the PEMS unit2 and 3 exhaust flows were biased low. The source of the problem was not known and it was suggested that the sample line tubing's were not hooked up properly where the static and the low pressure lines were switched. UCR investigated the orientation of

the lines and it was confirmed from photo graphs of each setup that all flow tubes were installed with flow tubes oriented from left to right as "red", "blue", and "white", as shown in Figure 6-20.

Given the same exhaust flow tubing connector was used for all PEMS and the connector is keyed to the PEMS surface, the only possibility for an error was to have the tubes switched internally to the PEMS unit. UCR applied pressure to each port for each unit. The unit1 pressure ports were in the correct orientation, but the low and static pressure ports were switched for units 2 and 3, as shown in Figure 6-20. This suggests that the connections internal to the PEMS2 system switched between unit1 to units2 and 3.
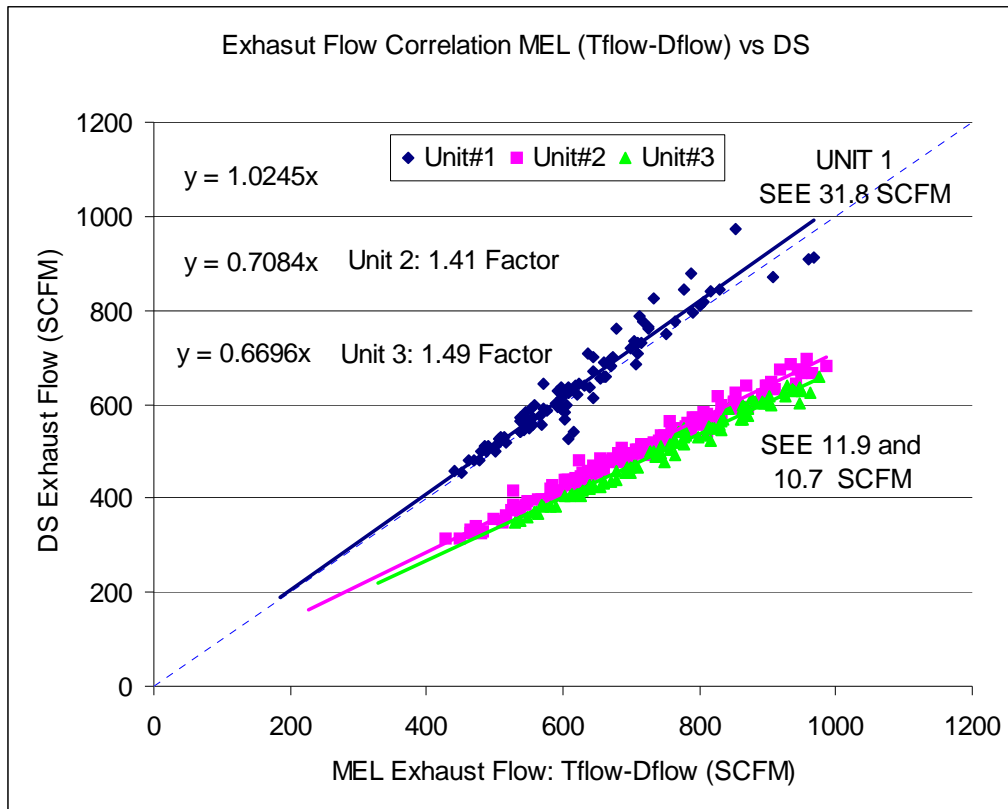
Figure 6-18 PEMS2 integrated exhaust flow comparison to the MEL
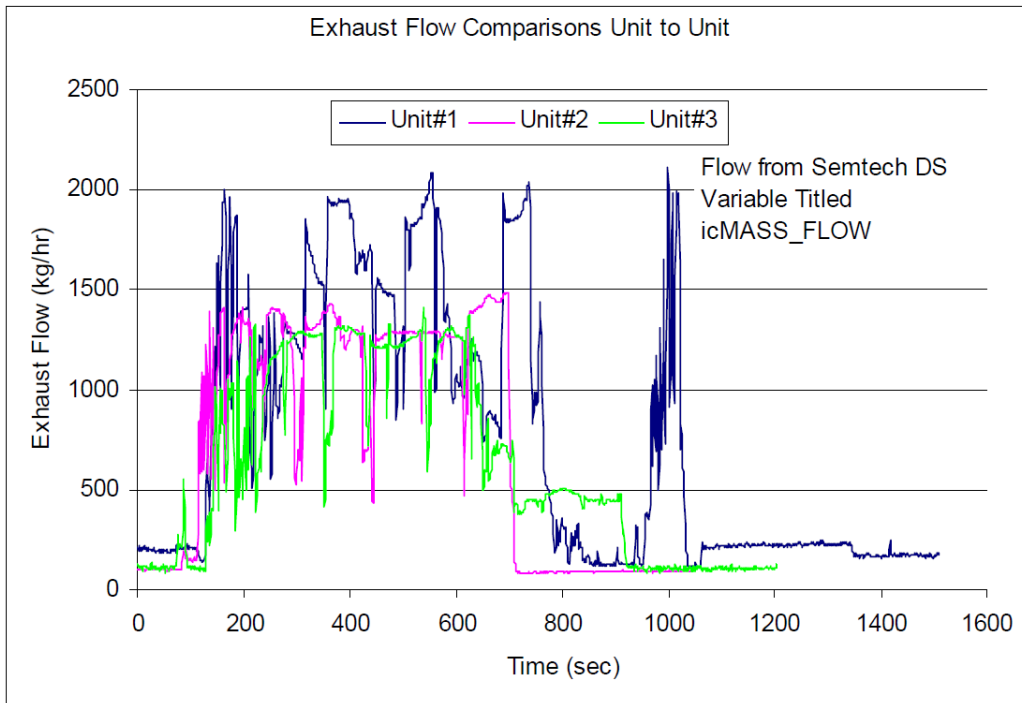
Figure 6-19 PEMS2 real time exhaust flow signal from selected tests for units1, 2, and 3

As installed on the vehicle, see A

Unit #1	Red	Blue	White
Unit #2	Red	Blue	White
Unit #3	Red	Blue	White

As determined by applying pressure at A

Unit #1	P high	P static	P low
Unit #2	P high	P low	P static
Unit #3	P high	P low	P static
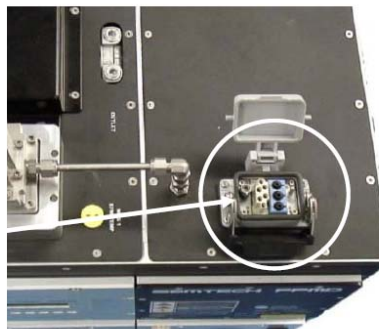
Figure 6-20 PEMS2 exhaust flow connection between units1 compared to units 2 and 3

The affect of switching these lines can be seen from Figure 6-21 which shows a schematic representation of the exhaust flow measurement system where the static, high and low pressure

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ports are shown. Equation 3 shows how these variables affect the exhaust flow calculation. The switched tubing caused units 2 and 3 P_{high} to be switched with P_{static} and these measurements could not be reprocessed and corrected due to P_{low} and P_{high} being measured as a differential pressure

The exhaust flow measurements were not completely invalid and were salvaged by recalibrating unit 2 and 3's flow meters using the same orientation as tested. New calibration factors were supplied to UCR for units 2 and 3 where the factors were 1.50 and 1.52 respectively. It interesting how close the flow corrections were to each other suggesting their may be a fundamental principle behind the factors which gives more confidence in using this correction than if they were significantly different.

In general the flow correction combined with the barometric pressure corrections did show good correlation to the MEL exhaust flow and carbon balance thus suggesting the recalibration corrections were reasonable.
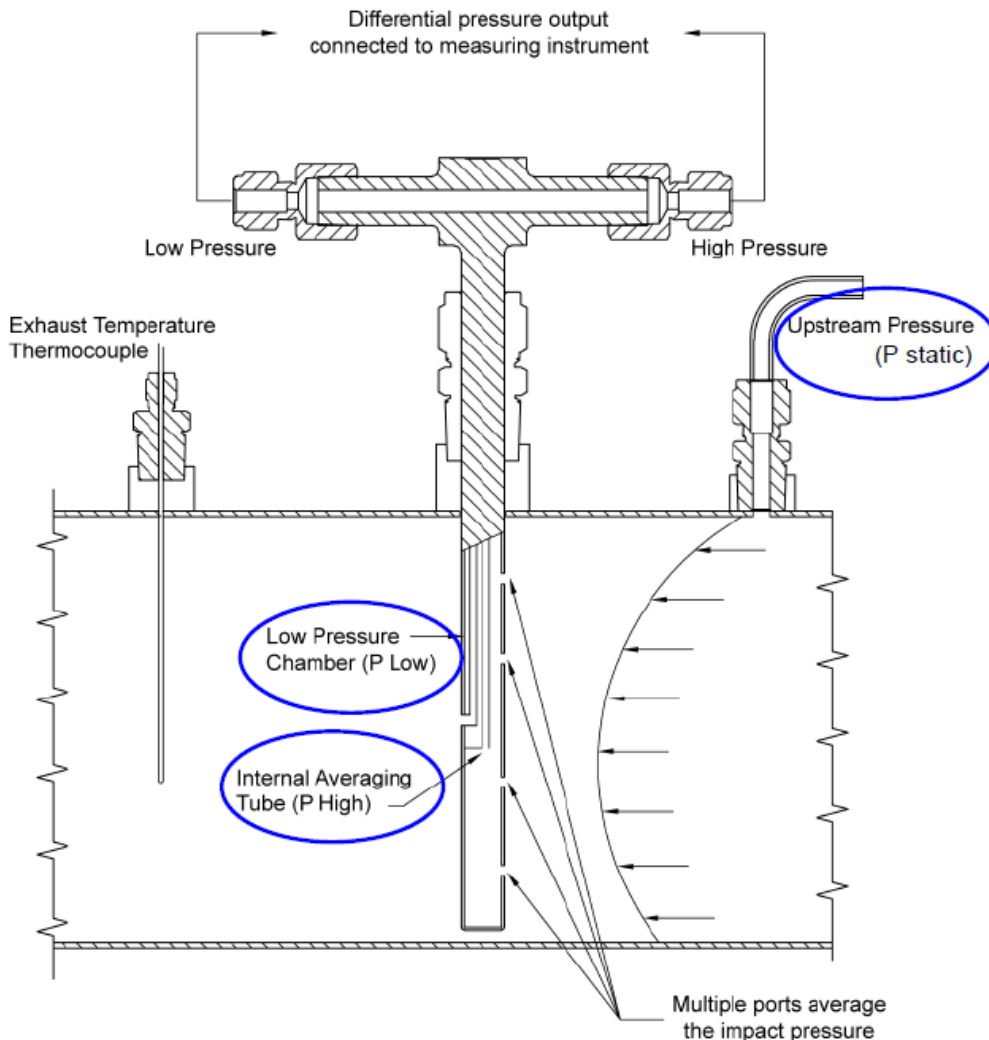
Figure 6-21 PEMS2 schematic representation of the exhaust flow measurement principle

$$Q = A * K\{RE\} * \sqrt{2 * \frac{(P_{baro} + P_{static}) * MW_{exh}}{T * R_u} (P_h - P_l)}$$ **Equation 7**

6.2.1.3   Sample flow: calibration

Sample flow is a critical part of PEMS2 measurements system and as such the manufacturer recommends daily flow calibrations. Daily flow verifications/calibrations are recommended to prevent possible deviations in the sample path from PM build up in the sample capillary. According to CFR40 Part 1065 the PEMS slope specification is 0.98 to 1.02 for a passing case and is also recommended by the PEMS manufacture.

The, as received, slope calibration of PEMS2 unit 1 was 0.7 which was significantly lower than the minimum 0.98 requirement. The supplied flow audit tools were out of calibration and as such UCR performed some in-house measurements using a primary flow calibration standard which confirmed the 0.7 slope. Due to the large deviation a new TSI audit reference meter was supplied by the PEMS2 manufacturer where the 0.7 slope was also confirmed. Thus, the as supplied slope calibration was 0.7 where a significant correction was needed and performed for Unit1. Units 2 and 3 were shipped with slopes close to or with-in the CFR specifications.

The daily sample flow calibrations were typically out of tolerance for the slope parameter where some were above the 1.02 standard and others were below the 0.98 specification; see Appendix J. Daily sample capillary cleaning and leak checks were performed to prevent sample flow deviations. Typically three or four repeated sample flow calibration checks were required to achieve a passing value. A passing value was some times achieved with no changes to the system suggesting the sample flow system is not able to routinely meet the slope specifications. Further analysis is needed to identify the reason for the deviations.

6.2.1.4   Major and minor MPS1 flow adjustment

The MPS1 dilution flow settings for unit 1 and 3 were within the expected ranges, but unit 2 was significantly out of tolerance as specified in the manual (Sensors 2009). UCR had to readjust the major and minor MPS1 flows to bring unit2 back into specifications. UCR followed the procedure in the manual with the help of a web-ex interactive session with the manufacture. The process took more than one hour as specified in the manual because the PEMS2 system had to be removed from the vehicle first then reinstalled and commissioned again after the adjustments were made.

6.2.1.5   Crystal burn-in

Predictable crystal behavior is important for the PEMS2 PM measurement principle. There is some speculation from the manufacturer that part of the bsPM low bias is a result of insufficient crystal burn in. This may be evident with the figures presented in the varying decay rates of some of the crystals as shown in Section 6.2.1.9. The manufacturer proposed improving the burn in

process to prevent incomplete crystal burn-in. It is unclear what impact this will have on future bsPM emissions, and as such further analysis is recommended.

6.2.1.6 Leak checks

Leak checks are an integral part of exhaust emissions sampling and typically are performed prior to a days testing based on good engineering practice. A simple quick leak check method is thus a necessary step to properly maintain the integrity of a testing campaign. The PEMS2 leak check method was fairly time consuming and required removing components that later could form a leak if not reinstalled properly. The equipment from Sensors did not function properly and a modified leak check system was implemented by UCR for this testing program. This section documents what didn't work, what UCR did to leak check PEMS2, and what some typical results were.

UCR fixed some broken cables from PEMS2 O_2 sensor, tried to install, but did not have a free RS232 interface to view the signal. The manufacturer did not have a solution how to view the signal from the external O_2 sensors shipped with the PEMS2. Tried to use the Semtech DS gaseous analyzer, but the O_2 value was zero while sampling ambient air and manufacturer said their may be an issue with the O_2 system. Tried to use MEL O_2 analyzer, but there was not enough pressure to push gas from PEMS2 to MEL. UCR had to install a pump to push the gas over which could introduce a leak. The amount of leak was evaluated and finally a valid leak check was performed following a slightly different procedure than what Sensors offered, but was with-in the spirit of the test.

The UCR leak check setup is shown in Figure 6-22 and Figure 6-23 and the results are shown in Table 6-1. Nitrogen was introduced into the sample inlet (Q1) and sample pump inlet (P1) with a small vent flow at Q2 bypass port and a sample pump pulling the flow from MPS1 outlet (Q2) over to the MEL gaseous oxygen analyzer.

Table 6-1 PEMS2 leak check results at different locations

Setup	Meausred O2 %	Actual O2 %	Comment
N2 at Pump Inet Base	0.15	0	Base
N2 at >4lpm Q1 & 500ccm Q2	0.30	0.15	with minor bypass
N2 at >4lpm Q1 & 2000ccm Q2	0.18	0.03	with typical bypass (Sensors)
N2 at >4lpm Q1 & 20ccm Q2	0.30	0.15	with minimal bypass
N2 at 4lpm Q1 & < 0 ccm Q2	1.20	1.05	with small negative bypass
N2 at 0lpm Q1 & << 0 ccm Q2	6.19	6.04	with zero bypass (diluted value)
No tube on Q1 (open to atm)	7.95	7.8	true diluated zero with no restrictions
Pump to MEL open to atm	20.95		instrument span on air

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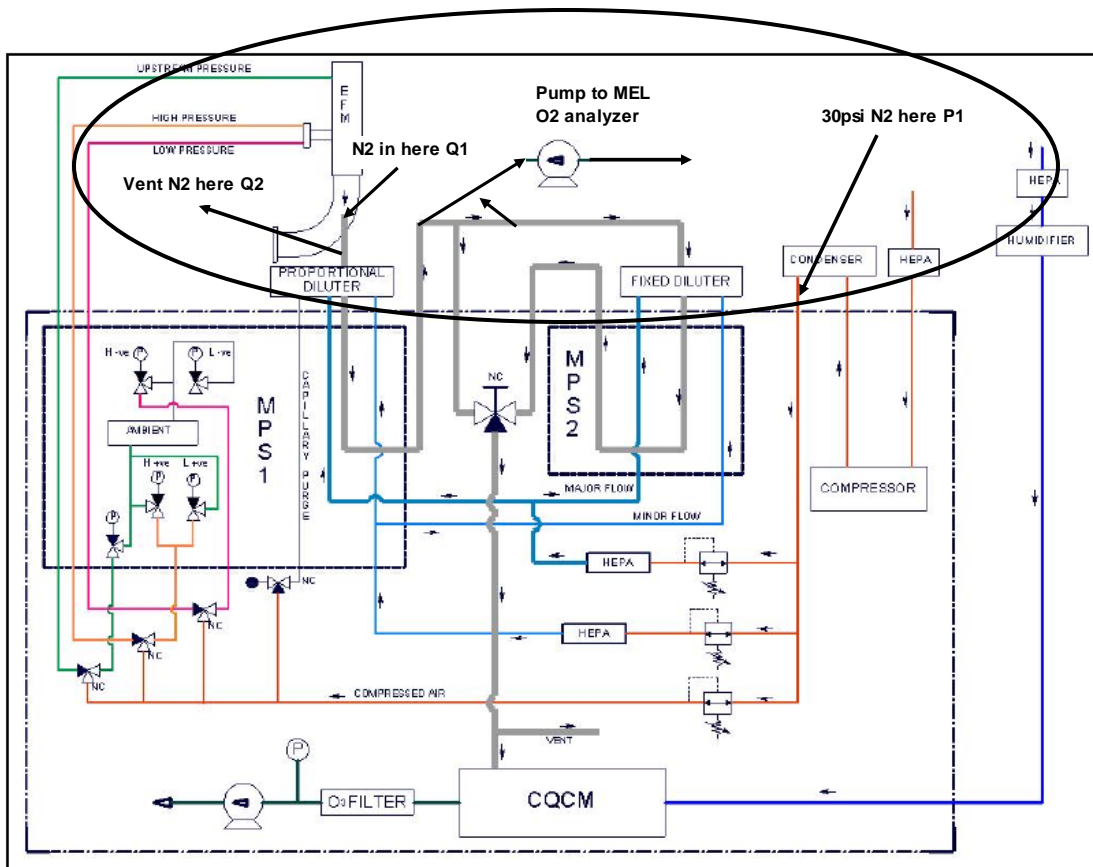
Figure 6-22 PEMS2 full flow path and leak check system schematic (Sensors 2009)
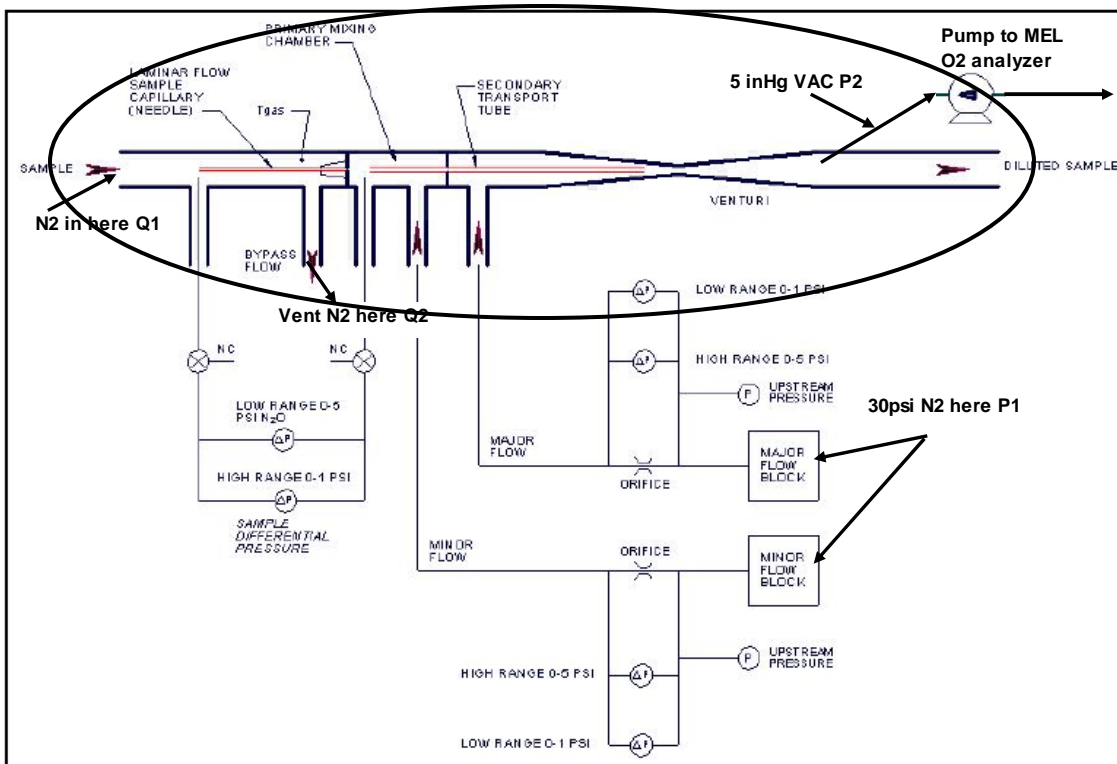
Figure 6-23 PEMS2 sample path leak check schematic (Sensors 2009)

Several conditions were attempted as listed in Table 6-1. Nitrogen into the pump directly showed a base reading of 0.15% and could be a small leak in the pump system thus this was removed. The remaining leak was identified as coming from the PEMS. With a reasonable 2 lpm overflow at Q2 the leak check pass, but if the overflow is low near 0.5 lpm the leak check fails the manufacturers 0.1 % oxygen measurement. As a point of reference with no nitrogen bypass (Q2 = 0) and no nitrogen at the sample location (Q1 = 0) the oxygen concentration was 6.04% with an oxygen concentration of 20.95%. It appears the definition of a pass or failure depends on the bypass flow (Q2).

It is recommended that PEMS2 manual be more specific on their leak check method and provide all the tools to perform the leak check. Also ideal leak checks should be performed with-out disassembling too many components.

6.2.1.7   Microcontroller parameters incorrect

PEMS2 instrument incorporates several microprocessors that communication over a CAN local area network. Each process contains hundreds of constants and parameters used to operate this PEMS. During the validation testing it was discovered that some of the constants were incorrect and were changed through communications with the manufacture. Those that were significant were described in details such as the sensitivity issue section, but others were fixed on the fly and not documented. Adjusting these parameters is typically done only by the manufacture, but some of the PM PEMS systems were not setup similarly which suggests some concern that future problems with parameters and constants may occur for this PEMS system.

6.2.1.8   Crystal stability checks

Part of the startup procedure for PEMS2 is to verify the crystal stability following a preprogrammed process. This process checks crystal behavior and provides metrics for the user to determine if the crystal passes the verification check. Several times the check would fail due to communications issues or crystals actually out of tolerances. When the stability checks failed the procedure would be repeated until it passed. Repeating this process adds time to the startup of this PEMS instrument.

6.2.1.9   Decay rates vary

PEMS2 PM results depend on pre and post sample QCM average measurements. The pre sample occurs 30 seconds prior to the start of the event and the post sample average occurs 300 seconds after the event. The decay of mass on the crystal is noticeable for some events and not others, see Figure 6-24 and Figure 6-25. In Figure 6-24 the decay rates were about -0.1 ug/min and in Figure 6-25 they were less than 0.01 ug/min. This suggests that the behavior of the PEMS2 mass detection system varies between tests. Further analysis is needed to understand what caused this. Due to limited time for analysis not further investigation was performed.
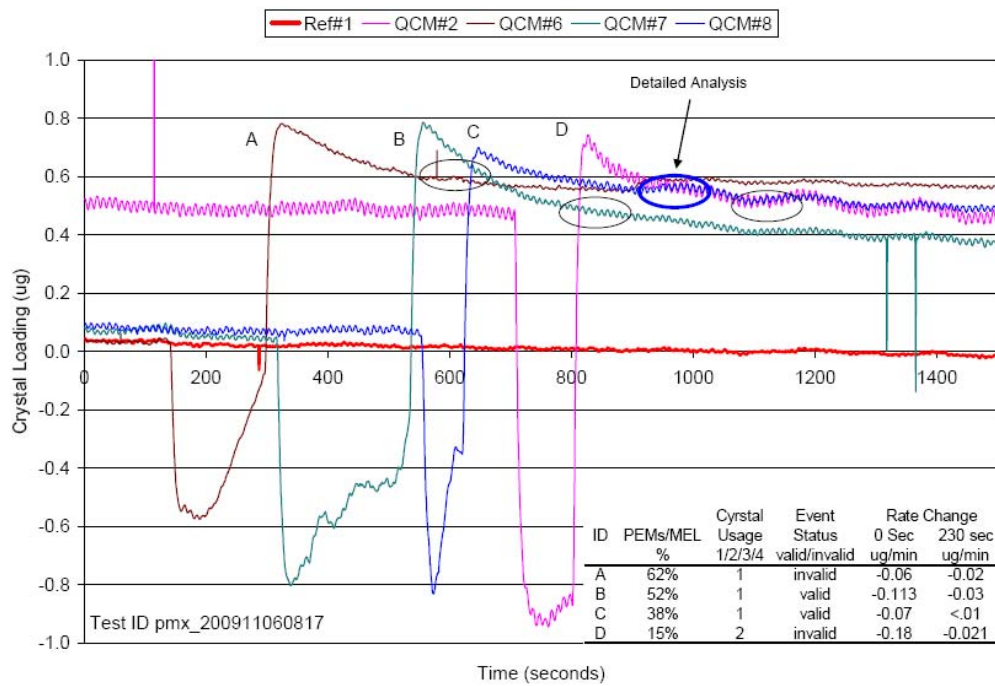
Figure 6-24 PEMS2 unit2 shows relatively large decay rates
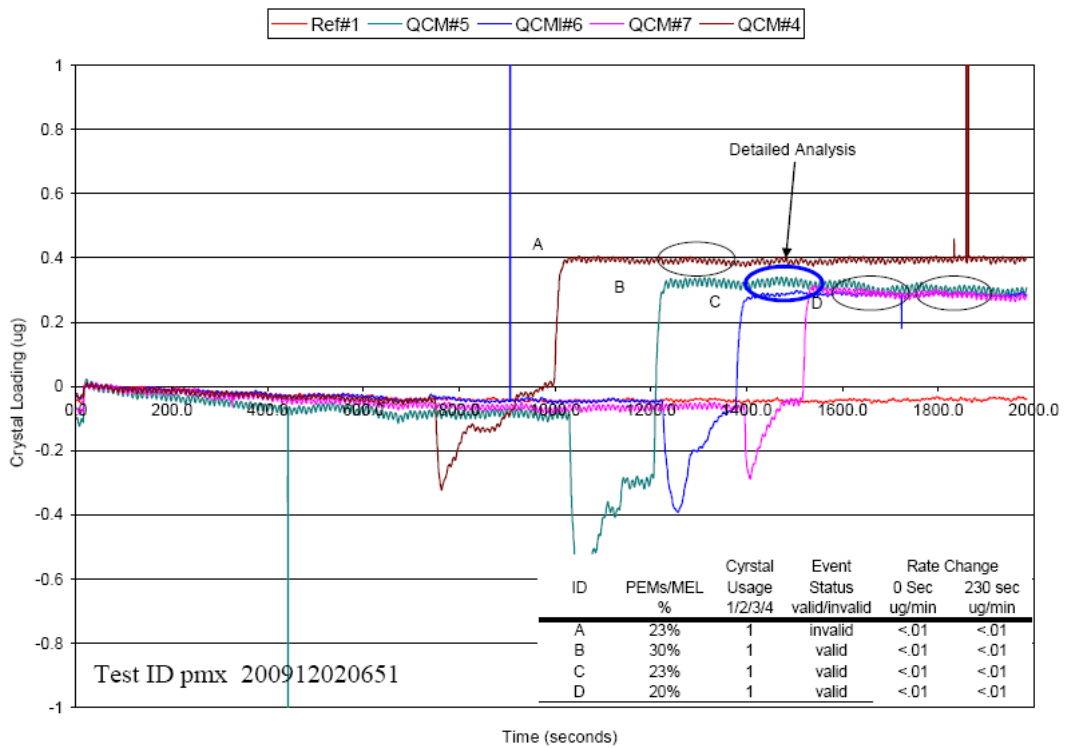
Figure 6-25 PEMS2 unit2 shows minor decay rates

6.2.1.10   Startup time

PEMS startup time is an important specification for in-use testing especially where quick setup and removal are needed to work within customer's vehicle work schedules. The startup time for PEMS2 from an unplugged instrument (cold and no power) ranged from 2.5 hours to 5 hours. The reason for the variation in warm up time was relative to the iterative issues with sample flow auditing and crystal stability verifications. All leak checks, crystal greasing, and sample capillary cleaning were performed the night before. The longer start-up times were typically due to instrument troubleshooting that occurred during startup. Some days the startup times exceeded the 5 hours where UCR chose to not go testing for the day.

6.2.1.11   Stepper motor failure

The PEMS2 stepper motor system is used to index the sample flow path to the different crystals for PM detection. During commissioning of PEMS1 the stepper motor assembly failed, as shown in Figure 6-26. It is unclear what caused the failure, but the recommended solution was to replace the head assembly. The failed stepper motor failure occurred to unit1 and also unit0 where unit 0 was never tested, but was commissioned.
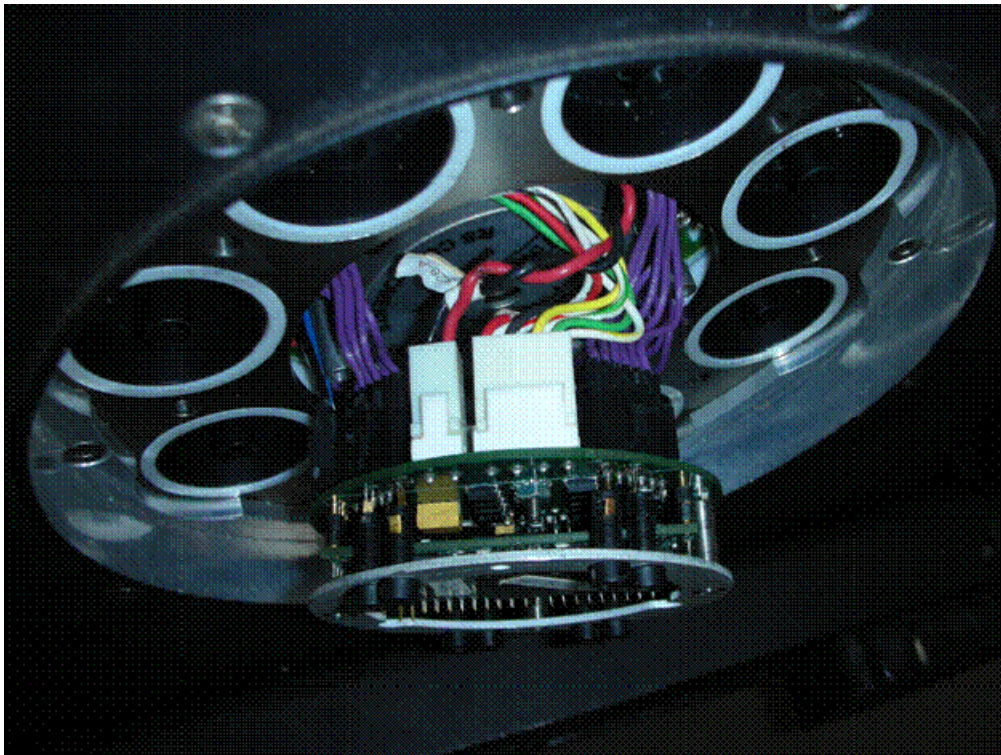
Figure 6-26 PEMS2 stepper motor and assembly failure

6.2.2 PEMS3 MSS

PEMS3 operational issues were basically software related due to the level of prototype from the GFM and some electrical connections. It is unknown what the PEMS3 full production GFM system will be like where additional testing is needed to complete this evaluation.

6.2.2.1 Data logging loss

During unit1 testing it was discovered the data logging rate for the MSS was not consistent and there was data loss for some conditions. This was not an issue for the Semtech logged analog data, but PEMS3 manufacturer provided a firmware update the solved the problem for parts of unit1 and all of units2 and 3. Given no future issues with data logging rates were experienced it appears this problem is solved.

6.2.2.2 Leak check not functioning

Leak checks are an integral part of any measurement system that pulls in a sample. The MSS system prior to the GFM had a simple leak check method. Since the MSS and the GFM are integral systems the GFM caused the leak check methods for the MSS to not function. UCR with the help of PEMS3 manufacturer developed and implemented a leak check method. As described early the leak check method did not capture a small leak in the bypass filter which resulted in much of unit1 data from being analyzed. In the end a final method was employed that prevented leaks for units 2, 3 and 4.

6.2.3 PEMS3 MSS + GFM

The commissioning issues with the PEMS3 with the GFM option were a result of the level of development this instrument had which was on the order of a few months. The validation testing at UCR was the first time the prototype was evaluated in the field.

6.2.3.1 Leak check

No leak check procedure was available for the GFM system as described earlier where a leak check routine was implemented. A leak was found while testing unit1 at a bypass filter. Future leaks were prevented by implementing an updated procedure using lessons learned testing unit1.

6.2.3.2 Warm up

The GMF system was not warming up properly and required low level commands to complete the warm up procedure. By the end of the testing campaign an updated firm was provided that solved this problem.

6.3 Post processing issues

Post processing issues are related to the ability of the PEMS system to post process their data and what needed to be done by the operator to achieve validated data. During this study both

manufacturers provided updated software to process their data. As such, this section also includes information on differences between processors and the affect it had on the overall bsPM results.

6.3.1 PEMS2

PEMS2 post processor had several issues that ranged from data filtering, bsPM differences between versions, data identification, and method calculations not available. This section covers all the issues noted from the PEMS2 post processor and differences between post processors.

6.3.1.1 Data QCM recombining

Recombining QCM data is needed for events that exceed the minimum specified duration time in the PPMD operational configurations for in-use testing. During the validation testing the maximum sample time was set at 1800 seconds by the PEMS2 manufacturer for Unit#1 and #2, and changed to 240 seconds on Unit#3. The reason for the change was a response at trying to prevent the low bias shown by the results of Unit#2, see the Results section. UCR had to identify crystal on a similar event signal and recombine these manually, where some of the crystal uses were less than 29 seconds. Typically this process took iterations between knowing the correct duration and looking for the events to add or average depending on the values in the summary of interest. This process can lead to usage issues and loss of data quality and needs to be implemented for proper operation of the PEMS2 system.

6.3.1.2 Method 2 calculations needed

Methods 1, 2, and 3 are available brake specific calculations methods allowed by the CFR40 Part 1065. For batched systems Method 3 is not possible, but Method2 is. PEMS2 system is not currently providing the Method 2 calculation for either version (3.40 and 3.10) of its post processor.

6.3.1.3 Default QCM polynomial order

The QCM flow polynomial order is needed to correct for flows for a orifice type flow device that is affected by changes in pressure which occurs with elevation at a level of 3% per 1000 feet typically due to the density of the gas. The default order for the post processor is 2nd order. Barometric pressure changes linearly with elevation. Thus the default for the post processor should be 1st order. Also once the order is changed the post processor does not maintain the change so subsequent executions of the software will default back to the install state which may cause the user difficulty in producing consistent and reliable processed data.

6.3.1.4 Post processor settings reverting

Several times the post processor was used where settings were changed and then not saved when restarting the program at a later time period. The problem this causes is the user must remember each setting and this could cause difficulty in producing consistent and reliable processed data given the many options available for data processing. The post processor should either offer to

save the setting or maintain the setting as used or have a restore to defaults warning the user that the restore will take you back to square one.

6.3.1.5 QCM polynomial recalculations

One of the evaluation tools for the PEMS2 system is to considered different polynomial orders for the QCM flow as explained above. During the validation testing UCR was asked to reprocess all the PEMS2 data using a polynomial order from 2nd order to 1st which makes sense for the type of flow correction needed. The correction is made by selecting the "QCM Flow" analysis order selection in the main analysis tab, see Appendix J for details.

All three units were reprocessed and the results for unit2 are presented in the Figure 6-27. Units1 and 3 did not show any change thus they were not displayed. The effect of the "Sample Flow" correction appears to be on the order of 2-5% and bsPM is inversely related to sample flow (ie more sample flow results in less bsPM for the same event). What is surprising is the sample flow had mostly no effect on most reprocessed data where a polynomial order should results in a change. There may be a possible bug in the software. Additional analysis is needed to understand the fact that most reprocessed data was not affected by the order change.
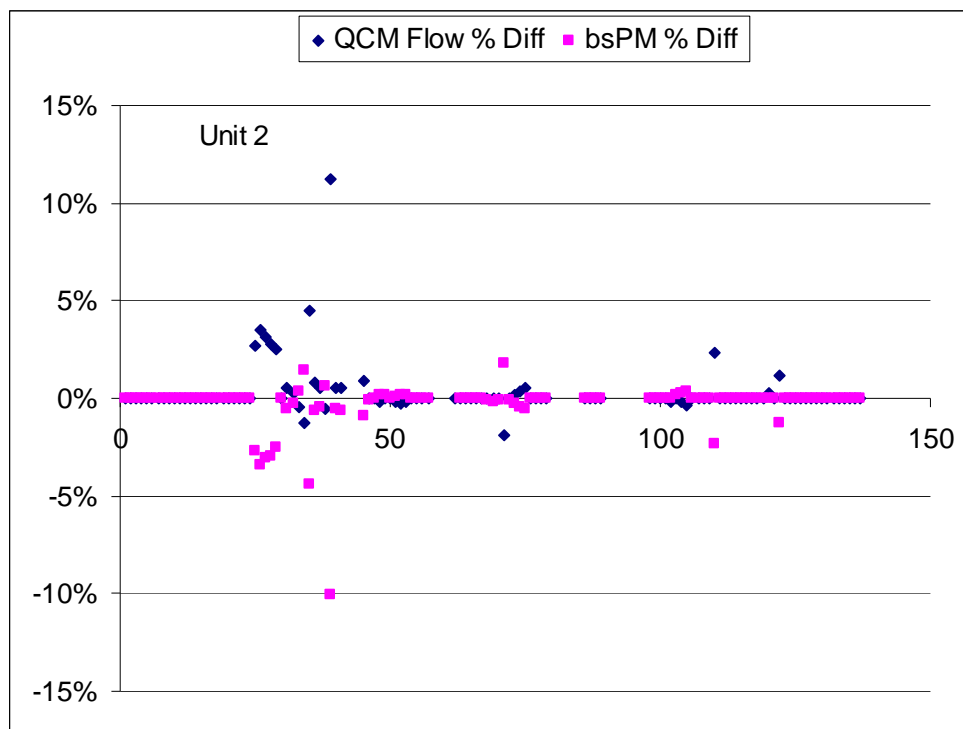
Figure 6-27 PEMS2 QCM flow polynomial order change

6.3.1.6 New postprocessor: data removal

An important step in preparing results from the PEMS2 system requires making decisions based on a series of data exclusion flags generated from its postprocessor. The manual does not provide explicit instructions on what data needs removal from these flags and thus each user must use

their judgment. During the validation testing, UCR consulted with the manufacturer and the MASC to make the decisions for valid data. All data presented in this report was reduced following best available practice, but should be documented in the manual.

The PEMS2 manufacturer suggested that one of the main causes for their low bias was a result of data points that should be invalidated due to problems with the PEMS systems. The PEMS2 manufacturers suggested that the latest versions (3.40 build 25) will catch these problems not caught by the version used at SwRI and UCR (3.10 build 10). Part of the MA program goals were to capture the PM PEMS measurement allowance frozen at a point in time thus necessitating SwRI and UCR to use the same post processer version. The post processor versions were allowed to vary up until SwRI steady state testing error surface development. In an interest to evaluate improvements with PEMS2 data, UCR did reprocess some data as selected by the manufacturer.

Table 6-2 shows a list of flags used to alert the user for what data is suspect for the main systems with in PEMS2, MPS, QCM and Sample Status. The first column for each of these systems is the original version of the post processor (used at SwRI) and the second column is the new version of the post processor. The new flags were, Temperature Ratio, Mass Headroom, Mass Limit, Crystal, and Ref Crystal. Using the new post processor, 19 points were removed due to these new data filters. Temperature ratio was an issue on all the data points where the data yield would have been very low and thus was decided to be not removed. Additional testing is needed to evaluate the PEMS performance with the latest version of the post processor filtering system.

Table 6-2 PEMS2 post processors data errors and warning flags

MPS		QCM		Sample Status	
Ver 3.10	Ver 3.40	Ver 3.10	Ver 3.40	Ver 3.10	Ver 3.40
	Temperature Ratio Fail			QCM Temp. Warning	QCM Temp. Warning
R2 Fail	R2 Fail		Mass Headroom Fail	QCM Temp. Fail	QCM Temp. Fail
Stnd Error / Max Fail	Stnd Error / Max Fail		Mass Limit Fail	Inlet Temp. Warning	Inlet Temp. Warning
Stnd Error / Mean Fail	Stnd Error / Mean Fail		Crystal Fail	Inlet Temp. Fail	Inlet Temp. Fail
Dilution Ratio Fail	Dilution Ratio Fail		Ref Crystal Fail	Insufficient Data	Insufficient Data
Max Exhaust Flow Fail	Max Exhaust Flow Fail	QCM Flow Fail	QCM Flow Fail	Mass Change Warning	Mass Change Warning
Q Total Fail	Q Total Fail	Corona Current Warning	Corona Current Warning	Mass Std Dev Warning	Mass Std Dev Warning
Operation Mode Fail	Operation Mode Fail	Corona Current Fail	Corona Current Fail	Mass Std Dev Fail	Mass Std Dev Fail

6.3.1.7   New postprocessor: bsPM changes

The MA SC requested UCR to verify Sensors data removal process and to independently evaluate the latest version of the PPMD post processor to verify that the bsPM values did not change significantly. If any change did occur UCR was to note the change for a later discussion. This memo (taken from UCR's final report) documents the changes to the bsPM from the SwRI

and UCR MA post processors version 3.1 build 10 (ver 3.1) compared to the latest version 3.4 build 25 (ver 3.4). An earlier memo was prepared that discussed the data removal effort and is not repeated here.

Figure 1 shows the absolute bsPM difference between the new and old post processors (ver 3.4-ver 3.1) in mg/hp-h and Figure 2 shows the percent difference relative to the in-use threshold of 25 mg/hp-h. This data is based on a small population from Unit #2. The new post processor showed an overall increased in the bsPM emissions up to 4 mg/hp-h with an average around 1 mg/hp-h for the small sample selected. At the in-use threshold this has an effect up to 15% with an average around 5%.
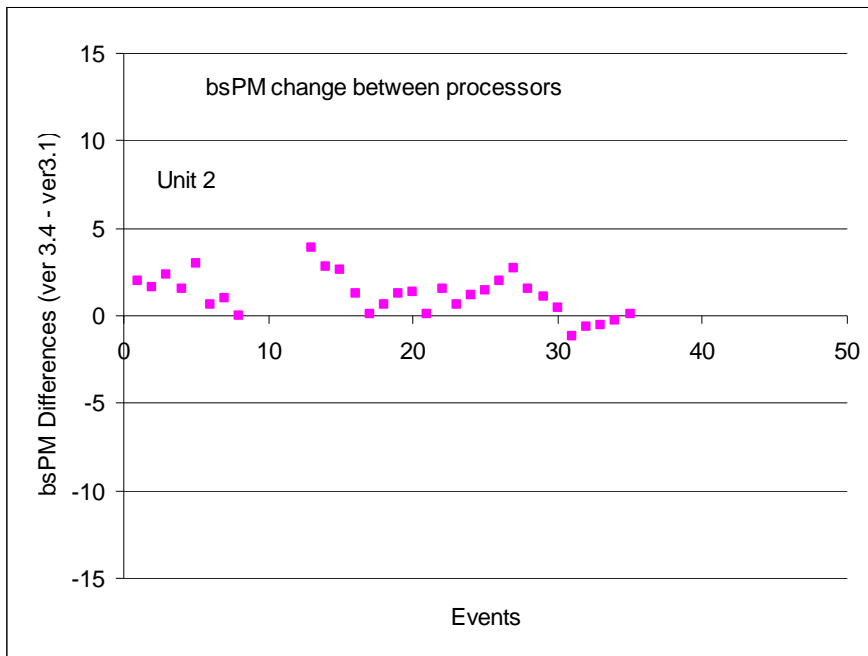
Figure 6-28 PEMS2 absolute bsPM change between two processor versions
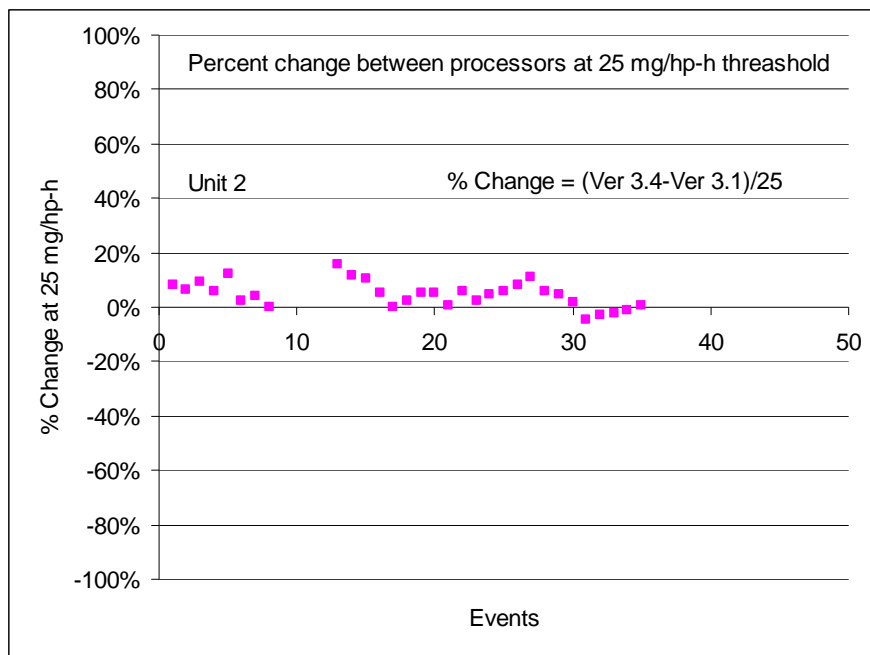
Figure 6-29 PEMS2 bsPM percent change at 25 mg/hp-h between processor versions

The latest version of the post processor did increase the bsPM compared to the earlier version. All deltas submitted to SwRI for validation are based on the old version (3.1) not the new version (3.4). This exercise did show that there was a noticeable difference in the post processors calculations methods for a small subset of the total data.

6.3.1.8   Data naming and consistency

The PEMS2 software does not create unique names for each file thus making it up to the user to manage the data and the integrity of the files. The problem comes from using the session manager and creating multiple files in one session as done during validation testing. The software exports each data file to the same sessions name thus when several files are available they are overwriting if not renamed. This should be changed to prevent data confusion and reporting issues.

6.3.2   PEMS3 MSS

PEMS3 post processor works with a Semtech DS file and is designed to work with a Horiba OBS system, but the OBS system was not evaluated at UCR. The post processor was developed prior to testing at UCR and improved during Unit #1 and #2. Due to the number of issues with Unit#1, most of the improvement was done with Unit#2 data. As such, it is expected that some change may be encountered as the manufacturer gains experience with their system.

6.3.2.1   New Postprocessor: bsPM changes

PEMS3 manufacturer provided processed data to UCR during the course of the program. At the completion of the program UCR reprocessed all the final PEMS 3 data for 3 units: Unit#2, #3,

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and #4 using the latest version of Concerto with the post processing macro called "PEMS 4.2.3". Unit#3 and #4 Method 1 data matched exactly to that calculated in the original data set submitted to UCR. There were some issues with the Unit#2 data thought as seen in Figure 6-30. Method 2 and 3 data was not provided earlier in the program and thus no evaluation of this change could be noted.

The reason for some of the deviations between post processors for unit2 was a result of different event start timing, improved filtering of exhaust flow outliers (explained previously in Section 6), and inclusion of the thermophoretic compensator that was not enabled for all the earlier processed events.
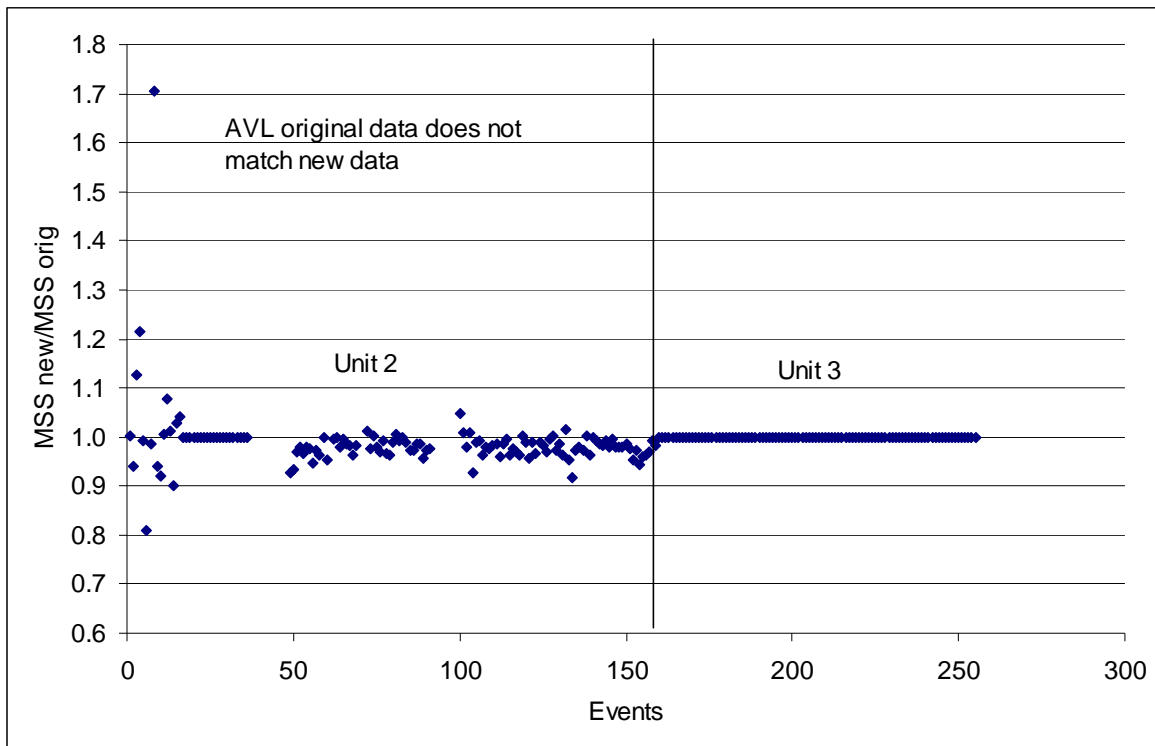
Figure 6-30 PEMS3 Unit 2 and 3 data processing comparisons

6.3.2.2   Post processor large memory usage

The PEMS3 post processor uses a large amount of memory after several data files have been processed. A large fraction of the PC CPU was busy and 1Gbyte of memory was consumed. This seems like an unreasonable amount of memory and CPU activity for the level of sophistication needed for calculating the PEMS data.
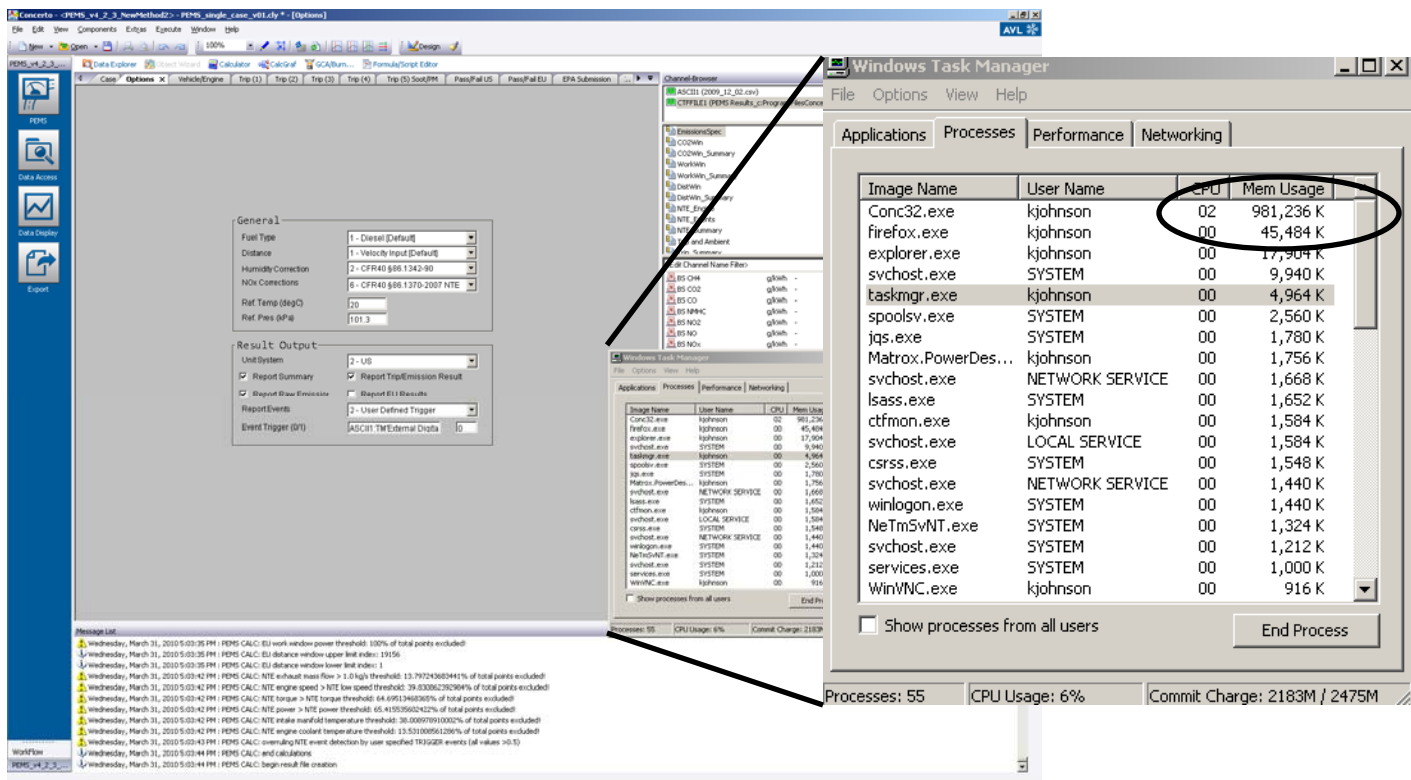
Figure 6-31 PEMS3 memory usage during post processing

6.3.2.3 Event timing analysis and decisions

Event timing, as shown by the results section, has been shown to be a significant source of potential bias (up to -50% bias) for real time PM PEMS like PEMS3. There are no guidelines either by the CFR or the manufacturer's manual where to start the PM puff event. Adoption of some type of strict event timing procedure or analysis method could be useful to minimize biases for short events. The question is when the engine load changes from 10% to 50% do you include all of the PM spike even though some of it was produced outside the power band. A simple solution would be to include all the PM by advancing the PM emissions by one additional second to ensure capturing these spikes. More analysis is needed to quantify the significance of event timing.

For the results presented in this report, event timing was fixed to a constant where time alignment procedures were performed based on transport times in the plumbing, sample rates, and response times of the instrument. All event timing was assumed to occur at the transition edge of entering the NTE event (no advance or retarding was performed). The PM signals were aligned to the probe tip and not the engine exhaust thus there is some delay between event and PM puff. It is suggested that additional time alignment be evaluated that allows alignment to the engine and the PM puffs are included. A tool within the PEMS3 post processor software to perform time alignment quickly would be beneficial.

6.3.3 PEMS3 MSS + GFM

Due to the recent development of the GFM system, the post processor was not completed at the writing of this report thus no new additional issues were discovered while performing the in-use testing. The author has seen the implementation of the GFM system and the GFM filter data seems conveniently integrated into the PEMS3 post processor. Also at the time of this report it is not clear the level of sophistication for using other measurements to model SOF and Sulfate PM contributions to the MSS signal to get at the total PM will be approached or allowed by EPA. It is evident though through the results that the modeling of PM has a significant interest to the research community so it is hopped that AVL will develop this to a point and offered to research through their standard post processor version.

6.4 Instruments 4, 5 and MEL

INST4 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 INST4 and 5.

INST5 required daily cleaning to prevent charge issues for the electrometers. Daily cleaning for INST5 was not necessary, only routine weekly cleaning. INST4 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 INST5 impaction cut sizes and overall concentration effect. No known barometric affect is expected for INST4.

The MEL reference system had some operational issues during the beginning of the testing program. The issues involved computers restarting where the MEL would have to reboot and repeat those tests. 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　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 is part of the main PM measurement allowance program, where the "measurement allowance" needed to account for measurement errors with using PM PEMS for in-use compliance testing were determined. The main goal of this work was to provide PM PEMS delta results to validate a Monte Carlo model generated at SwRI as part of the comprehensive MA program.

For this program a 1065 audit, a laboratory correlation with SwRI, and in-use PM PEMS comparison testing were performed using UCR's Mobile Emissions Laboratory (MEL). The MEL is a full 1065 compliant constant volume sampling system (CVS). The audits and correlation results were successfully completed and demonstrated that the MEL was an acceptable in-use reference laboratory validation tool.

Two PM PEMS were directly compared with the MEL under on-the-road driving conditions. Measurements were made from a 2009 class 8 truck equipped with a 2008 Cummins, 15 liter, heavy-duty diesel engine. The engine is certified to meet the 0.01 g/hp-h PM standard and used an OEM DPF to meet this standard. The vehicle was selected to represent a heavy duty diesel vehicle with DPF-out brake specific PM (bsPM) emissions of approximately 0.001 g/hp-h. An aftertreatment bypass system was incorporated to elevate those emissions from 0.001 g/hp-h to the targeted level of 0.025 g/hp-h.

In-use routes were designed and utilized to exercise the PM PEMS equipment over a range of environmental conditions, and included segments near sea level, in coastal regions, in desert regions, and longer uphill incline segments and segments at elevations up to 4500 ft. Measurements were made utilizing real NTE operation and forced NTE operation. Measurements were also made with different PM instruments for comparisons purposes. Regenerations conducted throughout the program were controlled with a proprietary ECM recalibration and a disable/enable switch provided from Cummins engineering support.

This report describes the in-use comparisons between the UCR MEL and the PM PEMS and the associated 1065 audits and SwRI correlation of the MEL. The results, lessons learned, and conclusions of this study are summarized below as follows:

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

- The MEL bsPM correlation with SwRI was successful, with the MEL bsPM agreeing to within 7.7% compared to the SwRI results, and showing an overall COV of 3.5%. Some of the low bias for the MEL relative to SwRI may be a result of additional heat loss from the longer MEL transfer line needed for the testing configuration.

- Forced events were utilized to target filter masses between 100 and 150 μg. The 50th percentile filter weight ranged from 133 to 147 μg for each of the units tested, where

Unit1 had the lowest filter weight and Unit2 had the highest and the overall 50th percentile was 141 µg. The overall 5th and 95th percentiles were 69 and 205 µg, respectively.

- A bypass system that simulates a cracked DPF and a properly functioning DOC was successfully designed to meet the targeted bsPM emissions of 25 mg/hp-h, with a range from 10 to 60 mg/hp-h. The non-regeneration 50th percentile bsPM emissions were 24 mg/hp-h, with a 5th and 95th percentile of 11 and 43 mg/hp-h, respectively. The bsPM emissions increased from Unit1 to Unit2 and 3, where the 50th percentiles were 18, 26, and 25 mg/hp-h, respectively. The regeneration 50th percentile bsPM emissions were 9.1 mg/hp-h, with a 5th and 95th percentile of 1.5 and 29 mg/hp-h, respectively.

- The MEL and PEMS in-use carbon balance and exhaust flow measurements were found to be in good agreement. The carbon balance between the MEL and the ECM broadcast fuel consumption showed an R^2 that ranged from 0.98 to 0.99 with a slope of 0.98 to 1.00 between units. The PEMS carbon balance showed an R^2 from 0.87 to 0.99 and a slope of 1.0 to 1.08 between units. The exhaust flow correlation between the PEMS and the MEL showed a positive slope that varied from 1.0 to 1.04, suggesting some of the carbon balance difference may be from the CO_2 measurement and some from the exhaust flow measurement.

- PEMS2 was selected for in-use validation testing at UCR based on a measurement allowance (MA) of 6.0 mg/hp-h at the 20 mg/hp-h standard from the laboratory testing and modeling. Calculation Methods 1 and 2 were performed for PEMS2. The calculation Method 1results are presented in the following conclusions.

PEMS2 measurement system had several issues that required data reprocessing such as exhaust flow, barometric pressure, bypass flow, crystal sensitivity, data filtering, and crystal overloading. The final data set presented is corrected for all agreed upon issues and represents the best available data from the testing on PEMS2. For PEMS2, a total of about 347 events were sampled by the MEL. PEMS2 provided valid data for 211 of these events, which is a data yield of 61%.

The PEMS2 non-regeneration mean bias at the 20 mg/hp-h bsPM emissions was -10 mg/hp-h, and at 30 mg/hp-h the mean bias was -18 mg/hp-h. The overall correlation showed an $R^2=0.37$, a slope of 0.24, and a positive intercept of 4.2 mg/hp-h. When the intercept was forced through zero, the mean bias at 20 mg/hp-h went to -15 mg/hp-h. The slope and R^2 decreased from unit1 to unit3, with the slope changing from 0.3 to 0.14 and the R^2 decreasing from 0.52 to 0.20. The PM concentration increased from unit1 to unit3 in an effort to reduce sample times which may be one of the reasons for the lower correlation from unit1 to unit3. Unit3 also had a large zero intercept at 8 mg/hp-h, which may be a result of changing its crystal usage logic.

The standard error estimate (SEE) between the PEMS2 and the MEL was relatively high at 5.4 mg/hp-h and 48 µg/mol. The two-tailed, paired t-test between the PEMS and MEL bsPM correlation results suggests the mean differences were statistically significant at a

greater than 99% confidence level, even though the SEE was relatively high. PEMS2 manufacturer suggested the high variability may be from differences in the individual crystal sensitivity.

The PEMS2 regeneration results also showed an overall low correlation with an $R^2=0.4$ and a slope of +0.11. The zero intercept was also fairly high at 3.2 mg/hp-h suggesting PEMS2 has a positive bias at zero measurements. The two-tailed, paired t-test between the PEMS and MEL bsPM regeneration data suggests the mean differences were statistically significant at a greater than 99% confidence level.

The total work and sample durations for the PEMS2 PM system were slightly lower than those for the PEMS2 gaseous system. The overall work correlation between the PEMS2 PM system and the MEL showed an R^2 of 0.985 and a slope of 0.93, while the correlation between the PEMS2 gaseous and the MEL showed an R^2 of 0.999 and a slope of 0.995. The gaseous PEMS and the MEL showed no sample duration deviations, while the PM system showed deviations of -0.5 seconds for the 50th percentile duration delta, with deviations of -3 and 1.5 seconds, respectively, for the 5th and 95th percentile duration deltas. Unit#3 showed some outliers at -7 seconds for sample duration deltas.

- PEMS3 MSS was not a full system and operated in conjunction with PEMS2 gaseous system to obtain gas-phase measurements, exhaust flow, and horsepower information. PEMS3 experienced a few issues that were isolated to an electrical connector and issues with their prototype gravimetric filter module (GFM) operational firmware that affected warm-up and leak checks. The PEMS3 data presented is only corrected for issues with the exhaust flow meter supplied by PEMS2. It is noted that calculations Methods2 and 3 do not need exhaust flow measurements and do show more consistent results between units for PEMS3. For consistency, the Method 1 calculation results are presented in the following conclusions.

  The PEMS3 non-regeneration mean bias at the 20 mg/hp-h bsPM emissions was -1.7 mg/hp-h, and at 30 mg/hp-h the mean bias was -2.2 mg/hp-h. The overall correlation showed an $R^2=0.94$, a slope of 0.95, and a negative intercept of -0.7. When the intercept was forced through zero, this PEMS mean bias went to -1 mg/hp-h at the 20 mg/hp-h level. The slope and R^2 were relatively consistent between units2 through unit4, where slope varied from 0.98 to 0.87 and the R^2 varied from 0.98 to 0.93. The high slope for unit2 may be a result of high exhaust flow measurements because the Method 2 bsPM results showed a lower slope of 0.9 for this unit which agrees better with units 3 and 4. The PM concentration increase from unit1 to unit3 did not have an effect on PEMS2 measurement system as seen by the relatively similar slope and R^2 between units for Method 2.

  The SEE between the PEMS3 and the MEL was relatively low at 3.0 mg/hp-h and 20 µg/mol. The two-tailed, paired t-test between the PEMS and MEL bsPM correlation results suggests the mean differences were statistically significant at a greater than 99% confidence level.

The PEMS3 MSS regeneration results showed an overall low correlation, with an R^2=-0.4 and a slope of -0.01. The negative correlation suggests there was no correlation between the reference measurement and the PEMS3 MSS measurement under these conditions. This is not unexpected since the PM generated during regeneration was predominantly composed of sulfur particles, see below, that are not detected by the photoacoustic measurement principle.

The PEMS3 employed a prototype GFM during the validation testing to allow their soot measurement to be spanned back to a total PM mass from a Teflon filter. The PEMS3 total PM approach utilized two methods. One approach uses only a simple filter correction the other includes corrections for SOF and sulfate models (alpha approach).

The PEMS3 GFM option was able to increase the slope on the non-regeneration events from 0.92 to 1.00 for the alpha approach and to 1.06 for the simple filter approach. The regeneration slopes increase with either approach. More testing is needed to understand the modeled approaches to characterize this PEMS total PM solution.

- Two other PM-only instruments were evaluated (INST4 and INST5). These instruments are both used in regular operation in the MEL. INST4 showed a reasonable correlation of R^2=0.86, a slope 0.76, and a negative intercept of -1 g/hp-h for the non-regeneration PM. The regeneration correlation was lower with a negative R^2 of -0.2. The good correlation for the non-regeneration events suggests this instrument has some correlation with the MEL reference method for the PM composition and size distribution for the non-regeneration bypassed PM. The instrument does not correlate with the gravimetric reference system for regeneration type PM, however.

  INST5 showed a lower correlation of R^2=0.56 and a slope 0.59 compared to INST4. This is somewhat surprising since the INST5 detection method is more sophisticated than that for INT4 and should detect a wider range of composition and particle size distributions. One explanation may be this instrument is more sensitive to span drift and the lack of a PM calibration standard is causing a low correlation with this measurement method.

- The non-regeneration, bypass PM was predominantly elemental carbon (EC), with some organic carbon (OC) and trace amounts of sulfur. The EC from the validation testing under non-regeneration, bypass conditions is estimated to be around 90% of the total PM. The number average particle diameter was 64 nm and is most likely the result of engine combustion followed by PM accumulation in the PM dilutions systems given the relatively large particle size and predominantly EC composition.

- The regeneration PM was predominantly sulfur particles, where the form of the sulfur was assumed to be sulfuric acid (H_2SO_4). The number average particle diameter was 15 nm, and is most likely the result of a nucleation formation process in the PM dilution system given the small particle size and sulfur composition.

- All PEMS showed a negative biased measurement relative to the MEL reference method for the non-regeneration bypass and regeneration type PM.

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- PEMS2 showed the largest negative bias and may be the result of issues with this PEMS operation. PEMS2 manufacturer suggested that improving the bypass flow, reducing crystal loading, employing improved burn in processes, and calibrating individual crystals will reduce variability and improve the correlation. It is recommended that the PEMS2 system be retested to investigate the potential impacts these differences in operation may have on decreasing variability and improving the slope of the correlation.

- The PEMS problems ranged from issues related to testing under in-use conditions, operational issues, and post processing issues. The in-use issues ranged from electrical and mechanical connections, crystal usage from short NTE's, valve switching, measurement signals, and crystal behaviors. Operational problems occurred during startup, commissioning, and with the systems prior to testing in-use. Typical issues include incorrect system configurations, procedures that don't work, and issues with the startup software and other recommended practices that didn't function according to the manual. The post processing issues ranged from data filtering, bsPM differences between processor versions, data identification, and method calculations not being available. In general, PEMS2 had more issues than PEMS3 for each of these categories.

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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.
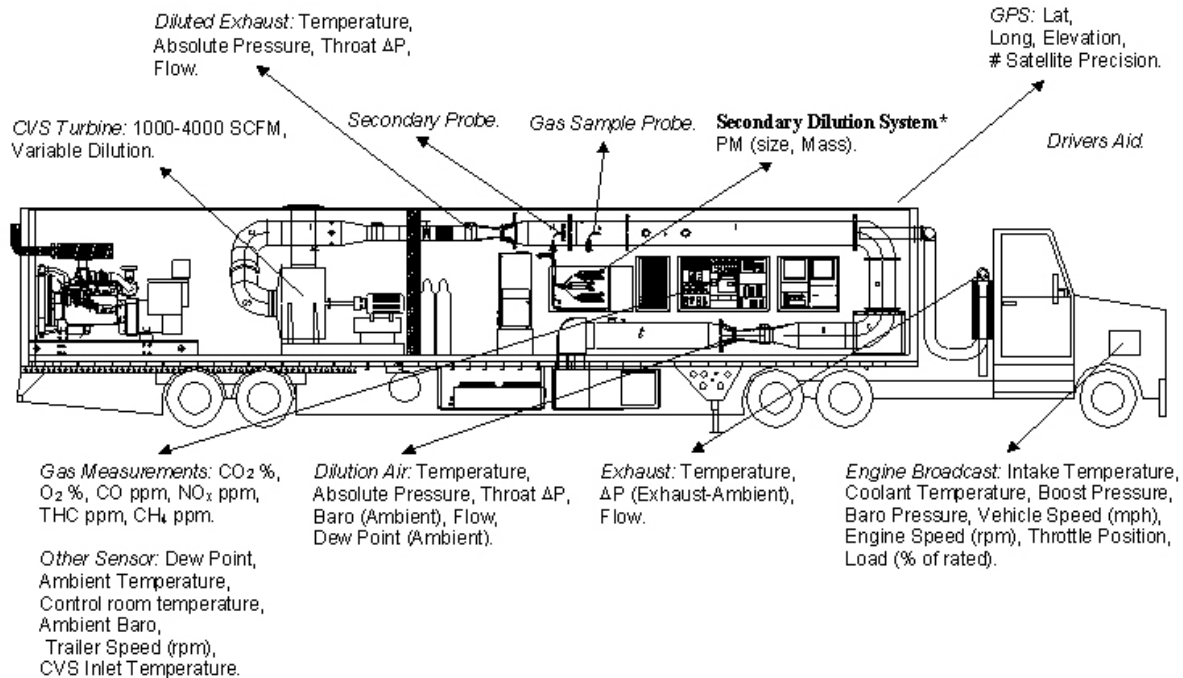
Figure A-A1 Major Systems within the Mobile Emission Lab

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 from 1000 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.

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
CVS	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 Daily Monthly	Zero span drifts Linearity Check	Zero Span
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Tunnel Banks	
	Monthly	Trip, 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

ISO 9001 : 2000 Registered

Calibration Certificate

Customer

Company:	UNIVERSITY OF CALIFORNIA RIVERSIDE		
Address:	1084 COLUMBIA AVE		
City:	RIVERSIDE	State/Province:	CA
Zip/Postal:	92507		

Device

Manufacturer:	Mettler Toledo	Asset No.:	
Serial No.:	1128270054	Dept./Room:	
Max Capacity:	2.1 g	Readability:	0.0000001 g
Model:	UMX2	Work Order No:	SV0907240269

Procedure Statement: The device referenced in this document has been metrologically tested in accordance with METTLER TOLEDO Work Instruction VW0152A. All translations into other languages are based on the referenced work instruction, which is in English. This certificate refers to: As Found

Test Date:	20-Aug-2009	Next Cal. Due Date:	30-Sep-2010
Service Technician:	Calvin Macklin	Signature:	ELECTRONIC SIGNATURE

Reference Weights

Traceability of Test Equipment: All weights used for metrological testing are traceable to national or international standards. The weights were calibrated and certified by an accredited calibration laboratory.

Weight Set 1

Weight Set No.:	354	Date of Issue:	10-Mar-2009
Calibration Due Date:	30-Mar-2010	NIST Traceability No	MT5061/1788.01
Class:	E2		

Measuring Results

Eccentricity

Test Weight	Position	As Found Displayed Value	As Found Deviation
C: 1 g	Center	0.0000000 g	N/A
1: 1 g	Left Front	-0.0000002 g	-0.0000002 g
2: 1 g	Left Rear	-0.0000001 g	-0.0000001 g
3: 1 g	Right Rear	0.0000001 g	0.0000001 g
4: 1 g	Right Front	0.0000002 g	0.0000002 g
Eccentric Load Deviation:		0.0000002 g	
Manufacturer Specifications:		0.0000025 g	
Manufacturer Specifications Rounded to Resolution of Eccentric Load Deviation:		0.0000025	
Specifications Met:		YES	

Sensitivity

Reference Weight	Displayed Value Without Reference Weight	Displayed Value With Reference Weight	Deviation
0.0020006 g	0.0000000 g	0.0020017 g	0.0000011 g
Sensitivity Offset:			0.0000011 g
Manufacturer Specifications:			N/A
Manufacturer Specifications Rounded to Resolution of Sensitivity Offset:			N/A
Specifications Met:			N/A

Form No.: VF0066A
Software Version: 4.0.1.9
This is an original document, an electronic copy is retained by METTLER TOLEDO

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METTLER TOLEDO

Linearity - Differential Method

Test Weight: 0.5000000 g

	Preload Weight	As Found		Deviation *
		Displayed Value		
		Preload	Test Weight	
1	0 g	0.0000000 g	0.5000004 g	-0.00000010 g
2	0.5 g	0.4999998 g	0.9999996 g	-0.00000080 g
3	1 g	0.9999997 g	1.5000007 g	-0.00000030 g
4	1.5 g	1.5000003 g	2.0000011 g	0.00000000 g
	Linearity Deviation:			0.00000080 g
	Manufacturer Specifications:			0.000001 g
	Manufacturer Specifications Rounded to Resolution of Linearity Deviation:			0.00000100 g
	Specifications Met:			YES

* This Linearity Deviation is zero point offset and sensitivity error compensated.

Remarks

BALANCE PASSED CALIBRATION.

Form No.: VF0066A
Software Version: 4.0.1.9
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Appendix C – INST5 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.
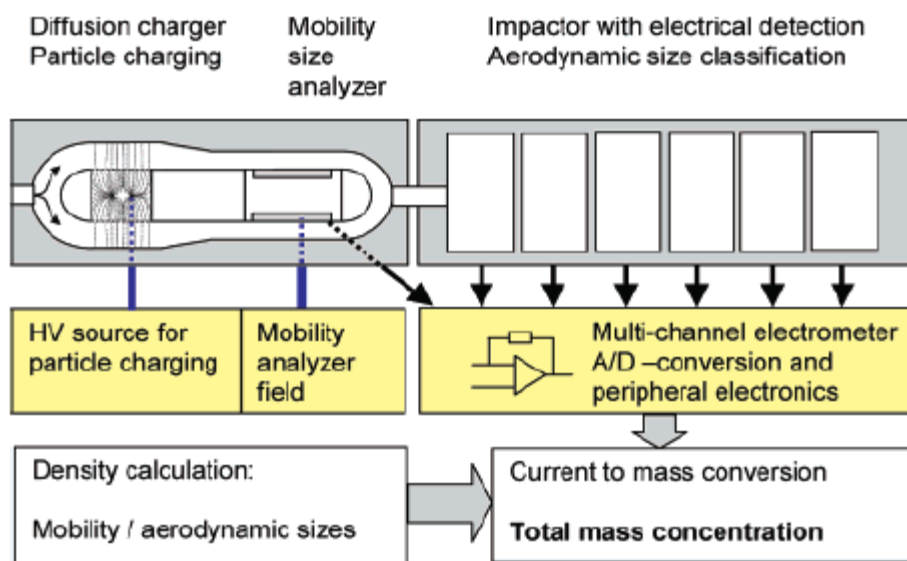
Figure A-D1 Principle of the Dektai mass monitor (DMM)

$$d_\mathrm{p} = 59\left(\frac{0.938}{\dfrac{I_\mathrm{mob}}{I_\mathrm{tot}} - 0.124} - 1\right)^{(1/2.13)}$$

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)**

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5. **Switch screens back to "Total Mass [μg/m³]"**
6. **Remove filter and record response measuring air. _____ μg/m³. Should be ~ 5 μg/m³ ± 5 μg/m³ (Record value on checklist)**
7. **Put sample line back as it was found.**
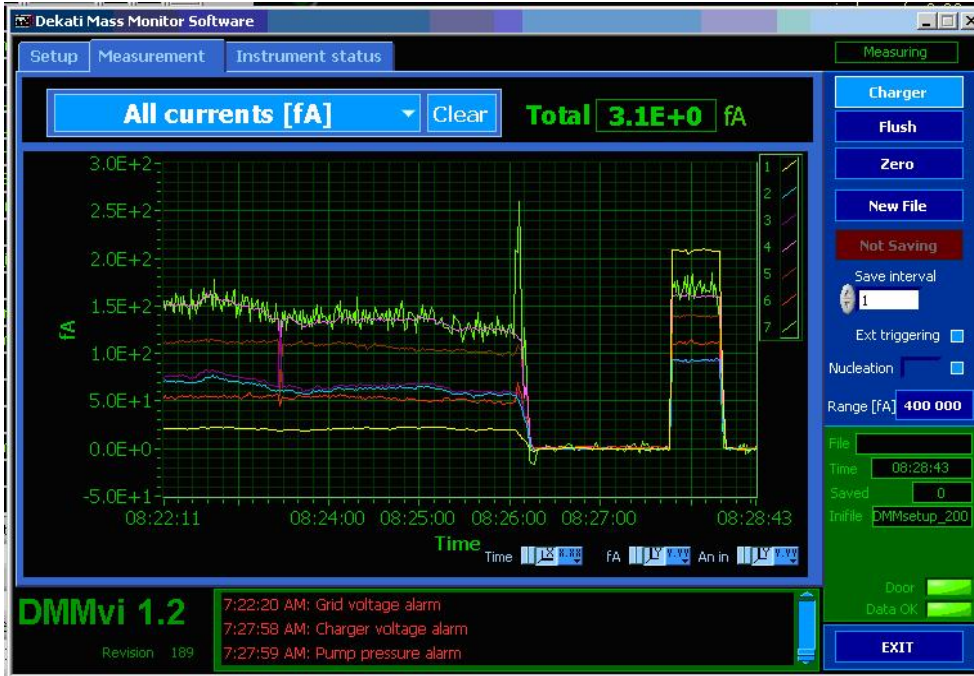
Figure A-D1 – Typical DMM zero in fempto amps
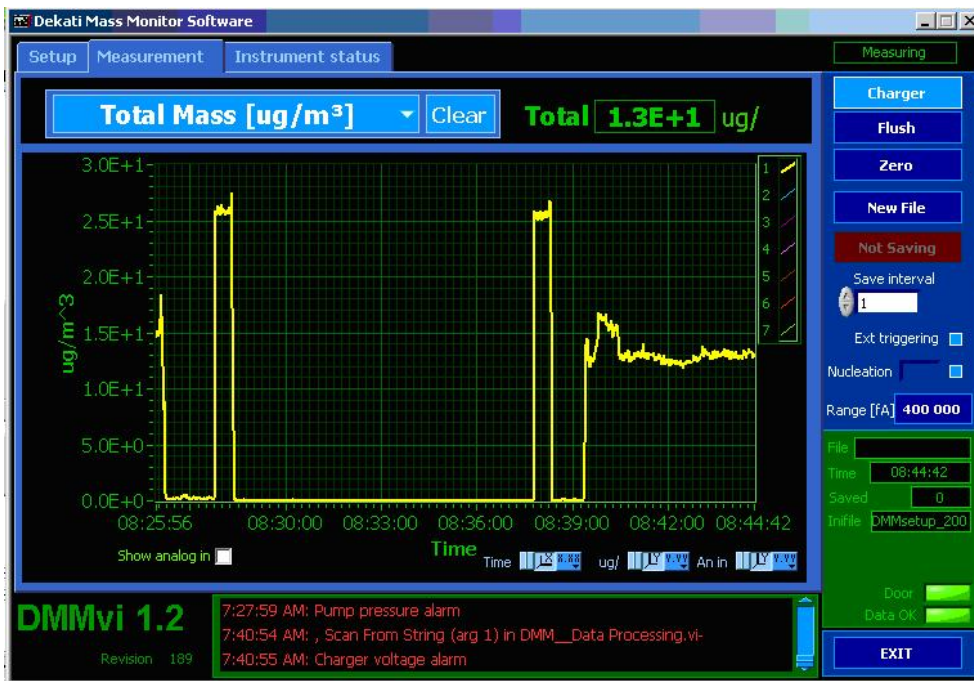
Figure A-D3 – Typical DMM zero in μg/m³

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Appendix D – PEMS3 + GFB Daily Startup Procedure

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

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.
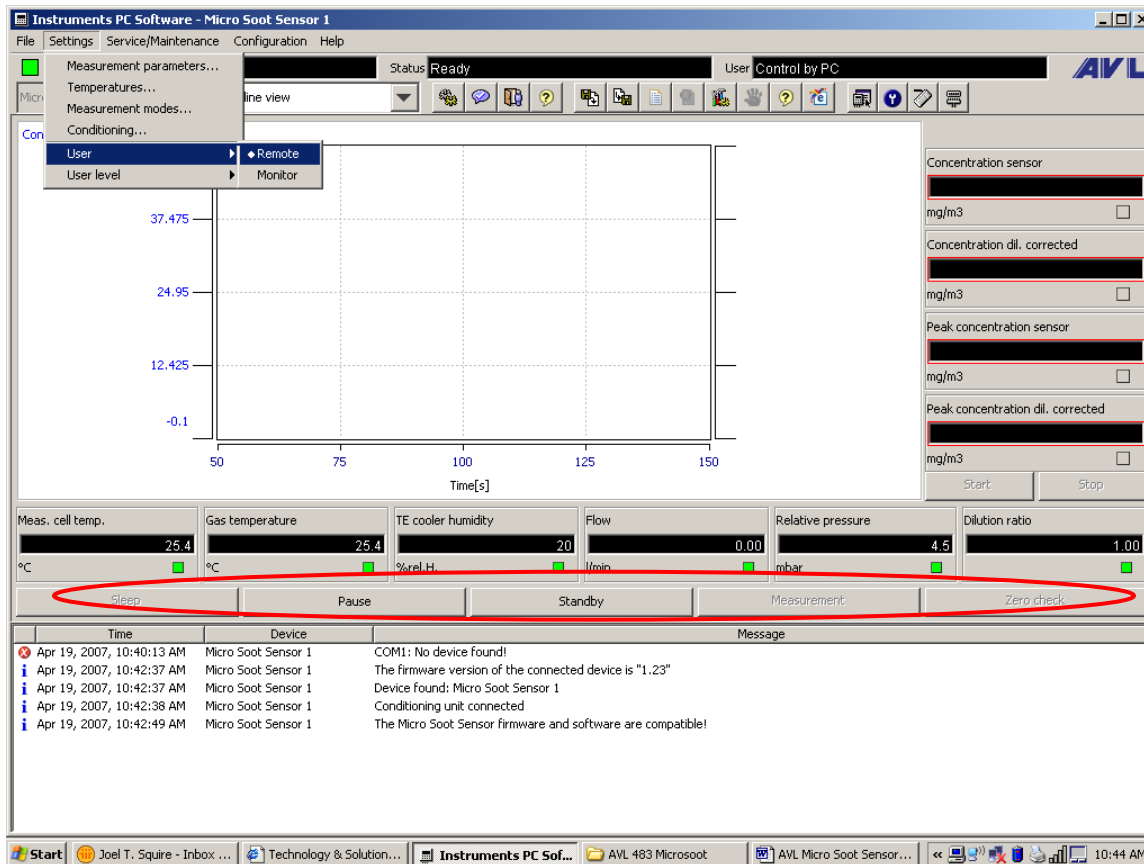
II. Purging

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.

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

II. Recommended Service Intervals

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

AVL - GFB instructions for Kent Johnson @ CeCert

Daily checks:

Absolute pressure CFO inlet

As this value is used to normalize the CFO flow rate it is important to verify or if necessary adjust it daily. Check if the pressure is +/-3mbar of reference, if not adjust it by using the Dialog "Sensor Calibration GFB unit" (see following fig.).
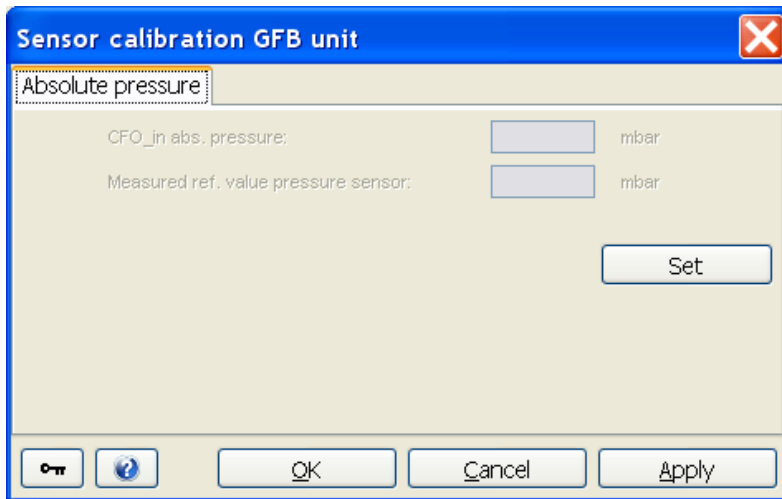
Filters on GFB -> same procedure as described for Filter of Standard Cond.Unit.

Check and routines on demand

1) adjust Trigger level of GFB's filter loading
2) adjust Flow rates of Sensor Unit necessary for GFB
3) adjust Analog Output of Sensor Unit for Sensor's Analog I/O

Ad 1) adjust Trigger level of GFB's filter loading

Target: Sensor Unit switches of the GFB's filter loading when a certain accumulated PM soot level on filter is reached. Default value of this trigger level is 700µg PM soot; if necessary this can be adjusted by an AK command.

Steps:

request: **ALIM** x *FlowLimit FilterLoadLimit*
                        (x=error byte; not used yet
set: User Level 2 necessary;

       ELIM *FlowLimit FilterLoadLimit*
       Range:
       FlowLimit = 1.9 (do not change)
       FilterLoadLimit [100 … 1500; default 700]

Note: To be able to use ELIM the User Level Service is necessary. It can be activated by the password "-316". This password also enables the "send" button of the PC program's AK terminal.

Attention: In user level "Service" the error handling is deactivated. Do not use it during measurement! It can be reset by opening the password dialog and close it without enter a password. Check in Service View (numerical) is User Level 0 is displayed.

Ad 2) Flow rates of Sensor Unit necessary for GFB

Original: Sensor Unit's flow rates are set to default (connected to standard Conditioning Unit):

Target: Sensor Unit should be used with GFB. An adjustment of flow rates is necessary

Steps:
1) set up MSS and Cond.Unit of GFB (don't connect the external GFB pneumatically to Cond.Unit) and switch it on
2) connect to 483PC program (AVL Device Control Software) and set system into measurement (ignore errors in that case)
3) choose Service View GFB
4) open MSS cover
5) fist unlock and then close adjustable bypass valve (see fig.1 Pos:1)
6) monitor flow meter (see fig.1 Pos:5) if it gets 0 and on PC MSS + CFO mass flow decreases
7) lock valve (see fig.1 Pos:1) again with screw nut
8) if MSS+CFO flow is not 1900ml/min +/-200 precede with steps otherwise finished
9) unlock adjustable sample valve (see fig.1 Pos:6)
10) adjust MSS+CFO flow rate until it is 1900ml/min +/-200 by unlocked valve
11) lock valve (see fig.1 Pos:6) again; during locking flow rate can change; if necessary readjust it

Figure 1: measurement chamber of MSS

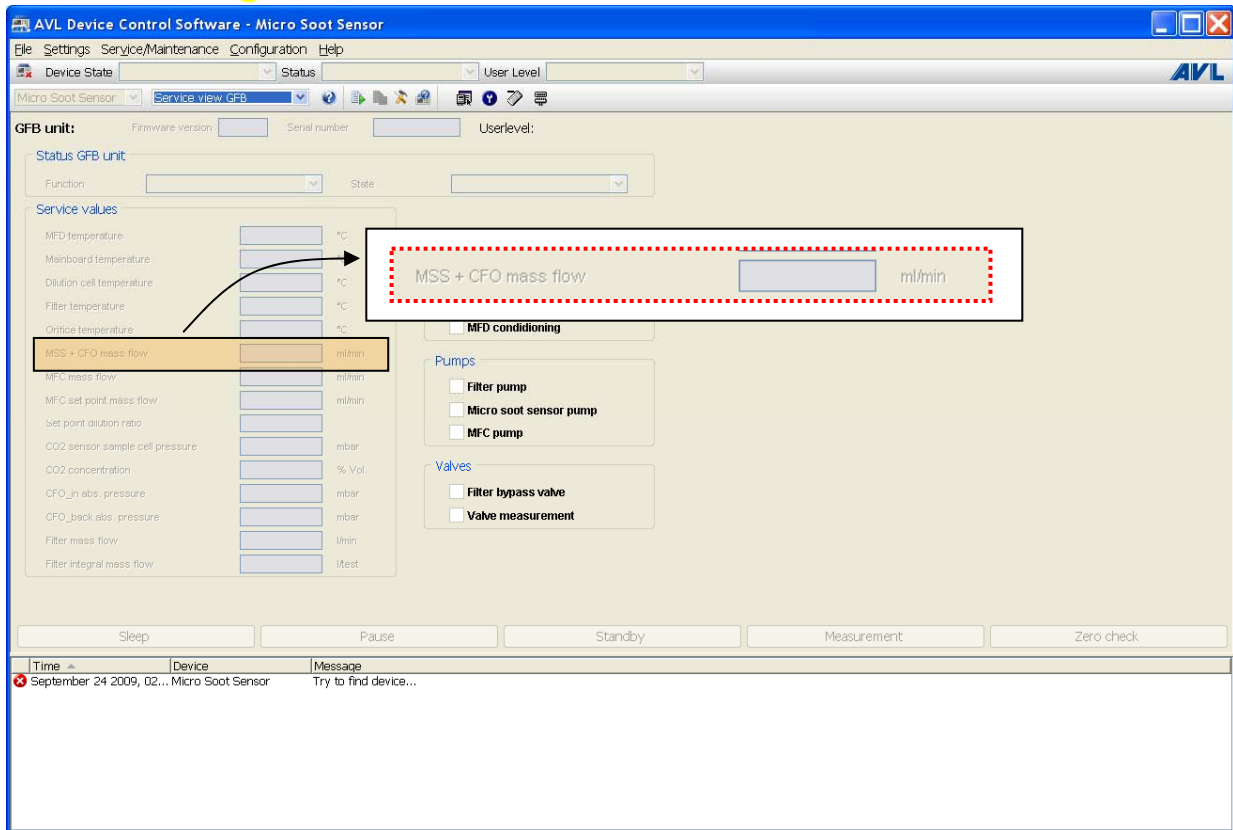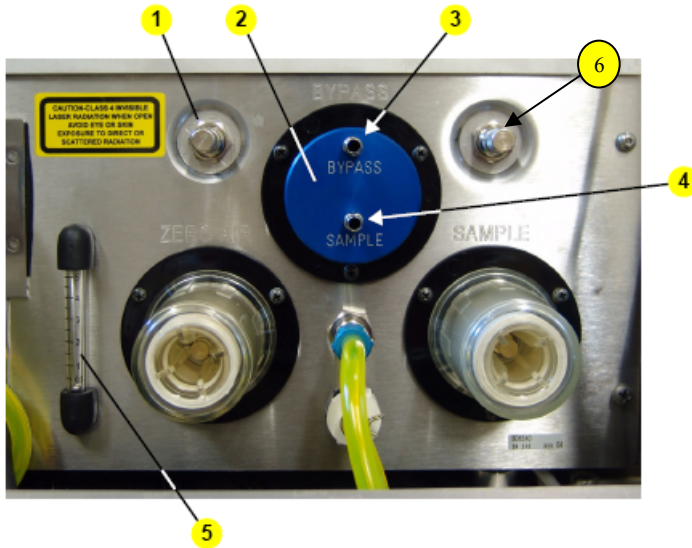Figure 2: Service View GFB

Ad 3) adjust Analog Output of Sensor Unit for Sensor's Analog I/O

Target: Verify analog Input values at Sensor's System. In case of higher deviations adjust MSS analog output by using the digital values displayed on Sensor's PC software as reference value. Doing this all deviations of analog interface are calibrated to 0.

Procedure:

MSS sets its analog output to zero (0V) and span (10V). Sensor's system should display appropriate values. If not MSS values should be adjusted as follows.

Steps:
1) use AVL Instruments PC Software (not the AVL Device Software)
2) First check if the "Measuring Range 10V OUT analog" (menu Settings | Measurement Parameter) is set to range [0…100] and the Offset is set to "no offset".
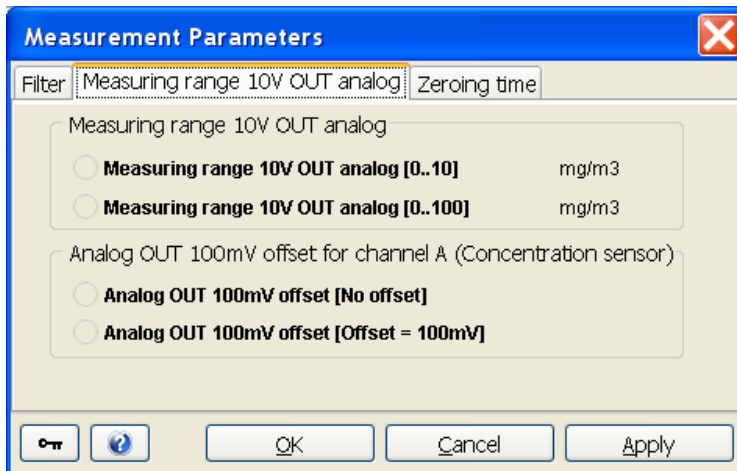
Figure 3: checking Measuring range

3) open dialog "Calibration Analog Outputs" (menu Service/Maintenance)
4) switch to "Zero Point" -> 0V set at all Analog outputs
5) Check for appropriate values on Sensor's Software for:
   MSS concentration: 0 +/-0,01mg/m^3
   Dilution: 0 +/- 0.5
6) If not adjust it iterative by entering the mV's unless limit or a minimum of deviation is reached:
   Use "A:" for MSS concentration: As mV must be entered first the deviation of mg/m^3 must be scaled into mV (e.g. 1mg -> 100mV)
   Use "B:" for Dilution: scale dev. of Dilution by factor 10 into mV (e.g. 0,5 -> 50mV)
7) Switch to "End point" -> 10V set to all Analog outputs
8) Check for appropriate values on Sensor's Software for:
   MSS concentration: 100 +/-0,05mg/m^3
   Dilution: 100 +/- 1
9) If not adjust it iterative by entering the mV's: unless limit or a minimum of deviation is reached:
   Use "A:" for MSS concentration: scale deviation of mg/m^3 by factor 100 into mV (e.g. 1mg -> 100mV)
   Use "B:" for Dilution: scale dev. of Dilution by factor 10 into mV (e.g. 0,5 -> 50mV)
10) Recheck Zero- and End points and adjust if necessary
11) Press OK to finish procedure
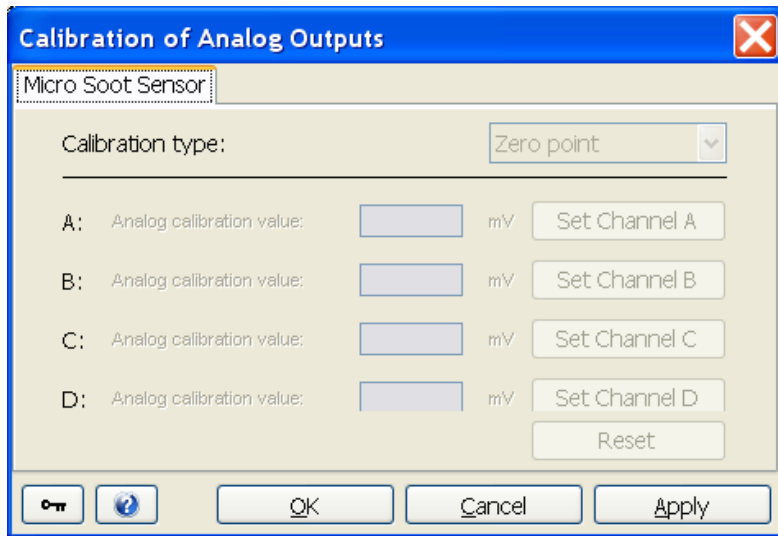
Figure 4: Dialog for calibrating Analog Output

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+2.3*SO_4.

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 2.2 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 2.33 lower. PEMS3 measurement principle does not detect sulfate so their dilution method is not considered and INST4 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 approximately 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.

Some 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.

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) 3776 which has a 50% cut point (D50) of 3 nm.

The f-SMPS is an in-house CE-CERT instrument that provides a complete scan over the size range ~5-200 nm, on a time scale sufficient to capture transient operation. For this program, the f-SMPS was set up to scan the ~5-200 nm once every 3 seconds. For more detail on the fSMPS see Shah and Cocker (2005). The fSMPS sampled from the MELS secondary real time dilution tunnel. This dilution tunnel is different than the main secondary filter tunnel. The real time secondary dilution tunnel is at a higher dilution ratio around 20 to 1 and provides a slightly positive pressure using an injector type venturi system.

The CPC3776 is a system purchased from TSI and one can refer to its manual for principles of operation. The 3776 was also sampled from the real time dilution tunnel as the fSMPS.

Appendix G – Supplemental Real-Time Tables and Figures

Three randomly selected tests were analyzed for particle size distribution from UCR's fSMPS and its in-house Dekati DMM. The fSMPS and DMM results show an averaged particle number diameter of around 60-50 nm for the non-regeneration case with a fairly high range from 20 nm to 140 nm.

Also included is a summary of the particle number concentration as a function of unit number for regen and non-regeneration cases. No significant findings except that the regen case had sliglh less #/cc particles. The #/cc particle count are corrected for tail pipe conditions.

Also in this appendix is an short analysis on time alignment for the CVS sampled real time PM instruments. No significant findings were found, but it is interesting that the alignment for CVS sampled instruments was much less than for raw tail pipe constant diluted instruments.
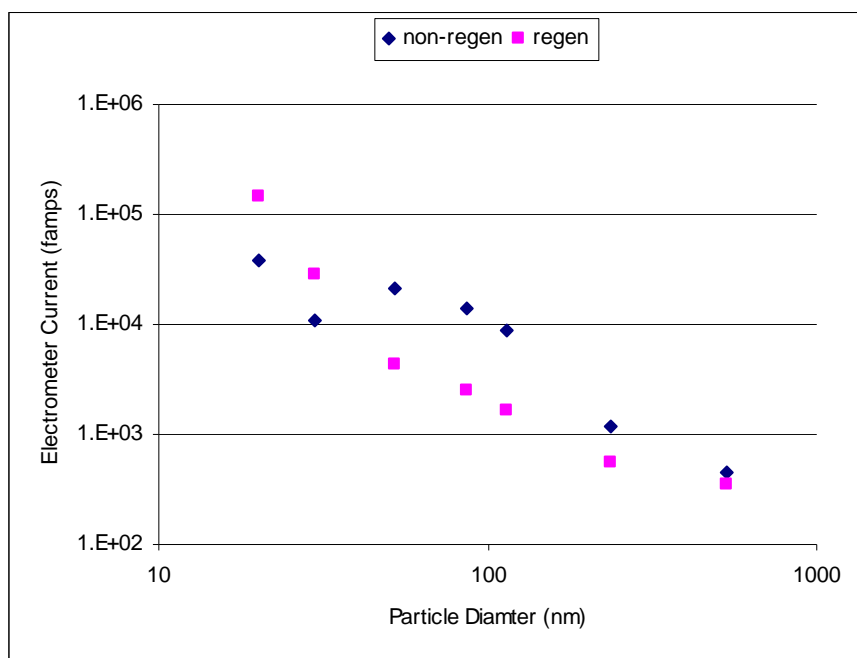
Figure AG-1 Typical DMM average electrometer current from 6 inertial stages and mobility stage (famps) for the non-regen and regen cases (200912180930 non and 200912010726 regen)

The following non-regeneration files have been analyzed:
1. 201001041041
2. 201001040932
3. 200912180930
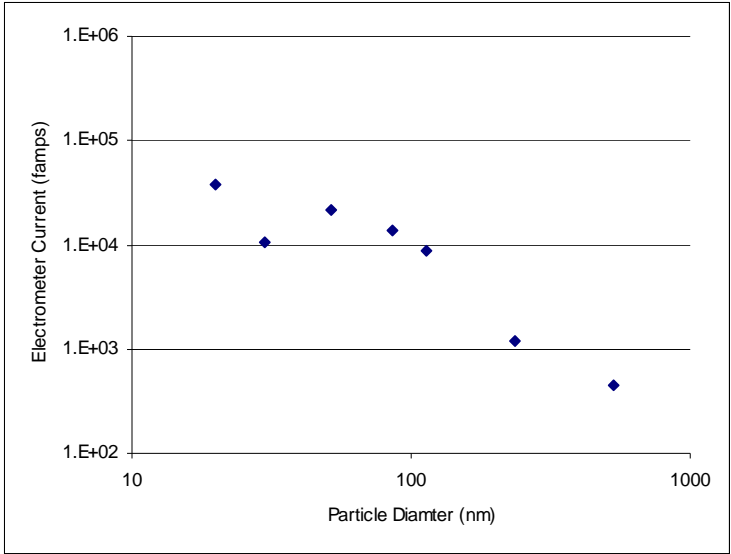
200912180930 DMM average electrometer current from 6 inertial stages and mobility stage (famps)
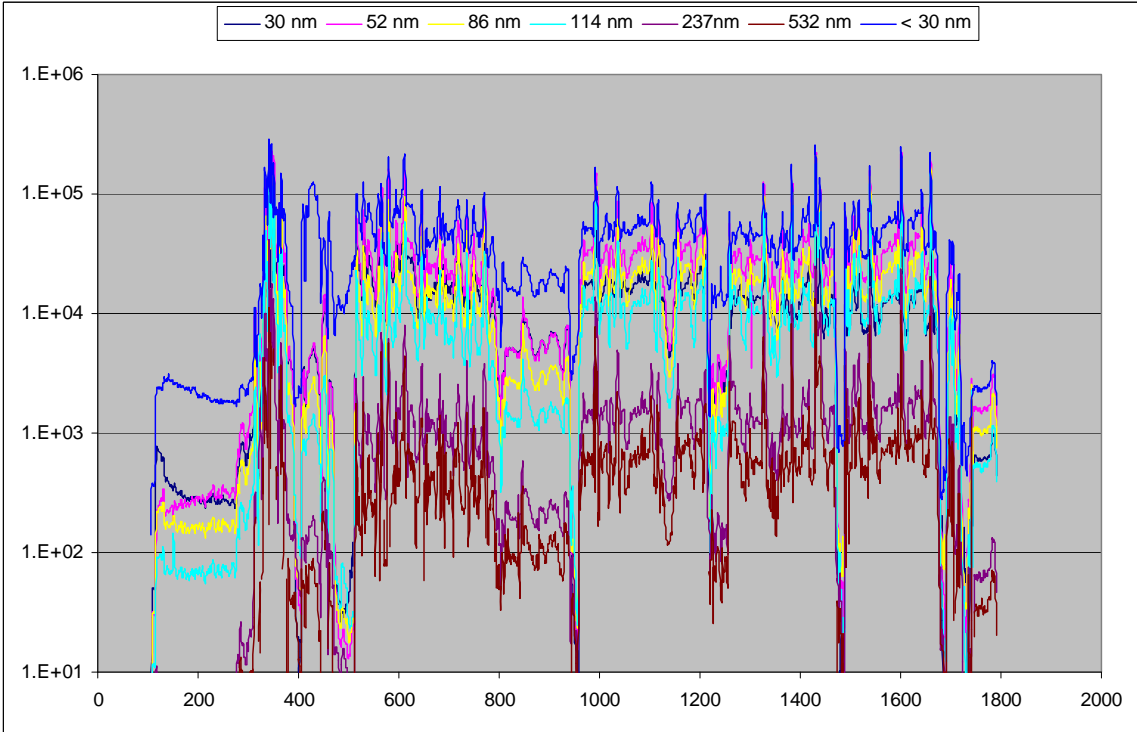
200912180930 DMM realtime electrometer current from 6 inertial stages and mobility stage (famps)
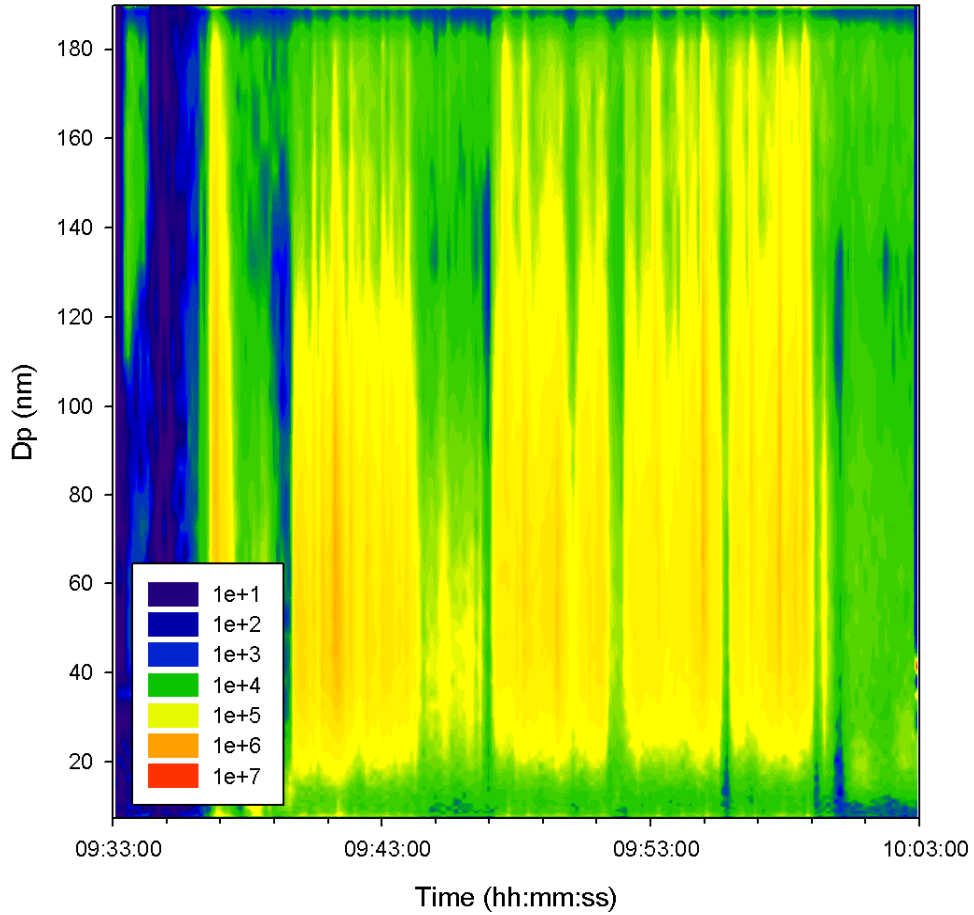
200912180930 fSMPS real time size distribution dN/dlogDp (#/cc)
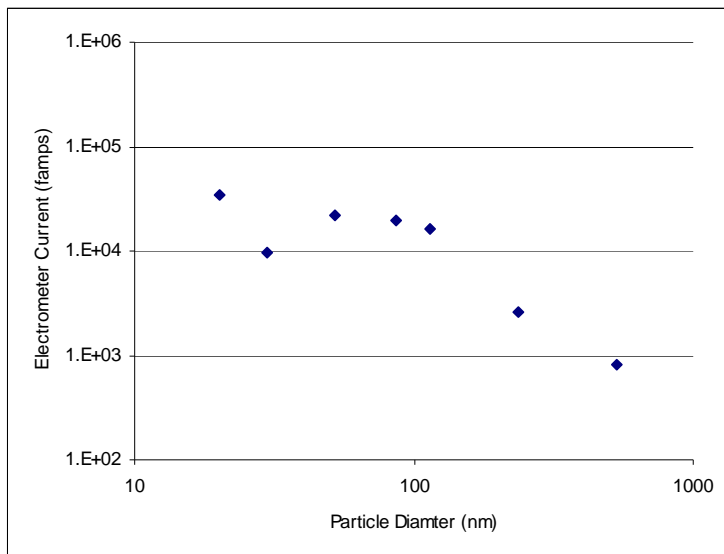
201001040932 DMM average electrometer current from 6 inertial stages and mobility stage (famps)
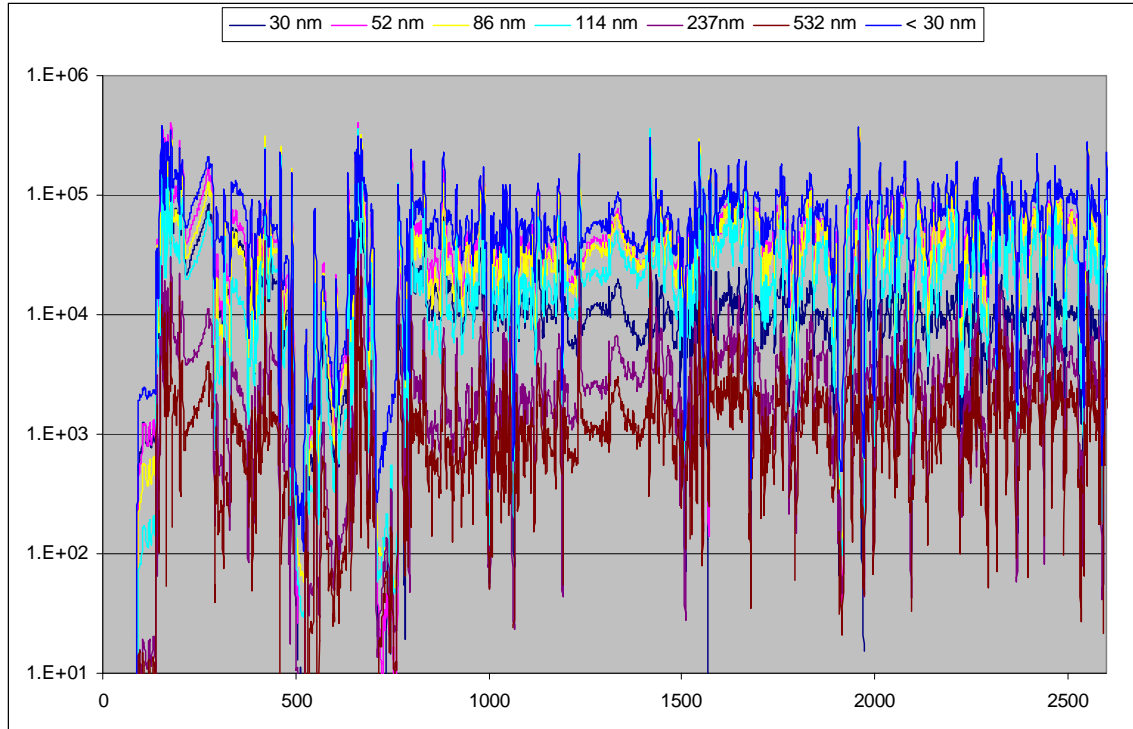
201001040932 DMM realtime electrometer current from 6 inertial stages and mobility stage (famps)
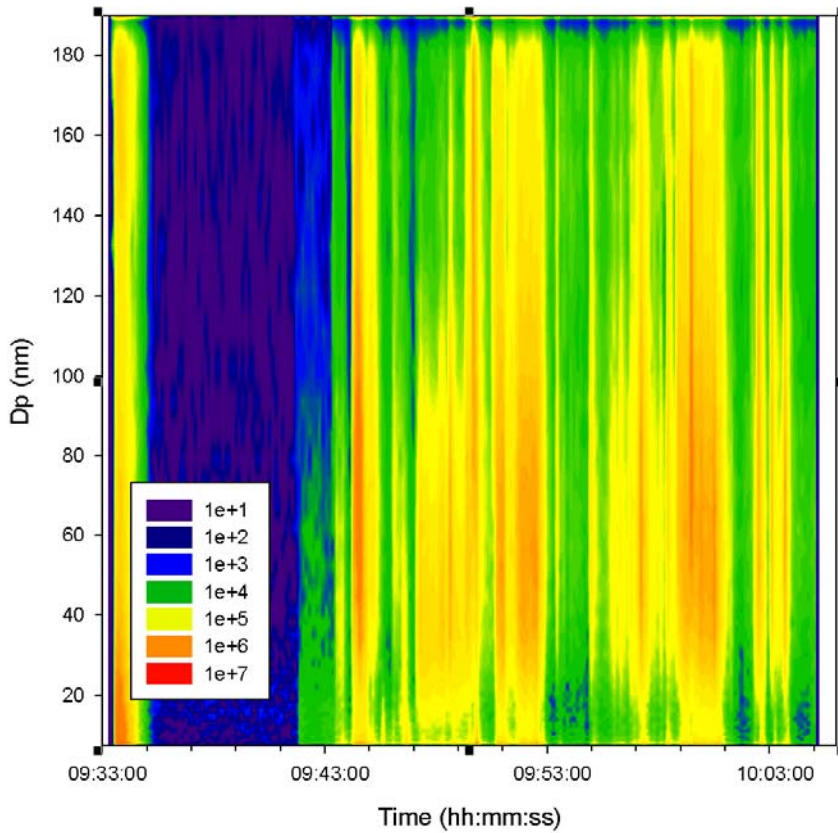
201001040932 fSMPS real time size distribution dN/dlogDp (#/cc)
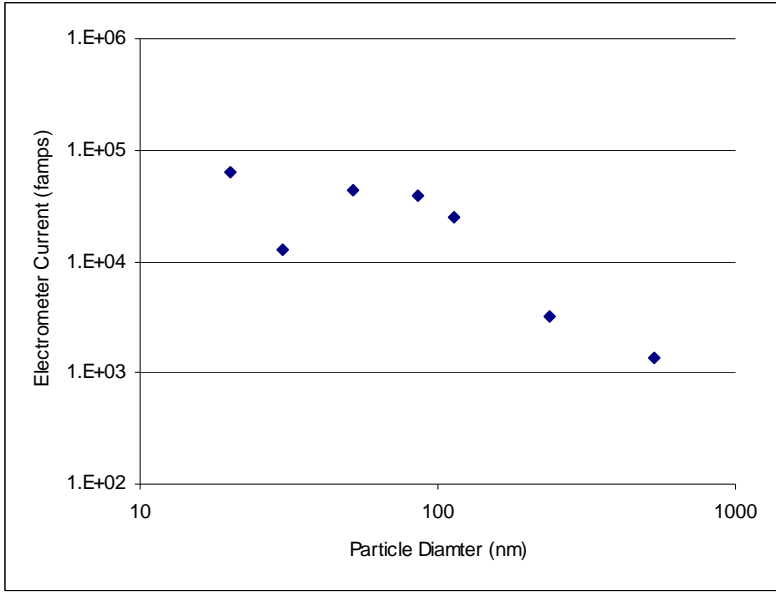
201001041041 DMM average electrometer current from 6 inertial stages and mobility stage (famps)
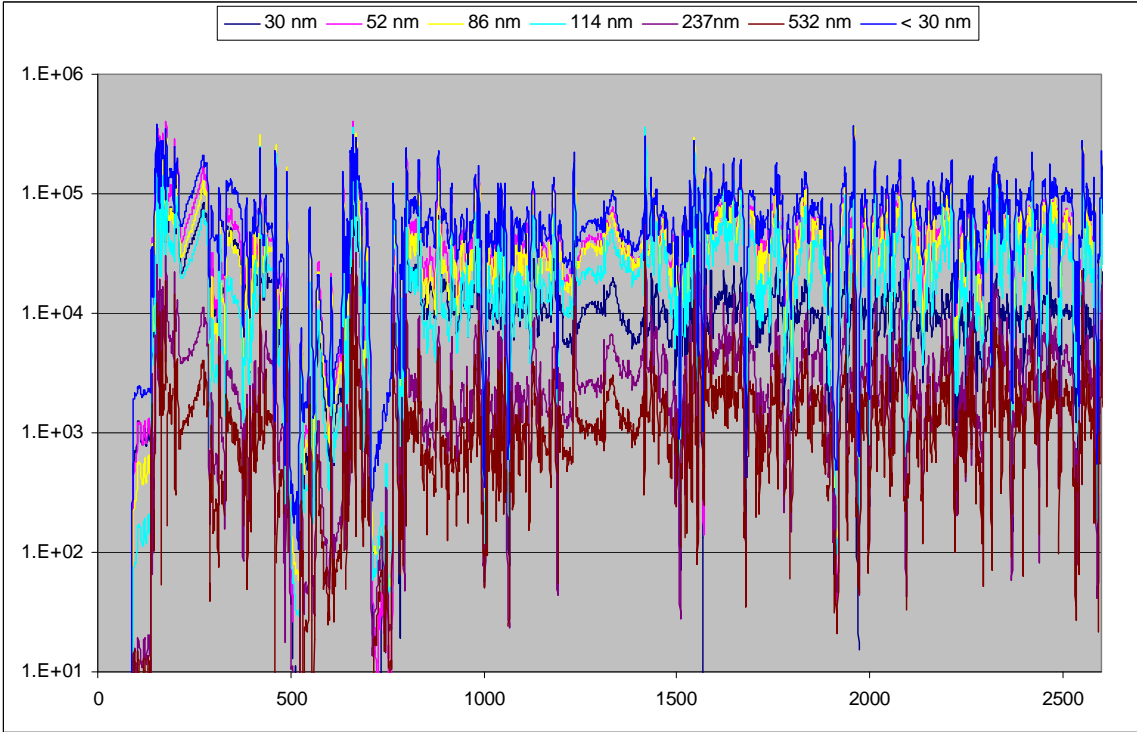
201001041041 DMM realtime electrometer current from 6 inertial stages and mobility stage (famps)
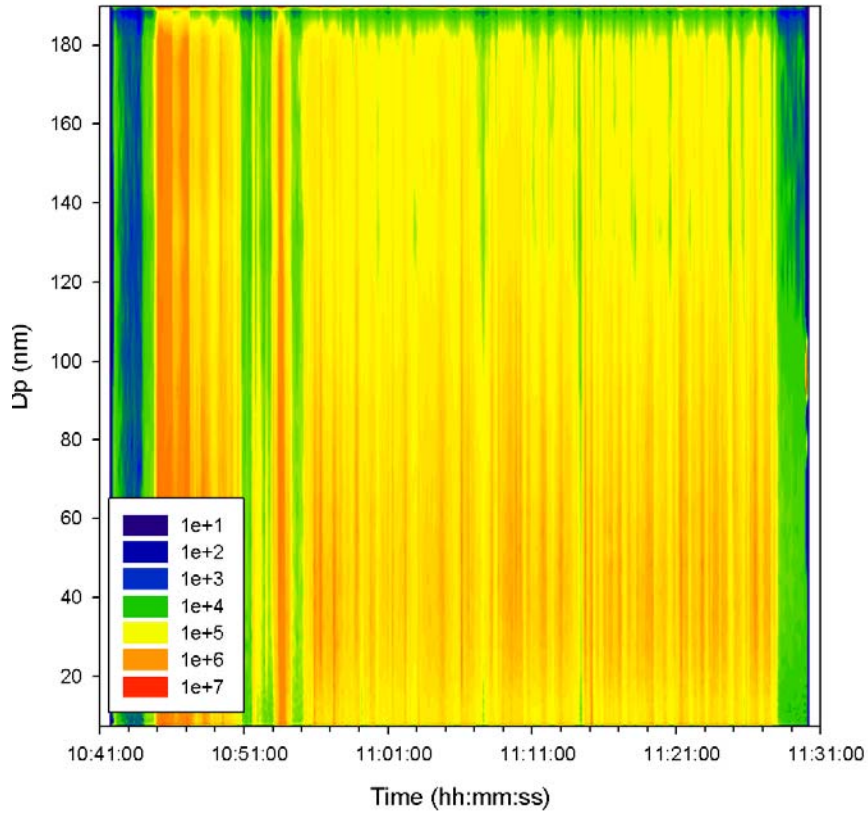
201001041041 fSMPS real time size distribution dN/dlogDp (#/cc)

The following regeneration files have been analyzed:
1. 201001050747
2. 201001050924
3. 200912010726
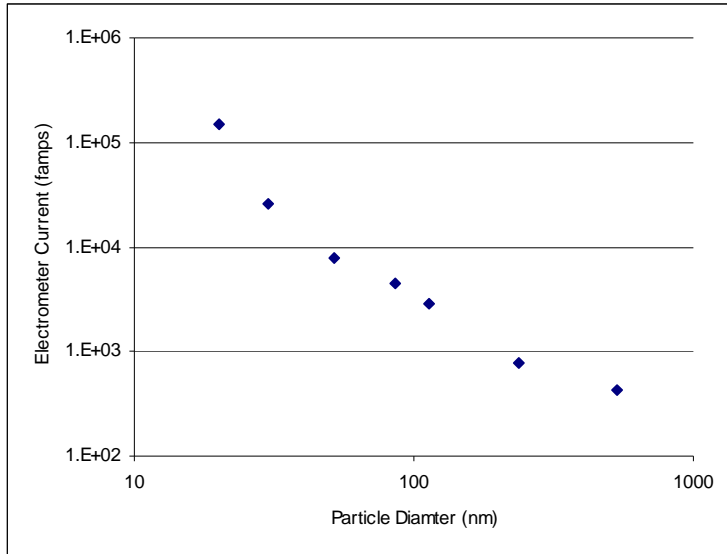
201001050747 DMM average electrometer current from 6 inertial stages and mobility stage (famps)
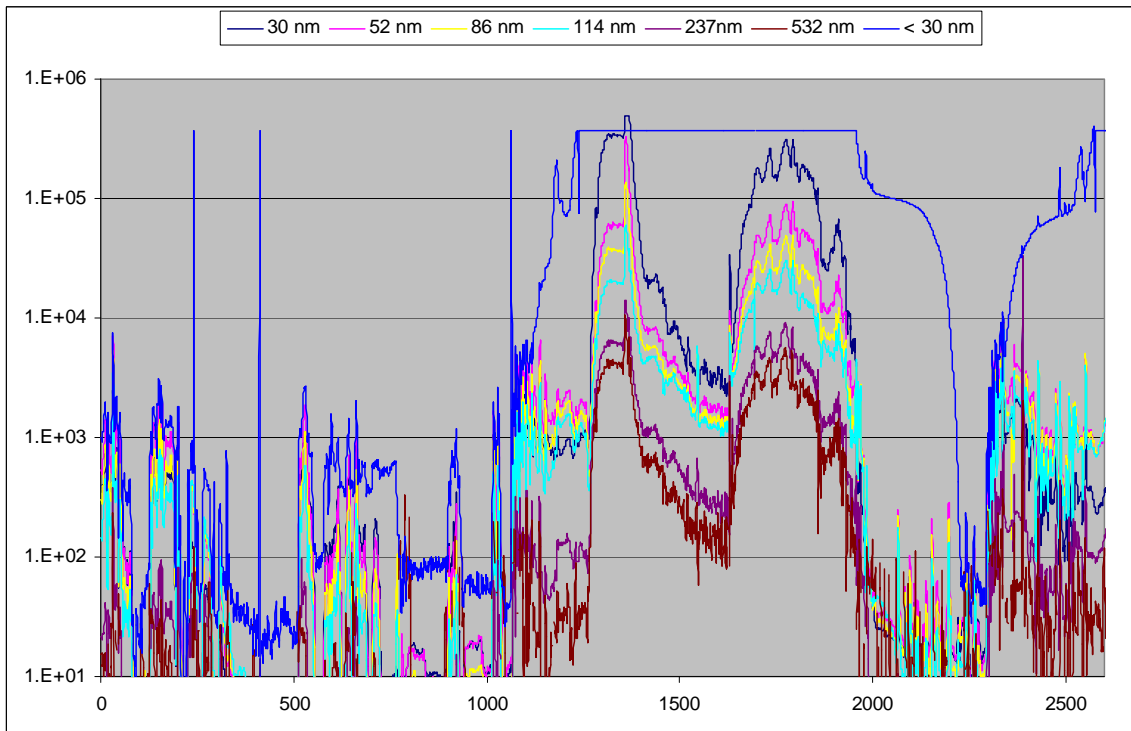
201001050747 DMM real time electrometer current from 6 inertial stages and mobility stage (famps)
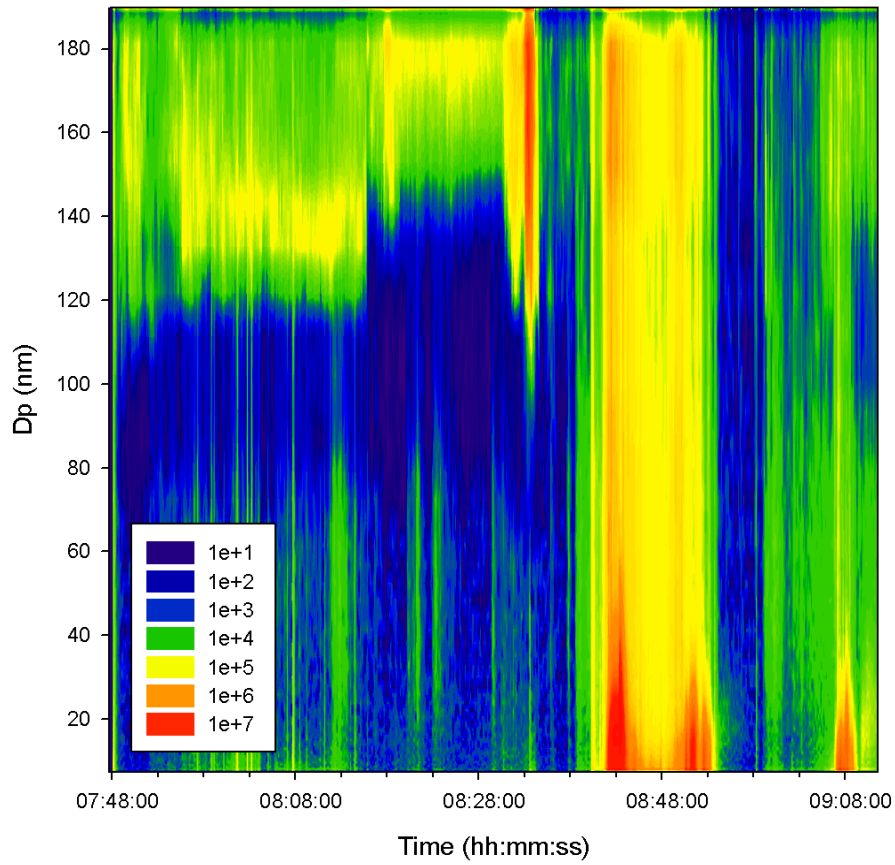
201001050747 fSMPS real time size distribution dN/dlogDp (#/cc)
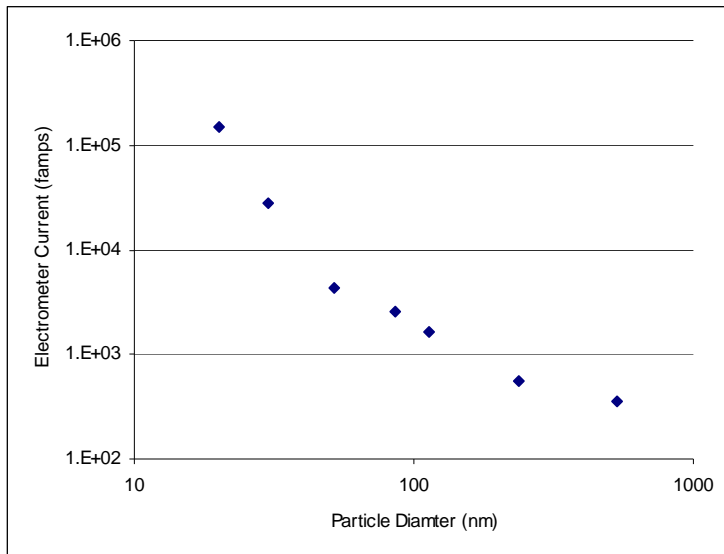
200912010726 DMM average electrometer current from 6 inertial stages and mobility stage (famps)
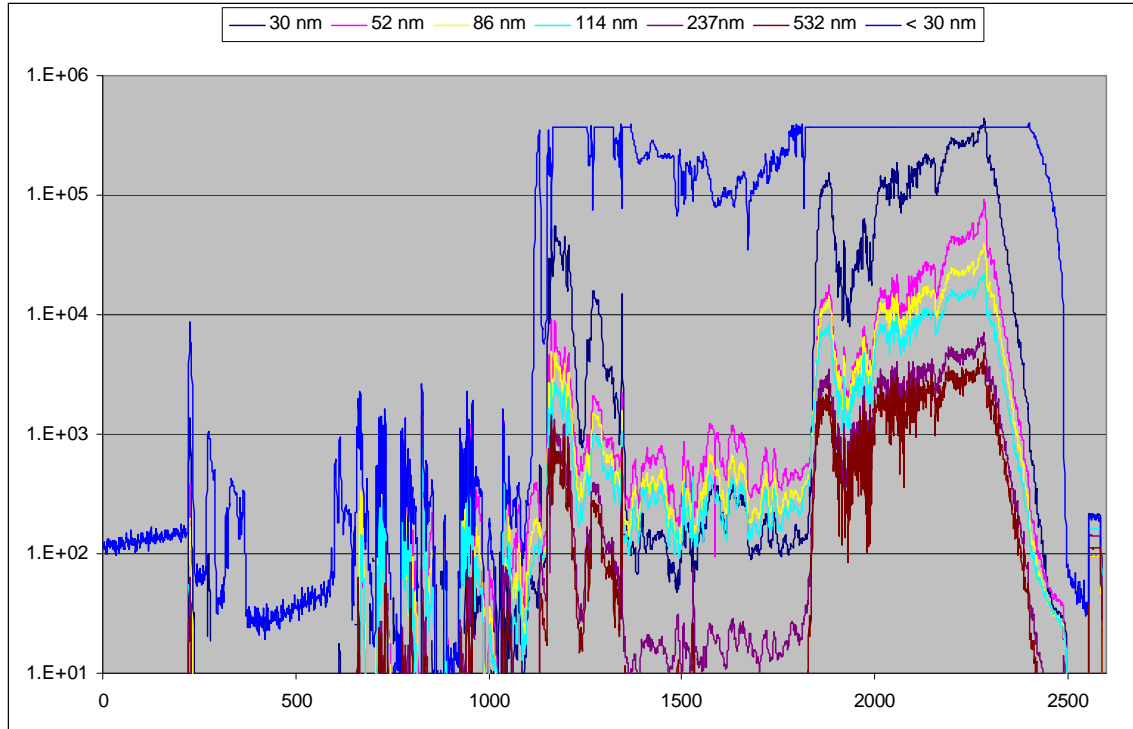
200912010726 DMM real time electrometer current from 6 inertial stages and mobility stage (famps)

The bsPM emissions for the fSMPS data in the following figure was 17.8, 9.8, 27, and 35 mg/hp-h for events 1 through 4 respectively. The sample times were392, 307, 225, and 192 seconds respectively. The most mass is coming from the last peak. The high concentration at large diameters and yet no EC suggests the high concentration is growing into large particles from small diameters. The diameter growth is very quick. The diameter statistics on this peak is.

200912010726 fSMPS real time size distribution average particle diameters

	Ave diams			Mass mean	Cut Diameters		
	#	area	mass	diam	D10	D50	D90
non-regen	61.7	74.5	85.6	134	17.42	49.24	117.96
regen	26.4	46.6	66.2	154	6.27	10.08	45.69
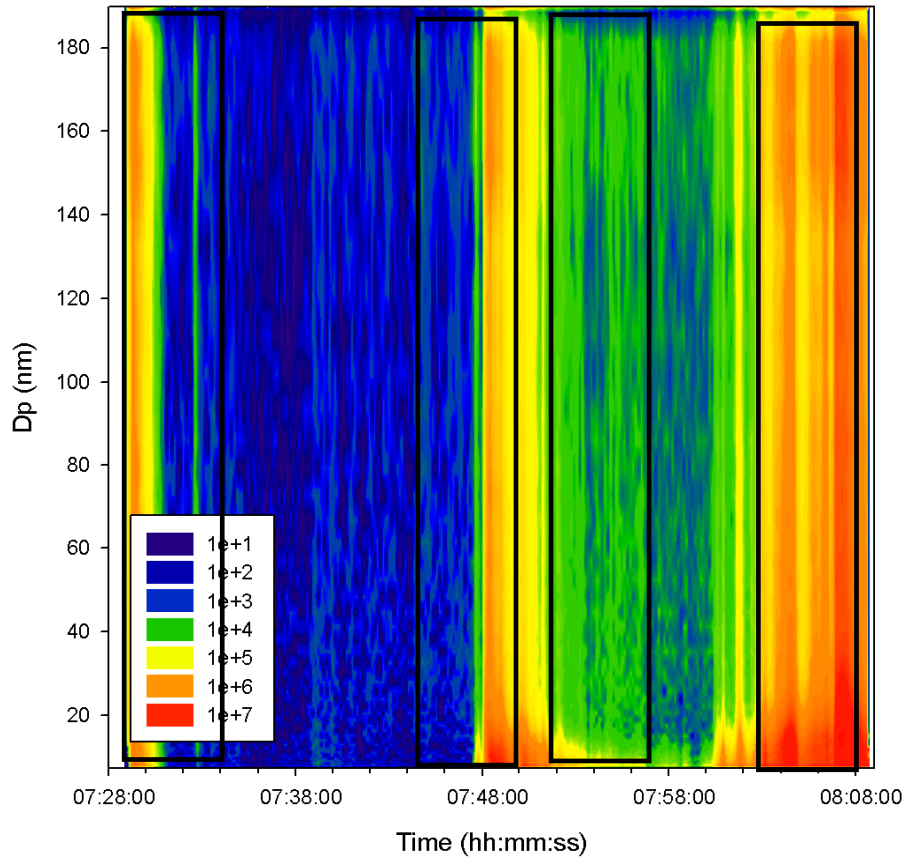
200912010726 fSMPS real time size distribution dN/dlogDp (#/cc)
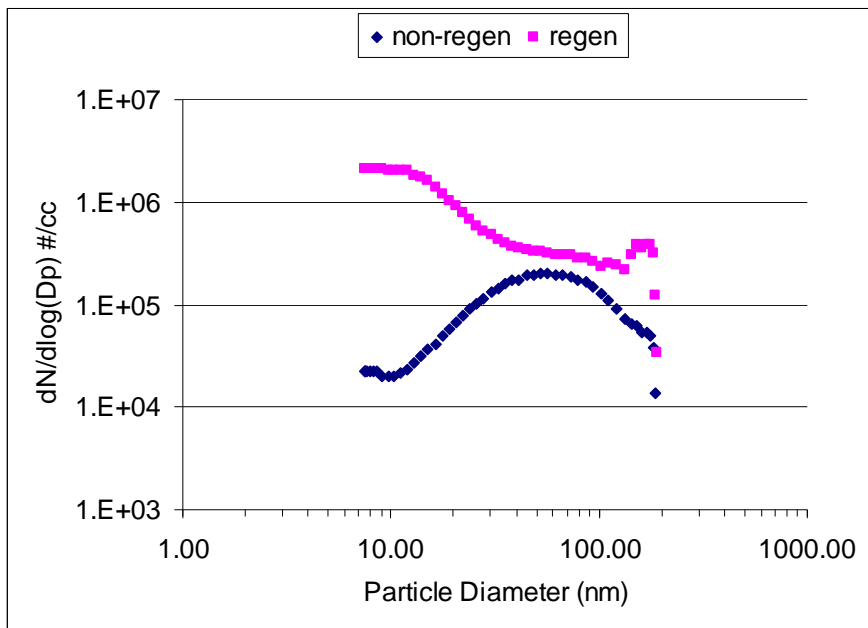
200912010726 fSMPS real time size distribution dN/dlogDp (#/cc)

The following figure shows the particle number concentration as a function of unit number for regen and non-regeneration cases. No significant findings except that the regen case had sliglh less #/cc particles. The #/cc particle count are corrected for tail pipe conditions.
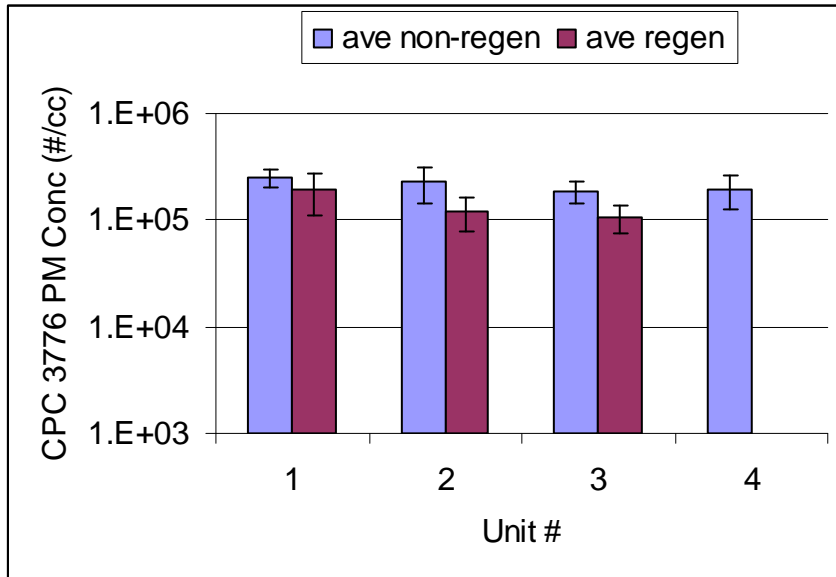
Figure of unit # and average particle concentration with 1 stdev error bars for regen and non-regen

The next figure shows time alignment variations for INST4 and 5 that sample from the MEL CVS. The reference is based on a calculated adjustment of 3 seconds shifted forward. Advancing the data is a result of the measured PM delayed response. The 3 seconds is from transport lengths, sample flow rate, and instrument response. The - 3 sec is the case with zero advancing or no adjustment and the +3 sec is an additional 3 seconds over the calculated 3 seconds for a total of 6 seconds advancing the data. The final +9 sec is a total of 12 seconds of advancing. From these figures the affect of aligning the signals with the sampled events does not seem to be significant and is on the order of less than 10-20% except for a few points out of 300. One reason for the less significant affect could be a result of the CVS sampling system. CVS's tend to dilute spikes with mixing, thus the transition for the event will be reduced due to the mixing and diluting. Raw sampling like for a constant diluted PM sample will show much larger spikes not seen in the CVS. Thus more analysis is needed for the PM PEMS signals to characterize this influence.
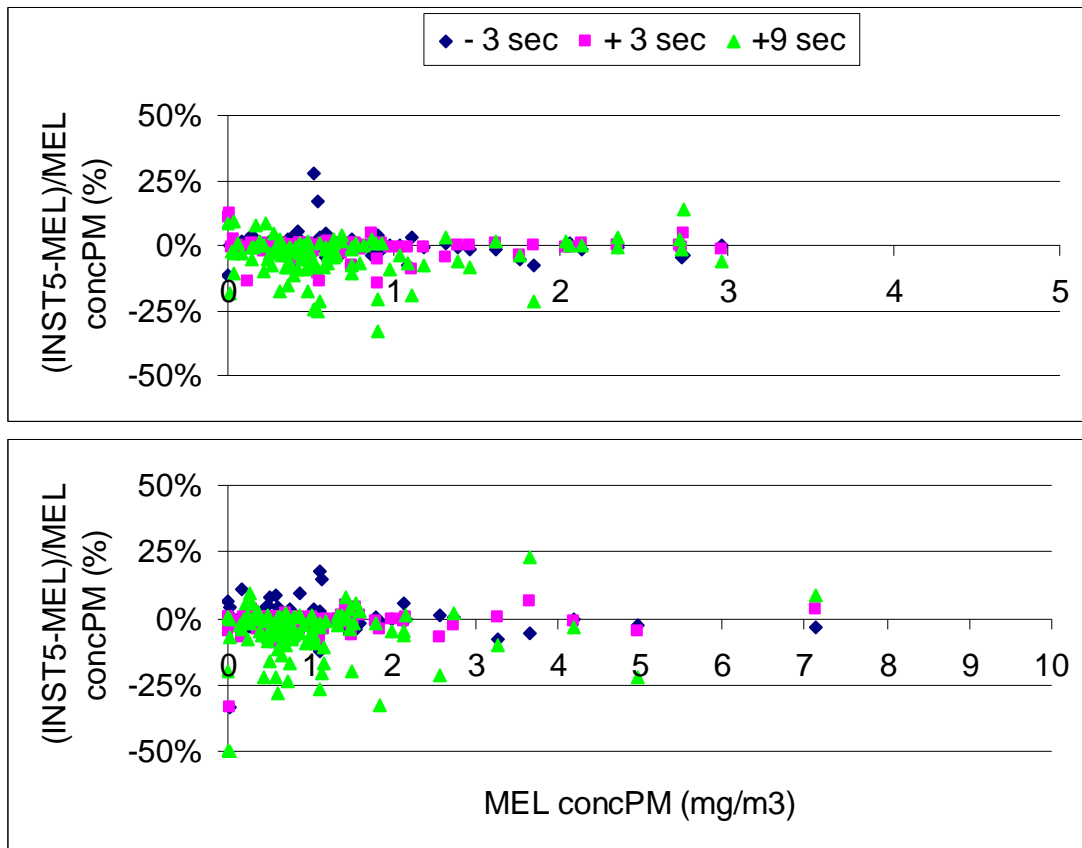
Figure Time alignment percent differences for INST4 and 5 sampling from the MEL CVS

Appendix H –Field Notes

01/05/2010	Regen Day via Baker Route. Capped first 2 runs to clean out MEL and transfer line. Then do regens
0643	Capped bypass to clean out MEL Did two QC filters. Regen ID 4298.
0747	Regen on this route. Regen ID at 42B2. Lost part of bypass and used a rubber boot with a C-clamp to fix. Event#2 and 3 had a lot of PM. Not so on #1 and #4
0924	Regen on this route. Regen ID at 4273. Consider temps on down hill had look at CO as indicator when DOC is hot enough. Saw high CO when exhaust below 200 C. This could be a good indicator for high SOF. Between event #2 and #3 skipped crystal #4 due to its loading being high.
1035NOCVS	Just logging with PPMD on regen disabled (off) no CVS connected. Real NTE mode
01/04/2010	Happy new year. San Diego route. Use crystal only 2 times all day. No real NTE's.
0651	Put spike at near front (2nd) for alignment. REGEN ID at 4264.
0725	Same as previous. Temperature spikes going in and out on this trip. Event 1 affected only.
0759	REGEN ID 4293. TC not good on this test run. All events are bad.
0932	Greased and partial regen on this run Regen ID at 4216. Fixed TC. 2nd event stated too soon and it was short. Alignment bias on this run
1002	same as previous
1041	same as previous
12/18/2009	Palm Springs route. Bypass same as previous day
0637	Regen PID 424B. No NTE cycling today. DMM charger voltage alarm. Not valid. Acually it looked good on the other three events.
0712	Regen PID 4262. Spike at beginning for time alignment
0745	Regen PID 4284 Regen PID end 429A. Set analog out command to AVST 00 for log range
0930	Grease/Clean and Park Regen (ID now 0000). Exhaust clamp broke. Improvised with vise grips.
1003	Same as previous. Data looks good. Regen ID 4157.
1133	Grease/Clean. Same as previous. These 1st time use events did not seem to be as effective as the previous two 1st time sets. Why????
1159	Same as previous Regen ID 41C4. Time alignment signal at start
1228	Regen ID 4200. Stuck at scales.
1305	Regen ID 422E.
12/15/2009	Baker route for test #1 with new Units. Bypass open more due to regen ID value.
0747	No regeens ID at 4238. Event#1 had some congestion. Same settings. No filter box sorry.
0833	Regen ID 4257. Same as previous
0849	Regen ID 4280. Same as previous

1007	Parked regen, clean/grease. Regen ID 0000. Same as previous with bypass slightly closed. Event #2 was high on MEL and low on PPMD. Strange.
1032	Regen ID 40CA. Very low loading after greasing in field. Strange.
1110	Regen ID 4162. Filter box started late
1139	Regen ID 41C1.
1200	Regen ID 41F4.
1232	Regen ID 4220. Same as previous Event #2 very steady and nice. Look at AVL data here.
Unit#2	
12/02/2009	Repeat Baker with no Regens this time. Try to get about 28 filters today to complete our project. This will be our last day with this unit. Only one problem this morning. The NDIR was not responding. Cycle power and it came to life. Noted that AVL GFB was on when I got in the cab???
0651	Regen off bypass at 25%. Regen ID at 420E. Fog
0725	Same as previous. Fog. Regen ID 4238
0757	Same as previous. Fog. Regen ID 4240
0818	Same as previous. No Fog. Regen ID 4255
0902	Same as Previous. Regen ID 4280
1019	Cleaned crystals and performed park regen. Regen ID 3FCA. Did some crystal cycling on this one (all crystals)
1048	Same as Previous (no cycling) Regen ID 40FC
1124	Same as previous (no cycling) Regen ID 418E
12/01/2009	Baker. Changed MEL trigger time back to 2 second delay and try to triggern systems not near peaks. Checked proportionality before leaving. It looked good with and with out CVS. See log file from this date
0726	Regens all morning. Regen ID at 42D3. First two looked light second two looked heavy
0811	Regen again. First good, but others seemed to end Regeneration. Run this out and change all filters and stop regens for next set.
0859	Regen off Bypass at 25%. Regen ID at 41A2.
0929	Same. Regen ID at 41FC.
1001	Same as previous
1127	Same as previous. Performed parked regen during crystal cleaning, greasing, burn in, and stability check. Regen ID started at 0000.
1213	Same as previous.
1242	Same as previous. Regen ID 416B.
1311	Same as previous. Regen ID 41D6
11/30/2009	Baker. PPMD fault abort testing due to problem with lookup table and sample flow tests. Turned out to be a bad barometric parameter set in MPS. Different between .215 and 3.10 software.
11/23/2009	Sensors making repairs to MPS board (all day event). Strange problem with proportionality. Sensors said to disable some parts during the lookup table check.
11/20/2009	Verified serious problem and asked to have sensors fly out to fix.

11/19/2009	Tried going out lost bypass flow again after getting on road. Diagnose and found EFM flows not working. Sensors needs to come out and replace a board on the MPS1 system.
11/18/2009	Drove around to see if bypass flow is working. It was working try going out tomorrow
11/17/2009	Palm Springs Route. Start went well. Some issues with sample flow. Bypass slightly more than 20% because my bsPM was still centered low. Leave at this bypass for the day.
0647	Regen ID 4283, No NTE cycling for morning run.
0735	Regen ID 4298. Increased bypass due to low loading last route. No NTE cycling. Event #1 DMM charger seened to saturate. Rough road. Did I forget to turn on the AVL filter. Opps.
~~0803~~	Ref flow not working. Had to reset the QCM, MPS1 and MPS2 to get it communicating. MEL PC crashed Aborted test
~~0824~~	Reboot. Restart all and Increased bypass. Event #1 did not trigger PPMD
0851	Reboot again. MEL triggers were not working. Replaced filter #1 and started over with a fresh batch.
0943	Did zero span and started next file. Same as before. Clean and grease on next.
1135	Performed parked regen and crystal cleaning/greasing. NTE 1 had a short regen by accident (AVL was sampling).
1213	good
1238	good
11/13/2009	Major problem with PPMD. Lost all parameters due to some glitch. Had to return back to CE-CERT.
11/12/2009	San Diego Route. Slow Semtech Statup due to low battery voltage even with charger on. Maybe too much load all at once (Semtech and PPMD)
0713	MSS Loc 1 also not working, check filter box. Regen ID at 4295, Real NTE at first (loaded to 10%). Loc 2 MSS not working, Bypass at 20% setting.
0755	No NTE cycling. AVL loc 1 and 2 still not working
0853	Regen ID at 42B4. Grease on next run, Same settings as previous. Problem with CO2 connector and will need to service conditioning box during greasing.Regen indicator came on for dash. We are going to do a parcked regen on the next test.
1054	Long crystal cleaning/greasing (2 + hr). Started AVL GFB late (middle of 3rd event). Sorry. No NTE on this run so these are first time use crystals for all of them. Completed Parked Regen. PID ID at 41AB. Loc2 MSS also working now.
1134	Same as previous. Loc2 MSS not working now (software issue). MSS Loc1 still okay. Regen ID 420C.
11/10/2009	Barstow Route. Use real NTE mode as much as possible. AVL fuse was fixed, and several PPMD issues resolved
0809	Bypass 20%, Regen ID 41BE (recently performed idle regen), Stated with NTE mode 1,2 the NTE mode on 3,4. Selected crystals of interest.
0851	Same as prev, Regen ID 4201 (a lot of NTE and events)

0927	Same as prev, Regen ID 422D (a lot of NTE and events)
1147	Greased crystals. Same as prev, Regen ID 425E, (a lot of NTE and events). Crystal flows not working (Data is probably not valid). Greasing took about 2 hr (start to finish with all the necessary checks)
11/06/2009	Barstow Route First time out setup day and see how it goes. Sample flow out was low at around 1.03 (off by 1%) go anyway. AVL with one filter for the day. Weird flakes on MEL filter. Change EC/OC every three.
0735	Bypass 20%, Regen ID at 41D0 (start), no regens. First run. No issues all events looked good.
0817	Same setup, Regen ID 4220 (end), All looked good
0859	Same setup, Regen ID 4234 (end), all looked good
0917	Same setup, all looked good
0xxx	Same setup, all looked good, 425A (end), did some crystal cycling
1043	Same setup, clean/greased all crystals (18s), Regen ID. DMM data is not valid on this test due to low charger voltage. Regen ID 4272. did some NTE cycling
1113	Same setup, all looked good, no cycling, fixed DMM
Unit #1	
10/26/2009	Regens for the morning then normal bypass events. All started okay, but AVL software is getting buggy. Found problem with AVL on test 826 (could be there sooner) where it looks like no signal (fond a large leak.) I don't have a procedure to check this with the FB option.
0645/6/7	Forced events, no cycling, regens for the morning (Regen status at 42A0). Event#1 missed by the PPMD. The semtech would not trigger the PPMD. Had to stop and start the test (new name 646) then it worked. Not sure why. Event #2 I noticed the exhaust temperature was broken (ie temp of 90C during a regen.) Fixed by jiggling probe. I have no spares. Need to take one from a different system. I noticed the bypass flow has dropped down to 3.5 lpm on Event #3. Probably due to grade. Startup was around 3.85. Not sure why? Event #3 and 4 were good.
0826	More Regens, capped, forced events Regen status 41DE. During regenerations where the CPC count is high, when Don lets off on the throttle the CPC count goes vary high (conditions of lean events lots of O2). Think abut on this test on Event #2. On event #3 the soot loading term went to 0000 and the stage was 5. Not sure what this means, but the DMM and CPC showed very high count when this happened. Did not use last filter. Last filter will be a dynamic blank.
1014	Bypass installed (same previous setting), regens off, AVL MSS1 not sampling and not FB trigger. Called about exaut temperature red light on MPS1 and Chris Darby said it may be a bug in the software. Ignor if it looks good.
10/23/2009	Tried going out, but PPMD bypass flow was not working. Removed equipment to trouble shoot.

10/22/2009	Every three then quarts change out. AVL replaced after first then in all day. Problem with semtech pressure on drain bulb. Data may not be valid.
0653	Regen started at 39A1. First test. Accidental regen on event 1, the others were good. Replaced AVL filter as a result.
0735	Forced events bypass 12% with no regens changed out AVL filter. Also sample filter on Semtech was dirty (daily replacement) cleaned and moved on this will affect the AVL soot prediction parameter. THC data may not be valid
0821	Forced events while cycling with NTE for awhile same bypass and other. Semtech still has alarm (high vac).
0910	Regen at 41D5 (very clean still) Same as above. Try increasing bypass. It still seems low. Forgot to enable AVL filter box on this run.
1003	Regen ID at 4218. Same as previous. Heading back now. Semtech DS has an internal bulb filter that needs to be replaced try to do this tonight. Remembered AVL filter box trigger. Bypass flow at top of hill 3.1 lpm (started at 3.87). 3rd event very rough road.
1045	Regen ID 425C high side of okay. Same as previous. I don't think I turned on the AVL for this run. Humm
1137	More of the same previous stuff (quarts staying in as this may be the last run). Regen ID at 4281. AVL filter is on. Last MEL did not line up with PPMD. Wrong trigger mode.
1234	on 15 freeway. Very ruff road. No cycleiing just forced events. AVL may have been left in zero mode (MSS1 and 2). Regen stat ended at 42AA.
10/20/2009	Second day of official testing Unit 1. Proportionality checked on startup. Looked good. Max exh flow 2000 this time
0646	QCM greased from then tared the night before. Light loads, bypass 13%, forced events, no regen, went through mist on #3. AVL filter installed (tore when removed)
0737	Same as previous. On filter number 3 ended cycle when the jake brake was engaged. Any time alignment will cause this to increase the mass on the PPMD. Engine looks like it tuned very differently for the NOx is high and PM is low. Very hard to get the PM I want. Im at stage 42BA in between high and very high. Will do regen on next cycle.
0857	AVL not working (stop using for the day) Regen, forced events, bypass capped, new AVL filter, new quarts filters. Regen status ID at 42B4. Looks like Dustrak is off or reading zero for some reason. It could be the fact that we have the bypass capped and there is no PM. Regen this time very strange. No large bursts of PM. Only did first 2 with PM other 2 filters (3,4) were dynamic blanks. Did park regen to cleanout rest
1006	Forced events with crystal cycleing by being in NTE mode for some part of the time. Bypass at 12%, no regens, crystals did not need greasing.

	Started filter #2 when PPMD was locked out. Opps. Short test. #3 it seemed that the PPMD started late. Large power lines on #4.
1052	Same setup as before. PMMD corron currents not working. Power supplies were off. It lookis like a parameter on the configuration for the CQCM head was incorrect and the corron currents did not want to initialize during events. The valves switched and the flows changed, but no corona currents. This may have occurred on an erlier cycle. Not sure.
1139	MEL computer (blue screen of death). Restared and loaded this file. Forced events with crystal cycling. Bypass no change. Messed up filter #3 (PPMD was in NTE and not forced event mode). This data point will not correlate.
1231	Four good filters. No MEL crashing. Forced events with only a small amount of real NTE in the beginning. Same bypass as all day. At 1321 MEL CVS removed . Regen setting is 42AB (REGEN LEVEL AT HIGH LEVEL AGAIN).
10/19/2009	Start all instruments, but problem with PPMD and AVL (CE-CERT kinked line). Spent all day trouble shooting PPMD. Fixed and continued. Swapped heads and then stepper motors. Found out it was either the stepper motor or the head. Final status was old head and new stepper motor.
10/15/2009	First day of official testing Unit 1. Proportionality improved by sensors with change to max flow and capillary diameters to tune proportionality with and without CVS. With out CVS the data was also bad. All day with 1400 due to sensors change
0714	Greased crystals night before. Bypass at 10% and forced regenerations. Soot loading started at 423D (50% of normal). Run looked good. Try increasing bypass for next run to increase loading rate.
0815	Bypass at 20% and forced events. Regen at 4270 (70% of normal) do a regen on next set.
0918	Bypass at 20% and forced events. Regan ID at 4289 (80%). Regen started at end of event #2, but way high on event #3. In fact filter loading terms are off the chart. Event #3 all regen ended short. Bulk of regen seemed to end ½ through event #4.
0952	Bypass at 20% and forced events. Repeat regens. Very high PM with high THC. Don't do regens with bypass anymore. Bypass at 25% with real NTE mode.
CQCM	1 hour to clean crystals. Lost 5 during greasing. Had to re-enable in micro. Repeated 3 times to get through process. After getting 10-15 µg. I reinstalled head and had to re-enable 2 of the crystals. Total time took 2 hr to clean, grease, burn, and verify.
1235	Greased crystals. Tried real NTE mode, but not enough grade to hold constant. Changed back to forced event mode with bypass at 25% no regenerations and a new AVL filter installed due to high PM on regenerations.

| 1309 | Performed similarly as previous. Intentionally went back and forth between NTE mode and forced event mode to cycle through crystals then load on a filter with control of the event. |
| 1351 | Decreased bypass with assumption that we are overloading and to high of a bsPM. Need to look at later. Set at the nominal 10%. No regens. Regen level at start is 427A (around 70% of nominal). First event was in purge sample mode (data not valid). Check previous test to see what mode 1309 was in for each event. |

| 10/08/2009 | Summary: All crystals functioning. Zero/Span/Audit Semtech DS. Audit sample flow. Had to recalibration because sample slope was 0.97. |

AVL 1 Time	0 (all clocks relative to AVL)
AVL 2 Time	0
PPMD Time	5:29:45 slow 20 sec fast
Semtech Time	5:29:45 slow 20 sec fast
MEL Time	6 sec fast
DMM Time	0

0851	Greased crystals night before. Bypass at 0% for regens. Trigger set in forced event mode. Regen start HEX 42B9 and end after 60 minutes 4218. First event the PPMD did not trigger. Enabled AVL filter box (peak measurement) once on freeway. Crystal 2,3,4 (events 2,3,4)
1004	Bypass at 10% desired position for next set of forced events. Enabled AVL box once on freeway. Did not change filter. Regen left off (disabled). Crystal 5,6,7,1. Event #2 had some amount of Jake Brake. Tried regen with bypass at 10% at 4223 for a short amount of time to see what happens. Left regen on for last event. Final soot term at 41E0
1133	No regens and tried out the real NTE trigger method. AVL filter box started after on freeway. PPMD was in standby while getting on and off freeway. Noticed that PPMD was triggered, but no PM went on filters. Very difficult to do real NTE with PPMD and MEL. Looks like some might be successful. Try again. Opened bypass to ~25% level.
1217	Repeat real NTE at same bypass level. One filter went short at 20 seconds. Did regen after all filters completed about 20 minutes of regen. 10 minutes before CE-CERT we pulled off the CVS and left the PPMD, semtech, AVL and mel sampling. This will give conditions with MEL removed. Two faults "High Vacuum on drain" and one warning "low sample flow"

Appendix I – PEMS Startup

PEMS2 Startup

Setup and configuration for each instrument is below. The goal is start one process while doing a second. This may involve setting up multiple instruments. This procedure assumes the leak check, and other monthly calibrations have been performed prior to this. Follow the manual for these procedures. This procedure will take the longest amount of time between 2-5 hours so start this process first.

PEMS2 Setup and Configuration
1. PPMD setup "Check Up Tests"
    a. MPS1 Warm-up   (while waiting get flow audit ready)
    b. MPS1 Zero Transducer
    c. Block Pressures
    d. Look-up Table
2. PPMD setup "1065 Audits Tests"
    a. MPS1 Sample Flow   (let Don/Joe hook up exhaust)
3. PPMD setup "Check Up Tests"
    a. CQCM Warm-up   (if busy start **Semtech DS** procedure)
    b. CQCM Tare Crystals
    c. CQCM Self Check   (while waiting perform **Semtech DS**)
        i. Evaluate **sample flow** (flow should be between **4.2 to 3.6**)
        ii. **Frequency stability** (no more than **20Hz** between rotations and baseline)
        iii. **Corona current** (currents must be between **10uA < Measured < 65 uA**)
        iv. **Frequency drift** (no more than **7Hz** between base and last row of frequencies)
4. Perform "SOP-003 Config"

Semtech Setup and Configuration (IP = 10.10.1.54 with Subnet of 255.255.0.0)
1. Start Session Manager
    a. Use file name "**yyyymmdd**"
    b. Click "**Open**" to start session
2. Light FID   (if waiting to warm up finish **configuration** SOP)
    a. "**Off**" Continuous leak check
    b. "**On**" Flame
    c. "**100**" FID Range
3. Zero instruments when ready (all at once)
4. Span instruments
    a. CO, CO2, NO, and THC
    b. NO2
5. Audit All
    a. CO, CO2, NO, and THC
    b. NO2
6. Perform "SOP-003 Config"   (if not already completed)
7. Ready for Testing

PEMS3 Startup

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).

INST 5 Startup

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

INST 4 Startup

Standard Start Up Practice (10 minutes or less and requires no supervision)
- weekly impactor cleaning
- weekly zero adjustments
- daily flow verification, but typically no correction

MEL CVS Startup

Standard Start Up Practice (60 minutes or less and requires no supervision)
- 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

Appendix J – PEMS Supplemental Issues and Comments

PEMS2

PEMS2 sample flow calibration is a daily verification/calibration procedure. For unit1 the results for all sample flow calibrations is listed in Table A-J1 and A-J2 below. Multiple sample flow calibrations were required in order to achieve a passed situation prior to testing.

Table A-J1 Sample flow calibrations using Old TSI meter.

DATE	TIME	Starting point	SLOPE	Intercept Standard	Error	R2	Intercept %Error	SEE %of max	STATUS
20090910	14:48:13	1	NaN	NaN	NaN	NaN	NaN	NaN	Fail
20090916	15:07:53	0	0.7	0.028	0.005	0.999	3.08	0.579	Fail
	15:18:14	0	1.02	-0.014	0.01	0.999	1.03	0.767	Pass
20090917	15:09:03	0	1.02	-0.012	0.011	0.998	0.928	0.836	Pass
20090930	7:57:33	0	0.88	0.018	0.01	0.998	1.47	0.848	Fail
	8:28:09	0	0.98	-0.004	0.01	0.998	0.266	0.707	Pass
	8:38:09	0	0.95	0.01	0.008	0.999	0.707	0.605	Fail
	9:24:52	0	0.79	-0.015	0.01	0.997	1.35	0.938	Fail
	10:02:34	0	1	-0.03	0.013	0.997	2.27	1.005	Fail
	10:10:46	0	0.97	0.018	0.007	0.999	1.34	0.537	Fail
	11:40:19	0	0.97	0.009	0.005	1	0.887	0.442	Fail
	11:48:22	0	0.97	0.01	0.006	0.999	0.934	0.546	Fail
	12:04:42	0	0.98	0.004	0.005	1	0.361	0.46	Pass
	15:18:42	0	0.99	-0.007	0.006	0.999	0.61	0.556	Pass
20091007	7:19:15	0	0.97	0.015	0.009	0.999	1.34	0.746	Fail
	7:21:15	0	NaN	NaN	NaN	NaN	NaN	NaN	Fail
	7:33:21	0	1	-0.041	0.008	0.999	3.58	0.729	Fail
	7:36:18	0	NaN	NaN	NaN	NaN	NaN	NaN	Fail
	7:46:34	0	1.01	-0.035	0.07	0.999	3.19	0.933	Fail
	7:50:23	0	NaN	NaN	NaN	NaN	NaN	NaN	Fail
	9:04:46	0	1.02	-0.041	0.008	0.999	3.65	0.71	Fail
	9:24:05	0	1.04	-0.043	0.007	0.999	3.83	0.653	Fail
	9:44:25	0	0.97	0.016	0.004	1	1.47	0.367	Fail
	10:04:49	0	0.98	0.012	0.006	0.999	1.16	0.611	Pass
	10:17:40	0	0.97	0.014	0.006	0.999	1.32	0.562	Fail

Table A-J2 Sample flow calibrations using New TSI flow meter

NEW TSI FLOW METER

DATE	TIME	Starting point	SLOPE	Intercept Standard	Error	R2	Intercept %Error	SEE %of max	STATUS
	12:44:13	0	0.98	0.014	0.006	0.999	1.14	0.462	Pass
20091008	7:03:03	0	0.97	0.007	0.004	1	0.719	0.407	Fail
	7:30:40	0	0.99	-0.006	0.005	1	0.648	0.551	Pass
20091013	10:57:39	0	0.97	-0.007	0.006	0.999	0.636	0.51	Fail
	11:05:09	0	0.99	-0.01	0.007	0.999	0.832	0.583	Pass
20091015	6:06:19	0	1	-0.009	0.012	0.998	0.891	1.121	Pass
	14:05:04	0	NaN	NaN	NaN	NaN	NaN	NaN	Fail
	14:08:44	0	NaN	NaN	NaN	NaN	NaN	NaN	Fail
20091016	14:16:17	1	NaN	NaN	NaN	NaN	NaN	NaN	Fail
	14:43:36	0	87.59	0.083	0.009	0.025	7.82	8.377	Fail
	15:52:07	0	1.01	-0.016	0.002	1	1.49	0.187	Pass
20091019	5:15:23	0	1.03	-0.016	0.003	1	1.31	0.272	Fail
	5:24:07	0	1.04	-0.023	0.004	1	1.89	0.362	Fail
	5:31:44	0	0.98	0.007	0.004	1	0.599	0.316	Pass
20091020	5:00:29	0	0.96	0.013	0.004	1	1.11	0.325	Fail
	5:30:25	0	0.98	0.002	0.003	1	0.19	0.265	Pass
20091021	12:40:09	0	0.94	0.023	0.006	0.999	2.17	0.577	Fail
	14:35:34	0	0.95	0.015	0.002	1	1.39	0.206	Fail
				CAPILLARY CLEANING					
	15:55:56	0	0.95	0.018	0.003	1	1.75	0.255	Fail
	19:53:39	0	0.97	0.018	0.003	1	1.62	0.233	Fail
	21:07:09	0	1.04	-0.042	0.007	0.999	3.8	0.599	Fail
	21:41:56	0	1.05	-0.046	0.005	1	4.14	0.417	Fail
	21:51:12	0	1.05	-0.043	0.005	1	3.91	0.454	Fail
20091022	5:15:07	0	1.08	-0.062	0.009	0.999	5.27	0.747	Fail
	5:24:03	0	1.08	-0.055	0.007	0.999	4.73	0.64	Fail
	6:13:00	0	1.06	-0.06	0.009	0.999	5.31	0.807	Fail
	7:39:52	1	0.99	-0.015	0.005	1	1.95	0.62	Pass
20091026	5:18:29	1	0.96	-0.018	0.005	0.999	2.48	0.662	Fail
	5:39:23	1	0.98	0.002	0.005	0.999	0.322	0.695	Pass
	13:58:22	1	1.05	0.018	0.006	0.999	2.25	0.73	Fail
	14:13:32	1	1.07	0.017	0.004	1	2.18	0.559	Fail
				CAPILLARY CLEANING					
	15:52:50	0	0.96	-0.001	0.004	1	0.806	0.348	Fail
	16:12:31	0	0.98	0.036	0.027	1	0.471	0.351	Pass

PPMD Bypass Flow Polynomial Order Selection

During validation testing Sensors Inc processed some of the validation raw data files and found that the data processed by UCR did not match what Sensor's processed. Sensors found that a parameter known as the "Bypass Flow" polynomial order may be incorrectly set for the post processor used by UCR during PPMD validation data processing. UCR followed the manual for post processing and did not see an instruction for setting the poly order and thus left the system in its default configuration. Regardless, Sensors said this was a necessary step in order to compensate their bypass flow measurement for changes in air density with elevation. The MA committee agreed this correction was a necessary step and thus, the data was reprocessed for this bypass flow correction.

Figures 1 show the location in the software where to change the bypass flow polynomial order and figures 2 – 4 show the effect of the different orders from 0 to 1st to 2nd. The 0th order is no relation between elevation and flow, 1st order is a linear relation, and 2nd polynomial relation. From the event selected in Figures 2 – 4 the 1st order relation looks like the most appropriate choise and supports making the change requested by Sensors. UCR's original data was processed with the default polynomial order of 2nd. All data in this report is based on the "Polynomial Order" of 1st order as per Sensors recommendations and the MA committee.

The effect of the "Sample Flow" correction appears to be on the order of 2-5% and bsPM is inversely related to sample flow (ie more sample flow results in less bsPM for the same event).

Figure 5 shows a trend where the trend is not linear (ie not 1st order. The results in figure 5 suggest that the poly order of 1st order may not hold for every event. Still events like the one in figure 5 are part of the data set and were processed with the same polynomial 1st order factor.
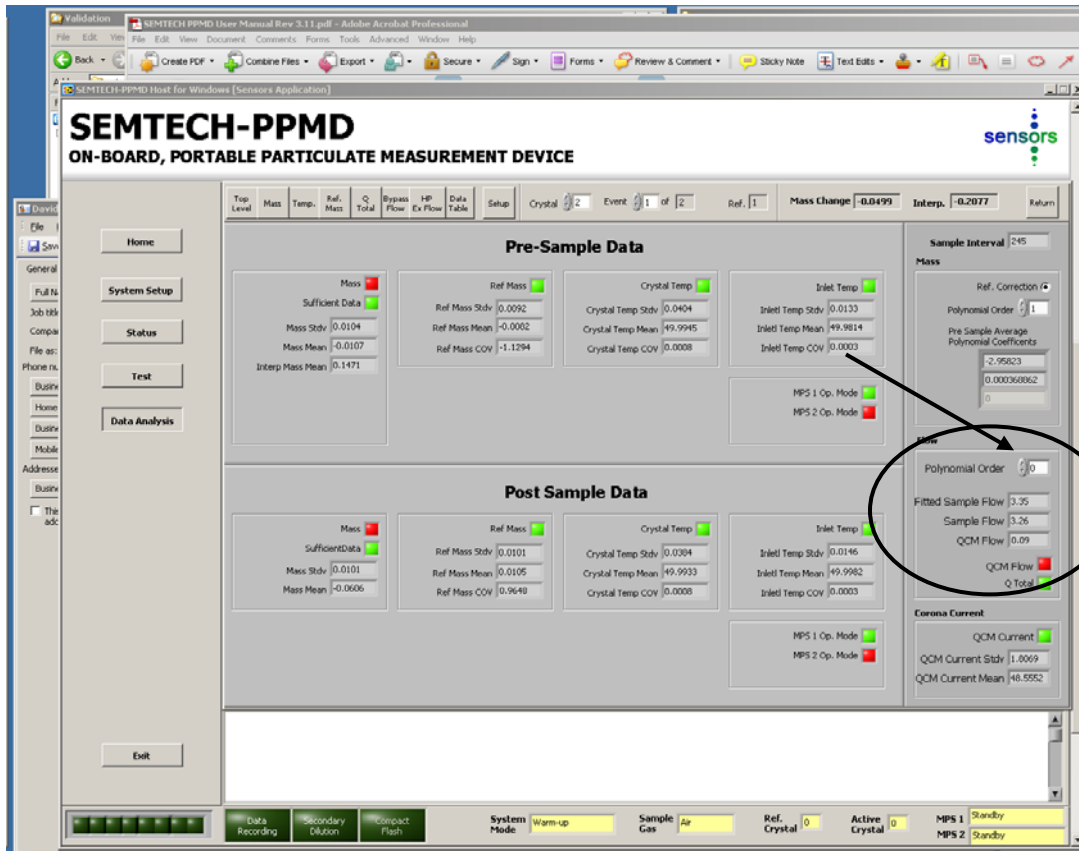
Figure 1 bypass flow polynomial order selection to 0 for PPMD post processor used during Validation
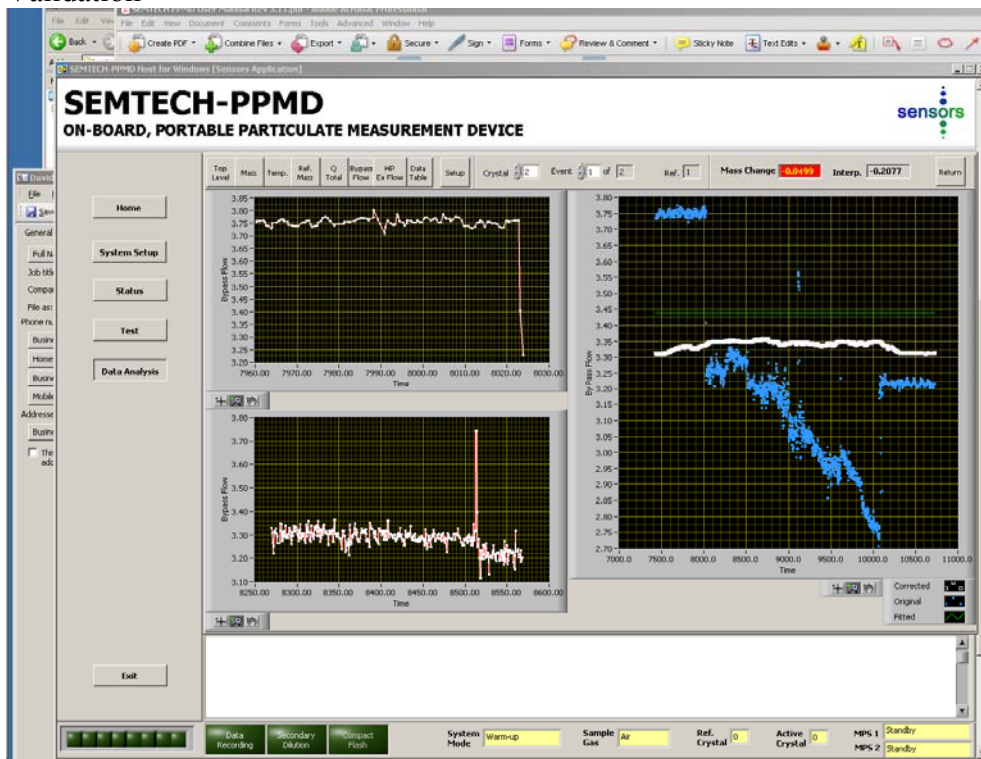

Figure 2 Resulting curve at bypass flow polynomial order of 0 for a selected event.
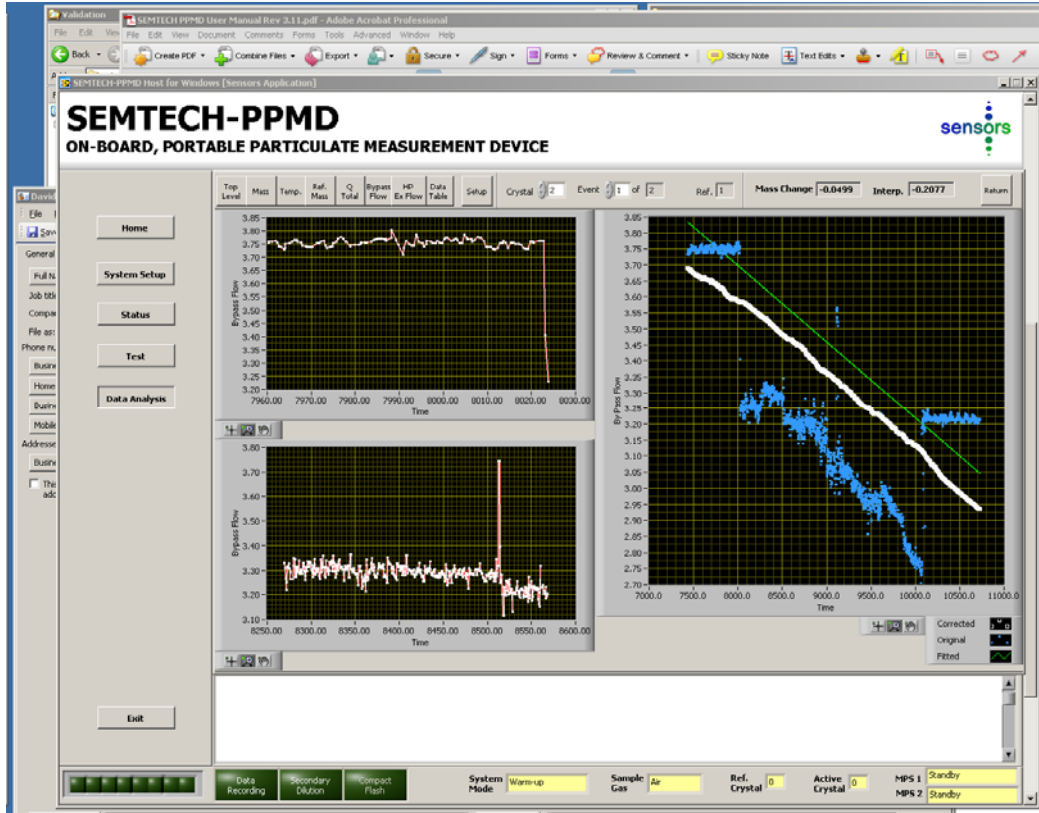
Figure 3 Resulting bypass flow curve with polynomial order of 1 for the same selected event as Figure 2
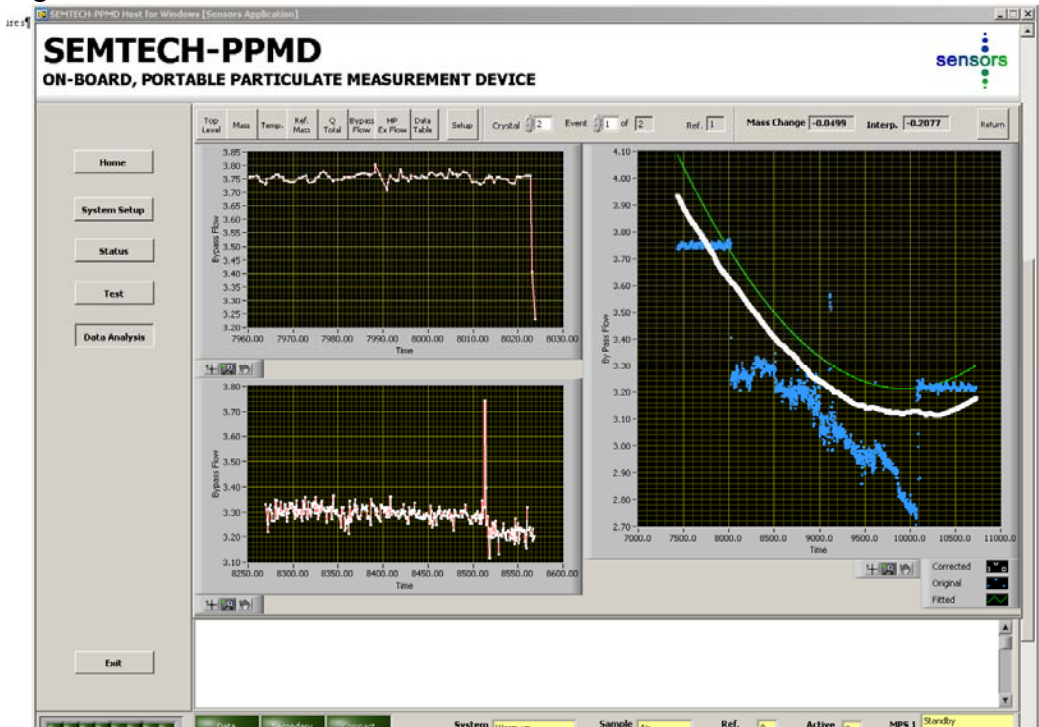

Figure 4 Resulting bypass flow curve with polynomial order of 2 for the same selected event as Figure 2
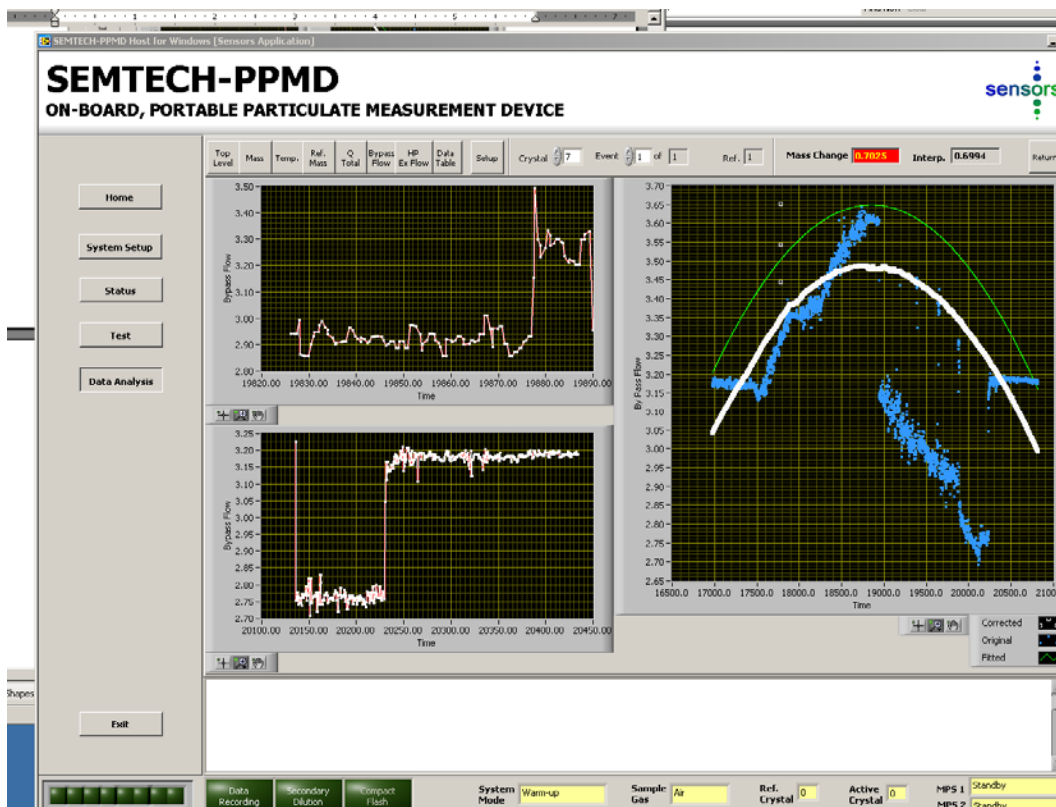
Figure 5 Resulting bypass flow curve with polynomial order of 2 for a different event pmx_201001050924.csv.

e-mail correspondences:

Many of the correspondences with PEMS2 were performed over the phone due to the level of complexity for the repairs and need for instructions. Thus there were only a few PEMS2 e-mails to list. They are listed from newest to oldest.

##

Kent, Imad, and David:

I was talking to Imad yesterday and he expressed concern that the exhaust flow offset may not be linear. I know that Kent and I also had this discussion earlier in the week. I would like to consider sending the PPMDs and flow meters to Sensors to have a calibration check run on them to generate new calibration coefficients with the flow meters plumbed the way they were run in the field (the incorrect way). From there we could correct the flow meter data and reprocess the data. I would like some input on if you guys feel that this is necessary. We are running out of time between now and the mid February meeting and on the the important aspects of this meeting is the exhaust flow correction. If it is determined that we need new flow meter coefficients for the flow meters with the incorrect plumbing, I would like to make sure that the equipment can get to Sensors in time to have the flows checked and the data reprocessed for the mid February meeting. Also, Kent may have discovered something in the last few days that may negate the need for this test, so if this is the case, let me know. Please let me know your thoughts on this. Regards,

Chris Laroo

###

Hi Kent,

This application has the fix for your AVL MSS Time alignment issue. You should be able to adjust those delays to tenths of a second. You stumbled upon a bug for MSS and GPS only that only allowed whole seconds, when writing the setting out to file. I fixed it in this build of the post processor app.

This is a zip file with a modified extension so that it will get through e-mail filters. Just change the extension back to zip, unzip it and replace the file with the same name in the C:\Program Files\SENSOR Tech-PC directory with this version.

<<Post Process.__p>>

Sensors, Inc.

PEMS3

###

Quick info from Michael.

The MFD temperature warning can probably be ignored.

For the flow warning, we'd like you to set the dilution ratio back to 6, and see if it goes away. We may not be able to change the dilution ratio to 9, we have to check that the firmware will do it properly.

From: Kent Johnson [mailto:kjohnson@cert.ucr.edu]
Subject: New Warnings

MSS Unit #3 has two warnings that I need clarification on, see enclosed screen shots for details. The warnings are Nr. 120 and Nr. 133 (MFC flow warning and MFD conditioning temperature). Is the system okay to operate with these errors?

Also I had an error with the "TE cooler humidity" (Saturday and Sunday), but have since gone away. I think the TE cooler is not working ideally. On days with high humidity (Saturday/Sunday) the cooler the RH% is around 90% and on dry days (today) the RH% is 50%. Any ideas what to do about this? As a point of reference the RH% on the MSS in the MEL is at 4% where the one outside is at 50%. Both have about the same input RH ambient air.

###

Dear Kent

I am a little surprised by a 16% increase in sensitivity, which the span check seems to indicate. Could you eventually re-check after the system has been heated up for more than 1 hr?

Can you tell me, what S/N the unit is,
Plus the calibration factor and date of the calibration currently stored in the Firmware?

I do not fully understand what happened with the analog output channel A. You write that channel A and channel B were adjusted to read closer to 0 and 10 Volts, and then you write that channel A read only 1 Volt. Does it read 10 V when it is not connected to the Semtech, and 1 V when it is connected to the Semtech? Then
  - Either the input to the Semtech must have a problem, I do not know what we can do against that. If this is really the case, can you verify the input problem by an external 10 V power supply?
  - Or the output on channel A "breaks down" when it is connected to a load (= input to the Semtech), a quick solution is also difficult. A new motherboard would need a full re-calibration of the sensors (except photoacoustic sensitivity f_kal). As a workaround one could use output C, which is the dilution corrected signal. The correct analog output description is only in manuals with revision 9, older manuals give a wrong description (for current firmware versions).

-----Ursprüngliche Nachricht-----
Gesendet: 11 December 2009 17:34

##

##

Enclosed is the all the data for Nov 10 which includes the AVL filter weight summary file, Semtech 2Hz data, MSS loc 1, and MSS loc2. The day seemed to go well for the MSS loc 1 with the exception of the power issue in the morning.

One strange issue though was with MSS in loc2 (it doesn't affect the primary MSS in location 1 which is on the truck frame). The software seemed to be so bad that I don't think data was logging consistently. I noticed the memory allocation for the loc2 MSS laptop was over 180 MB. I had to reboot several times to try and get it logging and responding to mouse clicks.

Sincerely, KJ

##

Hi Kent,
I've set up the system like discussed. The Semtech is reading the GFB trigger now at analog channel 2.
I adjusted the MSS analog signal to match the Semtech analog more or less sufficiently. I also configured it for the logarithmic scaling at the MSS side. As far as I remember that was the way you ran it.
Please set the MSS logging back to 2Hz before you start and fixate the GFB with the straps. I forgot that, sorry :-)
I did not yet include the integrated filter soot load into the logging. Please write it down for each filter before you reset it (we discussed that).
The system is ready to go and your procedure stays the same, except that you now only need the DCS (Your AVL startup icon).
The old Pc-Software is not needed anymore, but please leave it installed on your system for emergencies and diagnosis.
Thanks

##

Kent,
This looks pretty good. It is the quintessence of what we discussed yesterday.
The filter on top of the box could be a good point for checking the bypass (check 4). You should have a strong suction there when the filter loading is not triggered (Function <>10). Otherwise you should have suction at the inlet of the gravimetric filter holder (disconnect it from the quick release on top for checking it, check 3). In both cases you will have suction at the inlet of the box. You can also check the inlet of the black at the bottom of the filter holder (after removing the filter holder, check 2). For leak checking the MSS close its inlet and use the leak check procedure fro the Software (check 1). I made some test with our other box, which is leaking (not much) at the filter inlet (The small fittings leak). This small leak does not have a visible effect on the measurement (Filter and MSS). For seeing nothing on Filter or MSS the leak needs to be BIG! The only possible source for such a big leak is the quick release on top of the filter holder. Make sure that it is REALLY closed.
As I said I will be at Ce-Cert from Tuesday to Friday. I will perform FW and Software updates. We will have new versions with many bugfixes available next week.
Please perform the idle checks, it is a good idea.

Regards

From: Kent Johnson [mailto:kjohnson@cert.ucr.edu]
Sent: Wednesday, October 28, 2009 15:53
Subject: Leak Check

I did a basic sketch of how I think the plumbing looks inside the AVL (not all the sampling detail, but the basic idea). Can you confirm this so I can keep thinking on your leak check (see enclosed sketch)?

The strange thing is after all the checks I did it appears the problem is gone and I have good sampling suction. What I mean is, in sample mode with the inlet capped, the system goes to large negative pressures on the orifice abs pressure and back pressure (200 mb) as if there is no leak. I don't know what was going on now and when I tested in the field. The system may have been in zero mode (in the field) where capping the line would do me no good (since the dilute flow would be greater than the sample flow).

When I get a chance I'll put the exhaust back together and run some idle tests to see if MSS1 is sampling idle like it did in the beginning. Any other thoughts?

Kent C. Johnson
UC Riverside CE-CERT
(951) 781 5786 desk
(951) 313 5658 cell
(951) 781 5790 fax

Physical/Shipping Address
UC Riverside CE-CERT
1084 Columbia Ave
Riverside, CA 92507

###
Hi Kent,
Again, sorry for the inconvenience you had with our box.
If the flow drifts a bit it is not a big deal. We have set the 2.3l/min or 25mbar pressure drop as the upper limit in order to ensure that the measurement signal is not compromised. It can become noisy when the

flow is too high. As I said the drift behavior of the involved components still needs to be evaluated over a longer time period. **But there is another possible reason for the flow drift: Due to the vibrations the needle valve you readjusted could have moved. Therefore please ensure that the counternut is tight enough.**
Regarding the checks I requested: It would be good to carry out at least the one with the analog output, as described in the attached mail. I need to know if the Semtech reading is stable or not, because these data will be the "official" ones.

Thank you very much

From: Kent Johnson [mailto:kjohnson@cert.ucr.edu]
Sent: Wednesday, October 21, 2009 18:29
Subject: Update

I did the flow adjustment. Set the value from 2.4 to 1.94 and restarted the hardware and software. I am in "Pause" Mode and the flows went up to 1.94 then back to zero. I have no warnings or alarms.

The GFB system is ready but the Device State is still busy. It should go to ready mode in about 15 minutes. I'll let you know how it goes, but it seems to be working correctly now.

Summary of problem/solution:
The flow through the MSS drifted high (new design and not enough experience). When the MSS flow went past some threshold (2.3 lpm) then an alarm is set and this prevents operation (for good reason). The solution was to drop the flow and monitor this signal during startup. If it gets high document it and continue adjust if necessary.

Let me know if you have anything to add to the problem/solution statement.

I'll send an update when the system is "ready"

Kent C. Johnson
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###

Kent,
In Pause all values are ok (assuming that abs. pressure is 1013mbar), which means the pressure sensors are working correctly.
Does the error remain when you are in Zero check? As a matter of fact at this error the instrument switches to zero check when in user level 0. In level 2 it remains in measurement. Do you also get a flow warning? How big are relative pressure and differential pressure in Measurement? Does the error appear temporarily while the truck engine is running or always? Please forward the information to me in order to find out what it is. Please check if probably one of the yellow tygon tubings between GFB and MSS is pinched. Also make sure that the filter at the MSS front plate isn't clogged.
Regards

Sent: Tuesday, October 20, 2009 19:01
Subject: RE: Another Error at CeCert
Importance: High

Big correction from Kent. It is error 5, pressures out of limits. In pause abs press is 101.3, rel press 0.1 and DP zero.

Sent: Tuesday, October 20, 2009 12:24 PM
Subject: RE: Another Error at CeCert

That's an MSS error. It is the laser diode. Is there also error 7 and/or 8? If yes, is the absorber window still in the instrument? If not I can only advise to swap the MSS with another unit. It can be a connector problem (that's what it usually is), in that case we could instruct Kent how to fix it. I need to discuss that with our electronics expert tomorrow. So I would really recommend to proceed with the other MSS until we figure out what it is. The analog out needs to be adjusted in that case, like described in my previous mail.

Sent: Tuesday, October 20, 2009 18:09
Subject: Another Error at CeCert
Importance: High

Kent calls to report that he gets error code 4 repeatedly and the MSS1 will not sample.

Pls advise asap.

###
Hi Kent,
Sorry for bothering you again…
It is essential for us to know if the communication between the MSS and the Semtech is well established. Helmut did an adjustment of the MSS Analog signal during his visit. He told me you are aware of the adjustment procedure.
Since we know about the offset problems with the Semtech I recommend including a check into your daily startup procedure. Therefore please call the dialog box called Analog Output Calibration from the Service menu. Then automatically a zero point value is written to all analog channels. Open the Semtech service window were the voltage of the analog in is displayed and make sure it is reading zero on both channels. Then select the end point calibration in the dialog. The Semtech should read 10V then. If the values displayed by the Semtech are different then enter the displayed value in the dialog and click Set channel A (or B). For the communication we only use channels A and B of the MSS (concentration and dilution ratio), don't care about the others. If the difference is just a few mV it is not an issue. For this procedure you need to be in userlevel 2. It would be good to perform this check when the MEL is powered by the Generator as well (in order to find out if there is a difference between external power supply and generator).
I attached the MSS calibration manual. The analog out calibration is described in Chapter 8 (instead of a voltmeter you use the Semtech reading). If you need assistance with this procedure you may contact PJ Pankratz (Of course you may always contact me as well, but so the time delay is lower).
When you perform the test for the first time, please inform me about the result. Again, this is important for us to know. If it turns out not to be an issue and the voltage remains stable, then we can easily remove this procedure from the every-day-routine again.

Thank you very much!