Final Report

Development of a Portable In-Use Reference PM Measurement System

Contract No. 10-311

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Abstract

As particulate matter (PM) mass emissions continue to be reduced, there is increasing interest in the measurement of in-use PM mass with portable emissions measurement systems (PEMS). Unfortunately, the reliability of currently available PM PEMS is questionable, as comparisons to gravimetric reference methods have shown deviations often on the order of 100% and measurements are highly dependent on composition, particle size, and concentration. Real-time instruments are not necessarily faulty, rather their measurement principles do not correlate with the gravimetric method, and a combination of factors, such as size, shape, composition, and chemistry can contribute to a poor correlation. This report describes the development and evaluation of a high quality, multi-filter indexing gravimetric PM measurement system. The system is referred to as the PM PEMS (G) in this report. The PM PEMS (G) was designed for autonomous, all day in-use operation, for up to 30 gravimetric PM filter events in a single shift while following 40CFR Part 1066 and Part 1065 sampling specifications. The developed system was designed to quantify PM mass for in-use confirmatory testing on gasoline, alternative fuels, bio diesels, and diesel sources (on-highway, non-road, and marine) while utilizing the gravimetric reference method.

The system was evaluated in a laboratory and on-road with a heavy duty vehicle equipped with an exhaust bypass system where PM concentration, composition, and size distribution was varied. This PM source test article was developed during previous evaluations of other PM PEMS for the U.S. Environmental Protection Agency Measurement Allowance program and was fully characterized for its impact on its chemical and physical PM attributes. The bypass tool was also critical in the summary of conclusions identifying the limitation of most PM PEMS systems. The comparison between the University of California at Riverside's Mobile Emissions Laboratory (MEL) and the PM PEMS (G) was good and found to be on average within ±5% of the reference method from 129.7 mg/hp-h down to 3.6 mg/hp-h. Proportionality exceeded the specifications during not-to-exceed (NTE) operation and low power operation. Several tests did show high relative error between the MEL and PM PEMS (G) when using a flexible carbon containing silicon transfer line. These high relative errors were eliminated with a metallic transfer line. Results suggest that there may be some transfer line losses for sulfate PM. Additional testing is needed to characterize and quantify the impact flexible lines may have on in-use testing.

Acronyms and Abbreviations

AEI..Analytical Engineering, Inc.
ARB ....Air Resources Board
bs...brake specific
CARB...California Air Resources Board
CBD ....Central Business District
CFO...critical flow orifice
CFR ....Code of Federal Regulations
CRT...continuously regenerative trap
CO ....carbon monoxide
COV ....coefficient of variation
CO_2...carbon dioxide
CPM ....Continuous Particle Measurement
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
GVW ....gross vehicle weight (tractor + trailer + goods)
mg/hp-h...milligrams per brake horsepower hour
HDIUT ....heavy-duty in-use testing
Hp..break horse power as derived from ECM torque values
IO ....Input/Output
lpm ....liters per minute
MA ....Measurement Allowance
MASC ....Measurement Allowance Steering Committee
MDL..minimum detection limit
MEL ....UCR's Mobile Emissions Laboratory
MFC ....mass flow controller
MFM ....mass flow meter
MSS...micro soot sensor
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
PFD ....partial-flow dilution
PM...particulate matter
PMP...Particle Measurement Program
PN ....particle number
QCM ....quartz crystal microbalance
RPM...revolutions per minute
scfm...standard cubic feet per minute
SEE ....standard error estimate
SOF ....soluble organic fraction
SwRI ....Southwest Research Institute
TAC..Toxic Air Contaminant
THC..total hydrocarbons
TL...transfer line
UCR ....College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
UDDS...Urban Dynamometer Driving Schedule
ULSD ....ultralow sulfur diesel
WBW ....work based window

Executive Summary

Particulate matter (PM) is known to cause adverse health effects and a prominent source of PM is from diesel engines. PM from diesel engines is classified as a Toxic Air Contaminant (TAC) by the California Air Resources Board (ARB). ARB promulgated a Final Rule for 2007 and subsequent model year on-road heavy-duty diesel engines that included a 90 percent reduction in PM emissions compared to 2004 PM emissions standards. These PM emission reductions have been typically met with diesel particulate filters (DPFs) for on-road vehicles. However for Tier 4 non-road engines PM certification limits are slightly higher where manufacturers are meeting PM certification limits without the use of DPFs. Additionally, light duty vehicles are evolving where gasoline direct injected fueling strategies are growing due to improvements in fuel economy where PM emissions have been shown to vary from 10 mg/mi to 0.1 mg/mi. Future California PM regulations will limit these light duty emissions at 3 mg/mi in the short term and will ultimately limit these emissions to 1 mg/mi.

As PM mass emissions continue to be reduced, there is increasing interest in the measurement of in-use PM mass with portable emissions measurement systems (PEMS) to evaluate the effectiveness of regulations on protecting human health and for quantifying real world inventories. PM PEMS utilize real-time instruments for the characterization of PM. Unfortunately, the reliability of PM PEMS is questionable, as comparisons to gravimetric reference methods have shown deviations often on the order of 100% and that measurements are highly dependent on composition, particle size, and concentration. The University of California at Riverside (UCR) conducted a number of programs to evaluate the performance of PM PEMS as part of in association with the Measurement Allowance program. During these programs, research demonstrated that mass-based PM systems can show large biases and their operation can be unreliable. Correlations with the gravimetric reference have shown slopes ranging from 0.24 (Horiba PM PEMS) to 1.5 (Sensors QCM PM PEMS) and an R^2 ranging from 0.014 to 0.57, respectively (Durbin et al., 2009a,b; Johnson et al., 2010). Other instruments showed a much better correlation with slopes of 0.92 (AVL's Micro Soot Sensor (MSS) 483) and 0.91 (Dekati Mass Monitor 230) and an R^2 of 0.95 and 0.96, respectively (Durbin et al., 2009a,b and Johnson et al., 2010). Yet, when engines with lower fractions of soot in their particle composition were tested, the systems significantly underreported brake specific PM (bsPM), with the MSS slope dropping to 0.039 for a test using a high sulfate PM source and to 0.09 for a high organic type PM (Durbin et al., 2009b).

The effort of this research was to examine best practices from industry for gravimetric PM measurements and to combine these practices into a portable in-use gravimetric PM measurement system referred to as the PM PEMS (G). The PM PEMS (G) was designed to sample on 30 filters in an eight hour period triggered by time, work window, filter loading, or other desired conditions. The PM PEMS (G) was also designed to meet 40 CFR 1065, 1066, and ISO 16183 reference methods where practical for in-use testing. The PM PEMS (G) was originally designed to include a high volume sampler with a bypass-controlled flow system. As will be discussed in the results section, this approach resulted in instability and poor proportionality and mass correlation. The design was improved to include a mass flow controller (MFC) for the filter flow and an accurate venturi sample flow system. The filter MFC approach is more costly and slightly heavier, but provides the added control needed for proportionality. A

version of this improvement was tested during the on-road testing and favorable results were achieved.

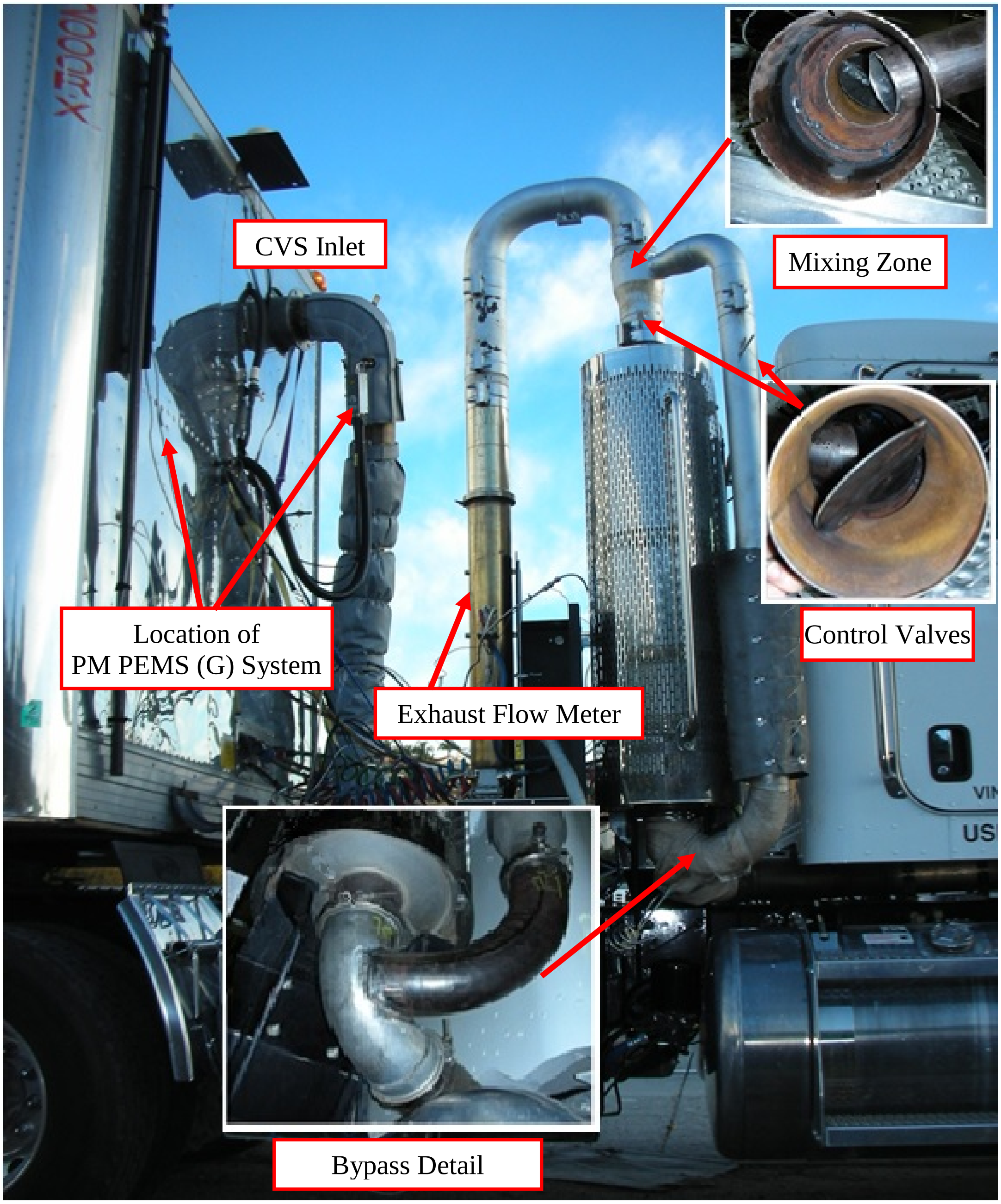


Figure ES-1 Test vehicle, bypass system, and PM PEMS (G) installation

The PM PEMS (G) was evaluated during laboratory and on-road testing utilizing emissions from a heavy duty vehicle equipped with a continuously regenerative trap (CRT) and a PM exhaust bypass system, see Figure ES-1. The CRT bypass system was designed where PM concentration, composition, and size distribution were varied. This system was characterized during previous evaluations of other PM PEMS for the U.S. Environmental Protection Agency Measurement Allowance program for its impact on the chemical and physical attributes of PM. This bypass tool was also critical in the summary of observations identifying the limitation of most PM PEMS systems and the need for a gravimetric correction filter as is common on all approved PM PEMS.

The multi-filter operation was successfully compared against UCR's Mobile Emissions Laboratory (MEL) during chassis and in-use on-road operation. The PM PEMS (G) was shown to be accurate, robust, and accurate as compared to the MEL. The PM PEMS (G) system met 1065 specifications for dilution ratio control, proportionality, filter face velocities, filter face temperatures. The on-road proportionality met the specification requirement of a <5% standard error estimate (SEE) at the maximum exhaust flow and typically met this SEE requirement for a mean exhaust flow for the revised system. The PM PEMS (G) system agreed well with the constant volume sampler (CVS) reference method with a slope of 1.016 and an R^2 of 0.9998 over a range of bsPM from 3 mg/hp-h up to 129.7 mg/hp-h, see Figure ES-2. The PM PEMS (G) system showed a poor comparison to the MEL for tests with high sustained exhaust temperatures with a CRT equipped engine, see Figure ES-3. The relative error was greatly minimized by the use of a metallic transfer line. It is believed the error may be from losses of sulfate forming species to the walls of the flexible transfer line. The high sulfate PM formation is typical of DPF regenerations found on most heavy duty diesel engines and thus the results is an important finding for in-use testing. Additional testing of the PM PEMS (G) with different transfer lines is needed for regenerating type PM to fully characterize and quantify the ability of the PM PEMS (G) to measure in-use PM emissions from modern diesel engines with aftertreatment. The PM PEMS (G) system was tested with a metallic line and this version agreed well with the MEL even for tests with sustained exhaust temperatures over 300˚C.

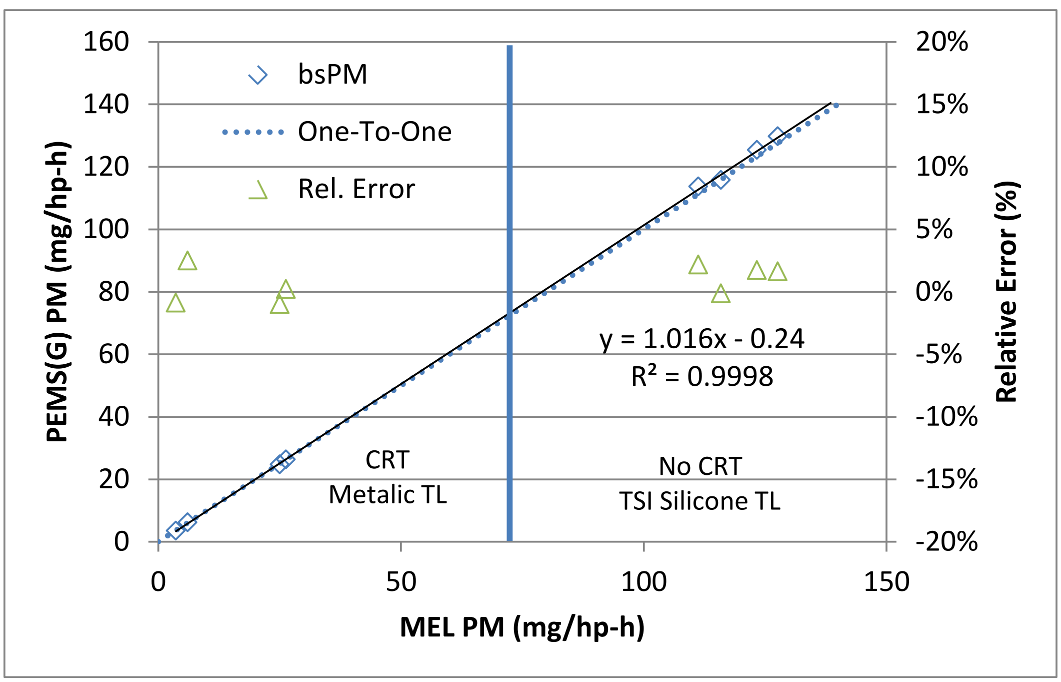


Figure ES-2 PM PEMS (G) Versions 2a and 2b final comparison with the MEL

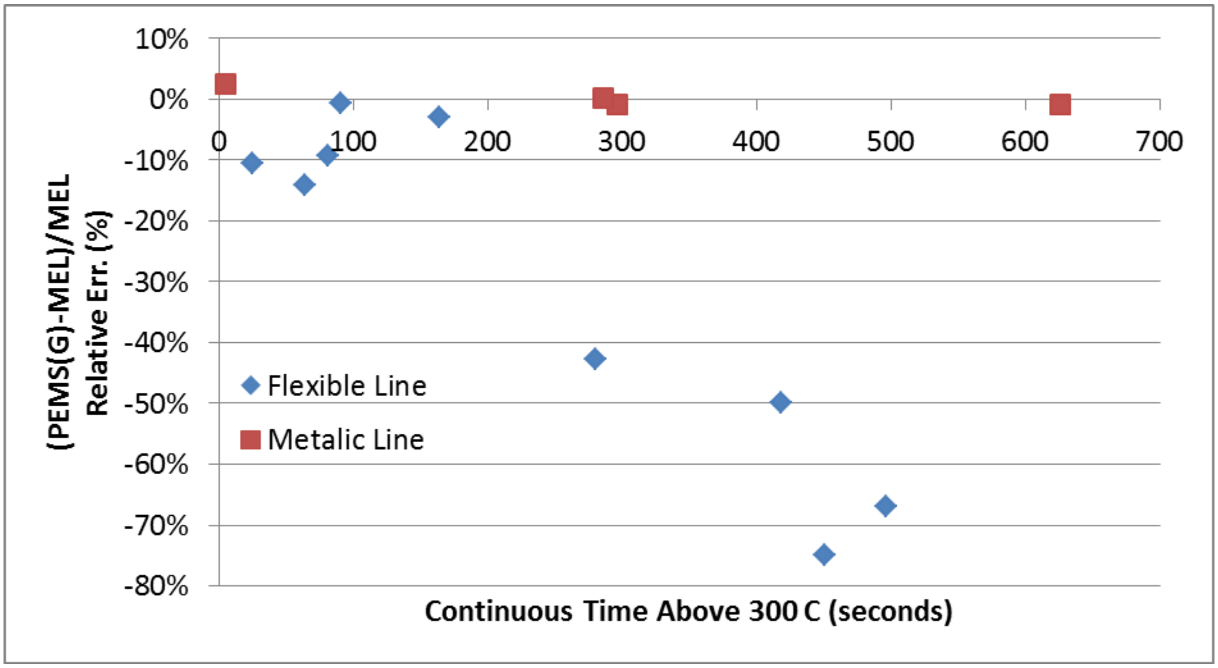


Figure ES-3 PM PEMS (G) Versions 2a and 2b deviation with CRT temperatures

The PM PEMS (G) system is robust and a unique tool for characterizing modern diesel engines. Additional research should be performed to evaluate the impact of possible PM losses from flexible transfer lines as reported in this study. The quantification of real-time PM emission factors from a surrogate of filter loading can be beneficial for in-use testing and may be more reliable than some real-time instruments that have demonstrated biases of up 100% at the current PM standard of 10 mg/hp-h. Additionally the PM PEMS (G) system will also be uniquely valuable for having numerous filter based samples from a day of testing that can be used for later laboratory analysis to help investigate unique events identified typically identified during post-test analysis. The PM PEMS (G) system is thus, a reliable, robust, and valuable in-use PM measurement system that will expand our understanding of PM emissions from in-use sources.

1 Introduction

Particulate matter (PM) is known to cause adverse health effects, and a prominent source of PM is from diesel engines. PM from diesel engines is classified as a Toxic Air Contaminant (TAC) by the California Air Resources Board (ARB). On-highway diesel engine regulations, implemented in 2007, required significant reductions in diesel PM, which led to the implementation of diesel particulate filters (DPF) on new diesel engines in this category. Non-road engines are also being regulated, and Tier 4 compliance may force DPFs to be used for some non-road applications. Additionally, light-duty vehicles are being subjected to new PM standards due, in part, to the expanding market of vehicles with equipped with gasoline direct injection engines.

As PM emissions continue to be reduced, there is increasing interest in the measurement of in-use PM mass with portable emissions measurement systems (PEMS). Unfortunately, the reliability of PM PEMS is questionable, as comparisons to gravimetric reference methods have shown deviations often on the order of 100% and that PM PEMS measurements are highly dependent on the particle composition, size, and concentration. Real-time instruments are not necessarily faulty, but rather their measurement principles do not necessarily correlate with the gravimetric method, due to a combination of factors, such as particle size, shape, composition, and chemistry.

Since 2005, the University of California at Riverside (UCR) has been evaluating the latest real-time mass-based PM measurement devices. The measurement allowance (MA) program, a program funded by the US Environmental Protection Agency (EPA), ARB, and the Engine Manufacturers Association (EMA). During these programs, research demonstrated that mass-based PM systems can show large biases and their operation can be unreliable. For example, the correlation between gravimetric PM filter measurements and PM measurements for one system evaluate in two different studies where the PM was primarily composed of soot ranged from 0.24 (Horiba PM PEMS) to 1.5 (Sensors QCM PM PEMS) and an R^2 ranging from 0.014 to 0.57, respectively (Durbin et al., 2009a,b; Johnson et al., 2010). Other instruments showed a much better correlation with slopes of 0.92 (AVL's Micro Soot Sensor (MSS) 483) and 0.91 (Dekati Mass Monitor 230) and an R^2 of 0.95 and 0.96, respectively (Durbin et al., 2009a,b and Johnson et al., 2010). Yet, when engines with lower fractions of soot in their particle composition were tested, the systems significantly underreported brake specific PM (bsPM), with the MSS slope dropping to 0.039 for a test using a high sulfate PM source and to 0.09 for a high organic type PM (Durbin et al., 2009b). The AVL PM PEMS upgraded their MSS system with a gravimetric calibration filter and a modeling element to estimate organic carbon and sulfate to allow for the determination of total PM from their soot measurement principle. Although this approach is promising, and has recently been approved by the EPA, it is not known how well it will perform with low soot, high soluble organic fraction (SOF) and/or high sulfate type PM, where the determination of the total PM is more dependent on the modeling calculation.

Other research has compared real-time PM mass measurement instruments with laboratory-based gravimetric reference methods (Durbin et al., 2007, Maricq et al., 2006, Kittleson et al., 2004, Lehmann et al., 2004, Podsiadlik et al., 2003, Witze et al., 2004, Bergmann et al., 2007, and Smallwood et al., 2001). While the studies have shown reasonably good correlations between PM gravimetric mass and real-time PM mass, the comparability of these two measurement methods over the range of conditions for which diesel PM forms (engine-out and DPF-equipped) is not well understood. Some studies show that assumptions used to convert from an instrument's measurement principle (whether absorbed energy, electrical mobility, inertial, light scattering, or aerodynamic properties) to PM mass do not hold constant for all PM combustion sources (Bergmann et al., 2007). Others in the scientific community suggest that the gravimetric filter reference method absorption artifacts could cause correlation differences (Lehmann et al., 2004).

The particle number measurement method is another PM measurement approach being considered by ARB. This includes the approach being used under the Particle Measurement Program (PMP). The approach measures particle number from a laboratory-constant volume sampler (CVS) after two additional stages of dilution and a volatile particle removing system. The benefit of the PM number method is improved sensitivity, as compared to the gravimetric method, but this method has been shown to have issues with repeatability (Johnson et al., 2009). In addition, the system is not designed for in-use conditions and may show similar repeatability problems in situations where sustained regenerations, failed catalyst controls systems, high SOF, high sulfur fuels, and other in-use PM conditions are possible.

Typical in-use PM investigations require a system that can measure PM as the particle size, shape, composition, concentration, and chemistry vary. These changes can occur at any moment and are usually the result of some event of interest. These events could not be quantified, if sampled on a single filter, because the PM emissions from all events over the collection period would be integrated together. Real-time instruments may respond to the event, but with varying levels of accuracy. Since the events are not known ahead of time, what would be needed is a system that could sample on a number of filters in one day. Typically in a day of in-use testing one would collect approximately 20 to 30 integrated measurement representing 20-minute durations or possibly 30 valid Not-To-Exceed (NTE) events. With real-time differential pressure measurements across the gravimetric filter, real-time PM emission rates can be estimated. These real time estimates may be sufficient to asses short 30 second NTE events. Additionally the gravimetric filters sampled during testing can then be sent to the laboratory for chemical analysis for PM speciation.

There are currently no PM measurement systems that quantify PM reliably, robustly, and consistently as it compares with the CVS reference method. The root cause of their inability to correlate with gravimetric measurements is tied directly to their measurement principle, as discussed. This suggests that a filter-based gravimetric PM PEMS (referred to as a PM PEMS (G) in this report) should correlate with the highest degree of consistency with the reference method since the measurement principles would be nearly identical with the only difference being the transfer line and proportionality control methods.

The Sierra BG3, AVL Smart Sampler, and Horiba partial flow systems do correlate well with the CVS gravimetric method, but their systems are neither portable nor practical for in-use measurements. Sensors and Control Sistem offer portable in-use gravimetric PM systems, but the Sensors Semtech Continuous Particulate Measurement (CPM) instrument utilizes low sample flows (a maximum of 15 liters per minute [lpm]) and achieves 100 cm/sec filter face velocities by reducing the stain area. High filter flows are desired for maximum filter weight gains during sampling intervals. The Control Sistem's approach (MICRO-PSS) meets the flow requirements of 100 cm/sec face velocity but utilizes only a single PM filter. Both the CPM and MICRO-PSS designs are compact and have low power consumption requirements, which is needed for in-use testing, but the single filter (MICRO-PSS) or three filter (CPM) systems limit the type of investigations and characterization that can be performed.

PM PEMS suppliers did develop a gravimetric based NTE in-use PM PEMS method possibly due to the short 30-second sampling times and the difficulty in managing a batched filter within 30 seconds. For measurements to characterize PM emissions during in-use operation, when it is not necessarily to meet NTE time requirements, a more general approach to sampling is recommended. The proposed PM PEMS (G) systems was designed to include real time pressure drop across the gravimetric filter to consider a surrogate for real time NTE PM event assessment. Preliminary analysis suggests filter pressure drop is sufficiently accurate to identify PM emission rats as low as 5 mg/hp-h. More testing and analysis is needed to validate this analysis.

The goal of the proposed work is to provide ARB with new tools to understand and characterize real, in-use behavior of PM emissions using a gravimetric method, with a focus on equivalence to the CVS reference method. The work focuses on providing PM measurement capability for in-use activity, such as on-highway, non-road, and marine, using measurement principles that follow 40 Code of Federal Regulations (CFR) 1065 gravimetric mass measurement methods, and using a proportional sample and a multi-filter, automatically indexing system. The system allows for the collection of multiple gravimetric filters/events, up to 30 filters, in a given testing session. The integration sampling window can be designed for NTE operations, a work-based window (WBW) approach, fixed time, total mass, and other approaches of interest to the ARB.

2 Background

2.1 Overview

This research emphasizes the ability to measure PM in-use over a variety of conditions representing different particle composition and size distributions. The focus of the PM measurement was based on the system's ability to correlate with a 40 CFR 1065 gravimetric CVS reference system. The reference methods were reviewed and a list of performance specifications is provided in Appendix A.

The intended uses for the gravimetric-based PM system are: in-use vehicle compliance, emissions inventory, and/or use with in-use, real-time PM measurement instruments. The system was designed to be flexible with open source software to allow for expansion, modifications, and updates as future needs arise. The system is capable of measuring using a WBW, fixed time sampling, or targeted filter loadings.

2.2 Design Approach

The PM system design was based on existing designs. Some designs of interest are AVL's remote diluter head, Sensors proportionality methodology, Control Sistem's filter flow variable pump controller, and the Cummins Inc. multi-filter auto indexing system. The University of California at Riverside's (UCR) Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) utilized design details and specifications from industry and created a cohesive sampler that is simple to operate, has low power requirements, and is light weight.

The uniqueness of the current gravimetric system—the ability to sample onto 30 filters in a given test day—allows the system the flexibility to be deployed for normal in-use operation, where the controller identifies sample windows and the indexer switches from filter to filter. UCR has been considering an automatic filtering system for years, but has not had success in finding a suitable design. Companies like MTL make robotic filter weighing systems for automatic filter weighing, but their indexing system is not compatible with in-use operations. Horiba offers an automated filter system for CVS laboratories, but this system is not portable and is very costly. Cummins Inc. operates a 30 cassette automated filter indexing system for their certification CVS laboratory. The system is sourced by Analytical Engineering, Inc. (AEI) and has worked successfully for many years. Cummins Inc. offered their design and contacts to help UCR duplicate the system. Other components (dilutors, proportional systems, and high volume samplers) have been around for several years and these approaches from different manufacturers were incorporated into the design. Thus, the indexing system provides the final step in completing the needed in-use proportional gravimetric system.

The proportional PM PEMS (G) system was designed around 40 CFR 1065.140 (7)(d) specifications for partial-flow dilution (PFD). Appendix A provides a list of relevant specifications. The main components were a close-coupled sample probe and integrated remote diluter, a proportional dilution system, a heated sample filter system (designed for approximately 30 cassette type filters), a sample pump, filter total flow metering system, an integrated embedded computer control system, a vehicle interface module, and a cooling system.

In general, the system samples a proportional amount of exhaust at targeted dilution ratios of 6 to 1 (defined at maximum exhaust flow). Maximum dilution ratios are based on the accuracy of the sample flow and are recommended to be less than 20 to 1 (at maximum exhaust flow). The dilution occurs close to the point where the exhaust is sampled to reduce particle loss in the transfer line. The system is designed around a 47 mm Teflo filter with the CFR-specified filter cassette holder and sample approach angles, screen sizes, and cassette geometry as per 40 CFR 1065.170. The use of smaller filters, such as the 37 mm filter, was considered, but smaller filter stain areas would limit the mass detection, so this approach was avoided. The total flow through the sample filter is quantified with an accurate mass flow meter that is integrated into the system. All power is managed internally so only a minimal amount of effort is necessary to operate the system.

The gravimetric system is designed to provide detection limits similar to laboratory reference systems, see specifications in Appendix D. The quantification limit of the CVS reference system is approximately 1 mg/hp-h, as evaluated on a DPF-equipped diesel engine. At 1 mg/hp-h, the gravimetric filter weight measurement is around 40 μg, with a 100 cc/sec face velocity, 38 mm stain area, and a dilution ratio of 6 to 1 at maximum exhaust flow. Lower filter flow rates such as used by others gravimetric PEMS would have the effect of reducing the filter mass in proportion to the flow which would make artifacts, contamination, and handling issues more significant at DPF-out conditions. The goal behind the measurement system, then, is to capture failures and high (relative to the standard) emitters. The system will be designed to minimize sensitivity with high flow capabilities of the laboratory reference system.

UCR is not a fabrication facility; therefore, all the systems utilized in this design were solicited from outside sources. AEI provided the filter indexer, the dilutor box was a modification from AVL's Micro Soot Sensors (MSS) 483 heated sample line, the high volume filter flow was obtained using a variable flow pump from Thomas Pumps (which has been proven by Control Sistem), the proportional flow system design was borrowed from Sensors Inc., and the valves and orifices were ordered from various manufacturers.

The functional operation and control of the system was based on an embedded control system. The proposed design was to use commercially embedded designed computers built on a platform that defined to stack up the needed peripheries, called PC104 stacks. The PC104 stacks, however, are no longer equipped with Lab View drivers and are not functional for embedded testing as they used to be. A new type of mini-embedded system with a Windows operating system was utilized. The embedded computer has integrated disk management, SD card capability, Wi-Fi, and other unique capabilities for data control and remote operation. Data acquisition was added to the system using popular USB interface systems.

One optional system that could be added is a cellular modem for remote operation, diagnostics, and test validation with control over a much wider distance available with Wi-Fi systems. Cellular modem control/operation has been performed by UCR on past projects, which include a 2009 Metrolink SCR verification study (Johnson 2009) and a 2002 LA Airport activity study (Miller et al 2002). Another consideration is low cost, line-of-sight radio frequency RS232 transmitters that have been used in the field with great success by UC Riverside during non-road emission testing (Miller et al 2007). Cellular applications are constantly changing and can be added at any time by ARB. The existing system does not come with the cellular package, as this would need to be negotiated and procured by ARB.

3 Design

In developing the design, UCR reviewed 40 CFR 1065 and ISO 16183 for proportional and PM sampling requirements to ensure the design meets laboratory testing specifications. A copy of the relevant requirements and specifications is provided in a summary table in Appendix A. UCR also reviewed several PEMS manuals by industry leaders, including Sensors, Horiba, and AVL. Cummins Inc., has also provided information on their proportionality and filter indexing system. Based on these reviews and discussions, UCR designed the PM PEMS (G) system.

The generic overview of the PM PEMS (G) is shown in the schematic provided in Figure 1. The figure highlights the major systems: remote dilutor, filter indexing system, variable dilution, low power filter controller, and a control system. The following subsections describe each of the major components in more detail.

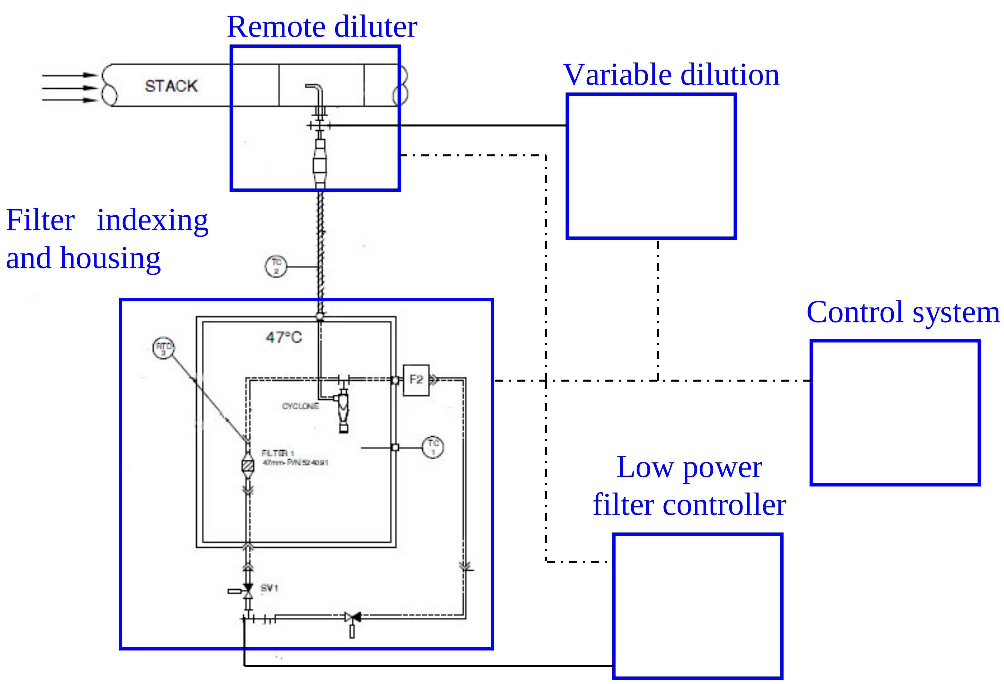


Figure 1 Schematic of PM PEMS (G) system critical components

Appendix B contains a list of the parts, materials and other hardware used for the development of the PM PEMS (G) system. These include a description of the filter indexing system, remote dilutor, sensors, heaters, control system with control valves, orifices, and other details of the integrated PM PEMS (G). The system was originally designed to include a high volume sampler with bypass controlled flow system. As will be discussed in the results section, this approach resulted in instability and poor proportionality and mass correlation. The design was improved to include a variable flow valve and a mass flow meter for control. This approach is more costly and slightly heavier, but provides the added control needed for proportionality.

3.1 Remote diluter and probe

To minimize thermophoretic losses and wall deposition, it is recommended that the exhaust be diluted at the exhaust stack. The remote diluter is designed to take a sample of exhaust from the tail pipe and dilute it. Images of the AVL system and cutaway views are provided in Figure 2 and Figure 3. AVL's remote diluter was utilized, which is compact and simple and includes axial sample dilution and mixing similar to a CVS. In addition, the probe, dilutor, and sample line are designed as per 40 CFR 1065 for residence time, temperature, and sampling techniques. The probe tip utilizes the reverse hat facing up stream sample methodology for particle pre-classification, as per 40 CFR 1065, see Appendix E for details.

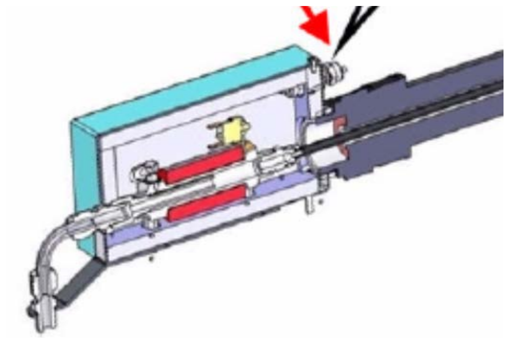


Figure 2 AVL's compact, lightweight remote dilutor and heating system (source AVL)

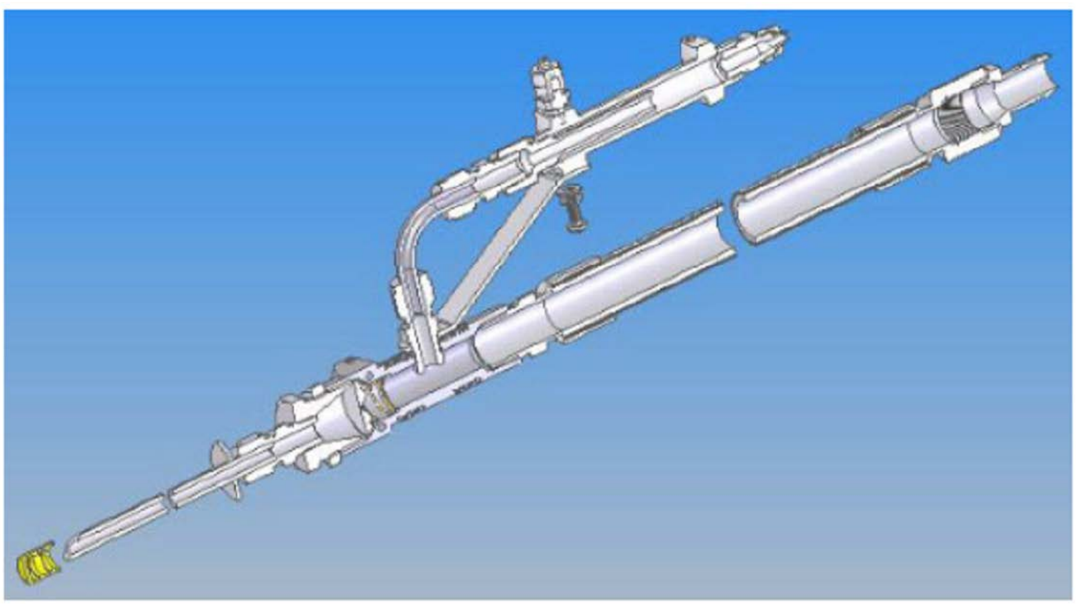


Figure 3 AVL's compact, lightweight probe heating system (source AVL)

3.2 Variable dilution

The ability to maintain proportionality – proportionality being the sample flow rate proportionally varying with the exhaust flow – is controlled by the variable dilution system. Proportional samplers have been around for several years, and Horiba, AVL, Sierra's BG3, Cummins Inc., and Sensors all utilize different approaches. From UCR's experience, Sensors' approach seems to have the fastest response time, meets the proportionality specifications, consumes the least amount of power, and is uniquely different from other approaches. Sensors' ability to maintain proportionality, as per 40 CFR 1065, was demonstrated during the Measurement Allowance (MA) study (Miller et al. 2007; Johnson et al. 2010), and suggests their approach is not only efficient, but accurate. The Sensors' approach utilizes fast-acting solenoid valves switched between different flow orifice combinations for fast control, and the controllers are low cost and fast-acting. Other approaches use mass flow controllers, but these are bulky, relatively slow responding, and require large supply pumps. Figure 4 shows a photo of the fast acting solenoid valve manifold with integrated orifices. These solenoid valves have a response time of 5 ms and were tested with a 10 ms control loop for verification. These valves met the needs and provide real time control using an exhaust flow signal, as will be shown in the results section. This system is designed with eight step changes and provides a flow control of less than a 0.5% fine step change at 50 lpm.

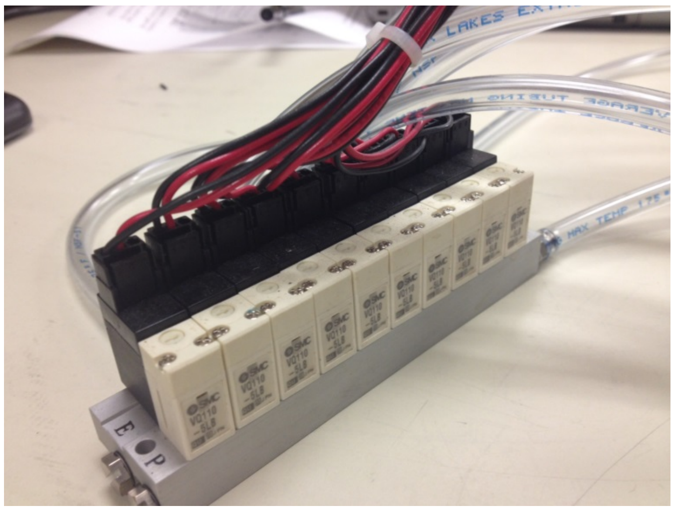


Figure 4 High speed micro valve proportional flow system

3.3 Multi-filter indexing system

The filter indexing system and housing are one of the unique aspects of UCR's design. The index system is designed around 40 CFR 1065 specifications as summarized in Appendix E. This includes the specifications on the filter holder (angles of approach, materials, cassettes), and temperature and residence time specifications. The design utilized a similar system purchased and operated by Cummins Inc. This system also includes the use of filter cassette separators and systems to prevent contamination between filters. The automated system consists of a tared column of filter cassettes, a motor indexing system, and a column for sampled filters, see Figure 5. As filters are used, they move from the tared column (canister A) to the sampled column (canister C). The design uses a small low power motor and pneumatics to open and close the filter holder automatically. The switching takes approximately 1-2 minutes and is not expected to be fast. A bypass flow is maintained at the filter holder inlet to minimize dead volumes. The system is also equipped with an infrared bar scanner that could be configured to identify the filter being used in real-time. Additionally, upgrades can be included to allow sampling on the same filter based on measured conditions.

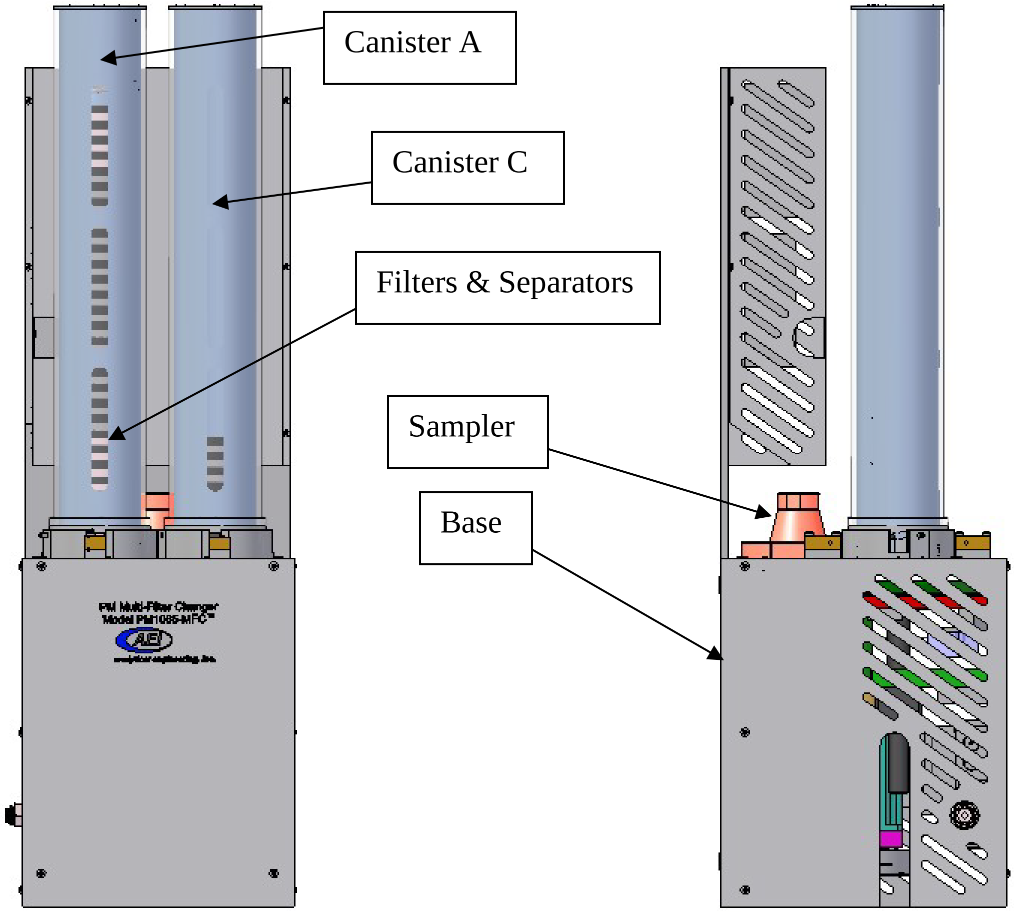


Figure 5 Filter indexing system (source ATI)

3.4 Low power filter controller

PM samplers often require the use of large pumps and mass flow controllers to pull high flows through available filter media, but this can make the systems bulky. To minimize weight, UCR originally tried to pull the flow directly through the filter utilizing control with a bypass flow. This system was denoted Version 1.0. As the pressure drop over the filter increased, due to PM mass loadings, the bypass flow would be reduced to maintain constant flow. The idea was that pressure drop through the filter could be overcome with a controlled bypass flow. The time it takes the filter to gain in mass is on the order of minutes per inHg pressure drop thus allowing time for a simple controller to maintain the stable flow. It was learned this approach was not going to work due to inaccuracies in the sample flow measurements and pressure pulsations from the vehicle exhaust. This approach was not utilized where the system was re-designed with a commercially available flow controller. Section 5 describes the details of the PM PEMS (G) version history.

Two additional approaches were then considered, conventional mass flow controller (MFC) or a variable flow controller pump with a mass flow meter (MFM). The first approach requires larger vacuum pumps and is bulkier, but easier to implement because it uses readily available off-the-shelf components. The second approach is lighter and more appropriate for in-use testing, but is not as commercially available as the MFC method. As the PM PEMS (G) was being developed, the variable flow valve from Thomas Pumps was discontinued, but a few units were still available. The required pump controller was not available, however. As such, the first option with the MFC was implemented. This system was denoted Version 1.1. A more detailed description of the variable flow pump method is still described in Appendix C, as this is a preferred method if a controller can be identified for the variable flow pump. The MFC option was originally implemented with a low cost Sierra MFC coupled with a TSI mass flow meter (MFM) for dilution flow measurement. This was subsequently replaced by high cost Red-Y smart series MFCs filter flow, a laminar flow element dilution flow meter, and a sample flow venturi meter in Version 2.0a & b of the PM PEMS (G) system.

The filter flow sampling system was designed around the Whatman filter, since this is the preferred Teflon filter for minimal artifact and tearing according to discussions with EPA during the PM PEMS and MA studies. Whatman filters are ideal for low PM concentration testing where artifacts need to be minimized. The Whatman filter has a thicker membrane and does not tear or have as many defects as the Pall filter. Although both filters are commonly used, there is a trend towards using the Whatman filter in the industry. Some tests were also performed with Pall filters to ensure adequate operation with both filters and to characterize pressure drop profiles for this filter. The Pall filters have low pressure drops while Whatman filter drops are much higher. If added capacity is needed, the lower pressure drop Pall filters could be used to prevent flow control issues when testing at high altitude or for high loading.

3.5 Control system

The control system was designed to accommodate Lab View and needed data acquisition and control (DAC) hardware. The controller hardware includes a keyboard, mouse, solid state hard drive, storage flash drive, DVI monitor support, Ethernet, wireless, and optional expansion for cellular and/or radio modem support. Additional DAC hardware was needed for sensor measurement. The DAC hardware included 16 digital input/output (IO), eight analog IO, and eight serial com ports. Figure 6 shows a picture of the embedded micro controller and DAC system that controls and operates the PM PEMS (G) system. The data acquisition hardware is based on measurement and computing popular USB interface systems. These USB interfaces are low cost, easy to expand, and are suitable for these measurements. The controller is configured with four USB ports where two of the ports are utilized and the others are available for expansion.

The embedded controller is stand-alone system where the data is locally stored during operation. Post-test analysis software was developed to process the data for later analysis. Copies of the data can be stored on servers for permanent backup. Data files are written to the disk in real time, thus if there is a power fluctuation or other problem during in-use testing, the data up to that point is saved on the embedded system's solid state flash drive.

Figure 6 Embedded micro controller and data acquisition interface hardware

3.6 Software

The software was developed around Lab View version 2011. Given UCR's in-house expertise with the Lab View and many existing programs, this was the software of choice. The software was provided as part of this report and is documented in the Appendix D and available for modification by ARB. The software is flexible, allowing for expansion and use in other ARB programs, as well as integration with other real-time measurement systems. Further documentation on the software is provided in Appendix D, Appendix E, and Appendix F.

3.7 Recommended operating procedures

Recommended operating procedures were developed during testing and evaluation of the PM PEMS (G) system. Procedures were developed for the Version 1.1 and 2a & b systems. These operating procedures are summarized the Appendix G.

4 Approach

The PM PEMS (G) system was evaluated for functionality, proportionality, and overall system accuracy. Functionality was evaluated based on the system's expected operational modes, which include self-triggering for event identification, duration sampling, managing filter flow rates, filter indexing, and other details. Sample proportionality was evaluated against 40 CFR 1065 methods for proportionality.

The accuracy evaluation was based on comparisons between the PM PEMS (G) and UCR's Mobile Emissions Laboratory (MEL) over a variety of different conditions. The MEL was validated as an accurate PM reference system during a previous successful comparison with Southwest Research Institute's (SwRI's) laboratory during the PM MA program (Johnson et al., 2010). The MEL showed agreement with SwRI at 10% for PM over three days of testing, where the coefficients of variation (COVs) for each lab showed precisions of a few percent. The MEL was used throughout the entire gaseous and PM MA programs and was found to be a reliable in-use mobile reference standard by regulatory agencies and industry.

The PM PEMS (G) was evaluated against the MEL on both UCR's chassis dynamometer and on the road during a number of different driving routes. The chassis dynamometer testing allowed the PM PEMS (G) to be evaluated in a controlled manner, where test conditions could be readily repeated. Once the system was ruggedized, it was evaluated against the MEL for in-use testing, where a wider range of operating conditions could be tested.

Another important element of this testing was the use of a bypass system. The bypass allowed the PM emission level and composition to be changed in a controlled manner, and hence allowed the PM PEMS (G) to be evaluated and verified under a wide range of testing conditions. A significant part of this study depended on the performance and characterization of the bypass system. As such, this section includes a detailed description of the bypass system design, setup, and regeneration influences. In addition, this section describes the details of the experimental approach which includes the test vehicle, fuel, emission measurements, and other UCR laboratories.

4.1 Vehicle

The test vehicle was UCR's in-house, 2000 model year Caterpillar C-15 14.6 liter engine equipped, Freightliner Class 8 Truck retrofitted with a PM aftertreatment system. This vehicle is certified to EPA 2000 model year standards, with a NO_x certification level of 3.7 g/hp-hr and a PM certification level of 0.08 g/hp-hr without a DPF. The DPF installed on this vehicle was a Johnson Matthey continuously regenerative trap (CRT) sized for engine displacements between 6 liters and 15 liters. The CRT was installed on the truck at the same location of the existing muffler. The CRT was utilized on previous projects that included 45 hours of use with a 14.7 liter CAT 3406C generator operated at steady state loads and during a two week in-use study on UCR's in house Caterpillar vehicle. The CRT has approximately 200 hours of use where only ARB ULSD fuel was used. The UCR truck had a mileage of approximately 44,500 miles during testing. For the in-use testing, the MEL trailer itself provided the load where the weight of the trailer including all emissions equipment and the tractor was 65,000 lbs.

4.2 Fuel

The truck was tested with commercially available ARB ULSD fuel, which should have a sulfur level of < 15 ppm. The engine uses typical on-highway lubricating oil from a local service center. The oil trade name is CAT DELO SAE 15W-40 which has a reported sulfated ash content of 1.35 wt. %. The engine has an oil consumption rate of approximately 1 gallon per 10,000 miles.

4.3 Bypass System

On a typical heavy duty diesel truck equipped with a PM-only ATS the exhaust travels from the engine through the ATS, which is composed of an oxidation catalyst and a PM filter, and then to the emissions measurement systems, see Figure 8. The bypass is added to route some of the exhaust around the ATS, but must manage the composition, heat, and flow mixing where a careful bypass design is needed, see details in red Figure 8. The bypass system design was utilized from previous EMA and MA funded programs (Durbin et al., 2009b and Johnson et al., 2010).

Bypassing only the DPF is difficult on production vehicles where several aftertreatment sensors are required for proper DPF soot management. The bypass system design used in this study incorporated a 4-inch bypass tube, an integrated bypass diesel oxidation catalyst (DOC), two control valves, and a mixing zone, see Figure 7 and Figure 8 (Johnson et al., 2010). The four-inch bypass tube was selected to allow sufficient flow with the valves in maximum open 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 and ensure fully distributed PM emissions at the PEMS and reference sample zones. Verification of the bypass mixing, and PM emission level repeatability and composition were established in a previous MA study, and was not repeated here (Johnson et al., 2010). Figure 7 shows the aftertreatment bypass installation on the test truck. Figure 7 also shows the sampling point for the PM PEMS (G), which is sampling raw exhaust between the stack and the MEL's CVS inlet. Note that the PM PEMS (G) system itself is housed inside of the MEL trailer with the rest of the CVS and emissions sampling equipment.

The bypass is generally designed to allow the normal functioning of the oxidation catalyst, but to allow the exhaust to bypass the particulate filter. Thus, the exhaust PM generated when using the bypass has volatile or organic portion of the PM largely removed, since the DOC will still remove this portion of the particles, while the soot, which is normally eliminated by the DPF, remains in the exhaust stream. Regenerations are still allowed to function naturally since these are a result of temperature dependent catalytic reactions on the surface of the CRT. It is expected at higher bypass conditions the CRT temperatures will be lower than during low bypass conditions at similar loads since the exhaust heat travels with the exhaust flow. This suggests at higher bypass conditions the CRT will perform less frequent regenerations compared to lower bypass conditions due to lower CRT temperatures. As such, it is expected that the sulfate contribution of PM will be least at high bypass conditions under similar load conditions.

The percentage of exhaust flow bypassing the CRT is a function of CRT pressure drop, soot loading, and varying velocities in the exhaust resulting from engine speed, load, and temperature. As such, simply adjusting the valves to different positions does not necessarily set the amount of exhaust flow that bypasses around the DPF. During previous in-use studies, UCR quantified that when the bypass is in the fully open position, approximately 50% of the engine out exhaust bypasses the DPF filter, and when in the fully closed position this reduces to approximately 1% (Durbin et al., 2009b and Johnson et al., 2010). During these studies markings were etched into the bypass valves sections to allow quick setup. Bypass 0 is the fully closed position (1%) and bypass 5 is in the fully open position (50%) and each mark in between represents about 10% of the exhaust flow. The remainder of this report utilizes the percent of exhaust bypassing the DPF. Thus, a 20% bypass indicates approximately 20% of the exhaust flow is bypassing the DPF.

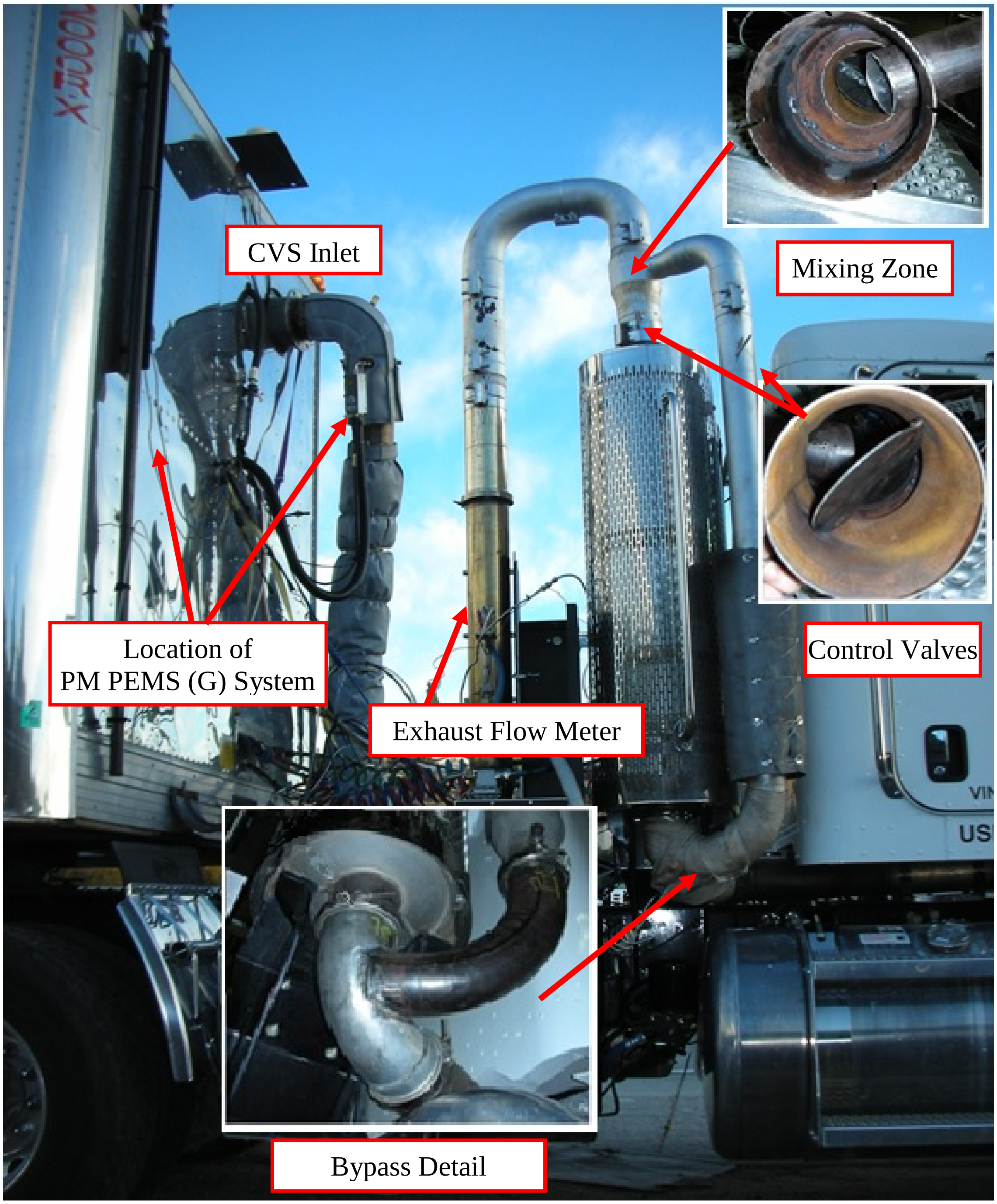


Figure 7 Bypass installation and PM PEMS (G) sampling point for the in-use testing

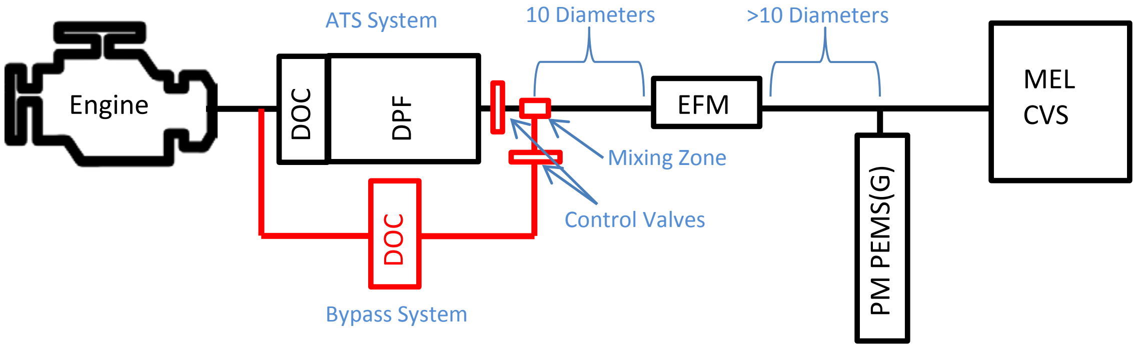


Figure 8 Bypass system and PM PEMS (G) sampling schematic for the in-use testing

The bypass system was designed to provide PM emission factors ranging from 0.005 g/hp-h (1% bypass) to 0.1 g/hp-h (50% bypass) where the actual emission factors depend on the type of driving conditions (i.e., transient vs steady state). During previous studies a fixed bypass setting of 25% produced an emission factor that ranged from 10 mg/hp-h to 60 mg/hp-h with an average of 25 mg/hp-h with-out the presences of regenerations. With filter regenerations the PM emission factor was shown to increase up to 0.15 g/hp-h (Johnson et al. 2010). The significantly higher PM emission factor from regenerations was suggested to be a result of sulfate PM formation across the CRT surfaces. It was also suggested in these studies that nucleation mode particles may be attributed to the conversion of SO_2 to SO_3, which is likely aided by the catalytic wash coat on the CRT. Because the aftertreatment system utilized in this study was a CRT, passive regenerations were expected to occur naturally. Previously it was shown passive regenerations with the utilized CRT occurred when the exhaust temperatures exceeded 300 C for extended periods of time (Johnson et al., 2009).

4.4 Reference laboratory MEL

The approach used for measuring the emissions from the test vehicle was to connect the exhaust from the diesel engine to UCR's MEL. The MEL was designed around the measurement methods of mass emission rates from heavy-duty diesel engines as specified in the CFR: Protection of the Environment, 40 CFR 1065. The MEL is designed and operated to meet those stringent specifications in a mobile platform making it a very unique laboratory. MEL was designed to be a comprehensive laboratory including many sub-systems as shown in the schematic in Figure 9. The accuracy of MEL was verified against ARB's and Southwest Research Institute's heavy-duty diesel laboratories during previous cross lab comparisons and was found to be in good agreement. The MEL routinely measures a wide range of speciated and PM emissions from diesel engines. Design capabilities and details of MEL were described in Cocker et al (2004). Instruments within MEL continuously measure emissions of NOx (NO and NO_2), CO, CO_2, and NMHC (THC and CH_4) with one-second resolution analyzers meeting 40 CFR 1065.

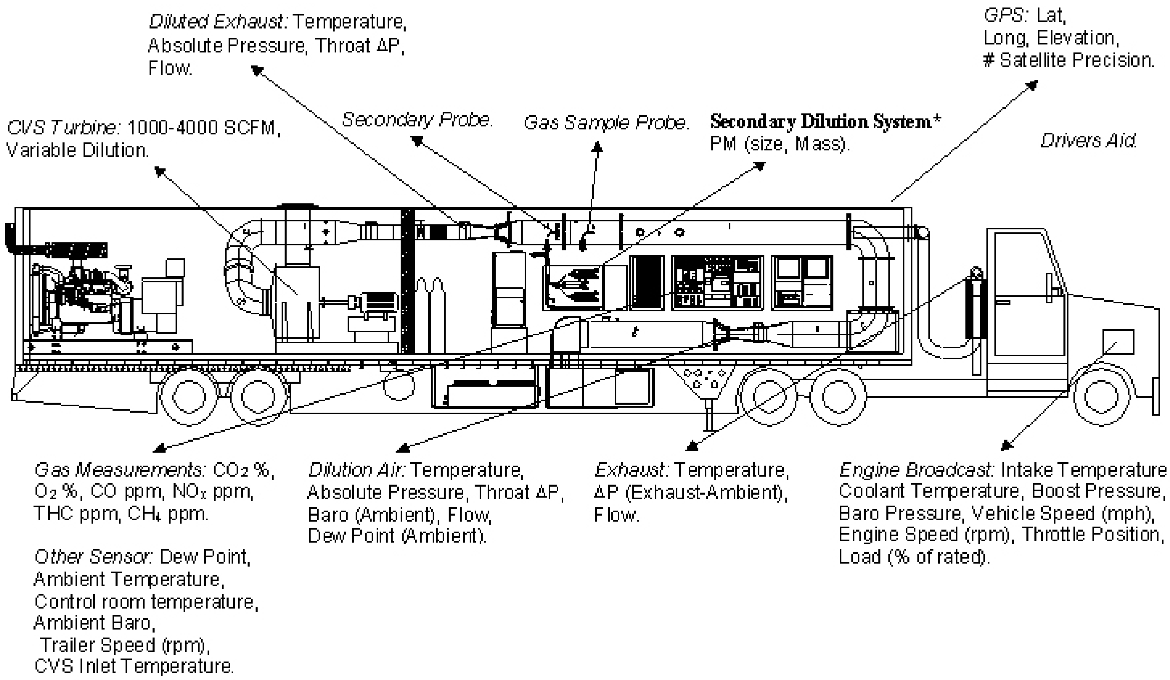


Figure 9 UCR's mobile emission laboratory (MEL)

4.5 PM measurements

For the gravimetric PM measurement systems, total $PM_{2.5}$ mass was collected using 47 mm polytetrafluoroethylene (PTFE) filters from Whatman and weighed with a 40 CFR 1065-compliant microbalance and conditioning facility. A minimum dilution ratio of 6 to 1 was used for both the MEL and the PEMS. The minimum dilution ratio of 6 to 1 was based on the measured maximum exhaust flow of 2.6 x 10^6 kg/hr (1100 scfm). The PM filter sampling conditions for the gravimetric methods were similar where the filter temperature was targeted to 47 °C with a face velocity of 100 cm/s, and a dilution air temperature of 25 °C was used, as per 40 CFR 1065.

In addition to the gravimetric PM measurements (MEL and the PM PEMS (G)), a real-time Dekati Mass Monitor (DMM) was also used. The DMM is a real time PM instrument that utilizes electrometers and aerodynamic impactions for its measurements. The DMM was attached to the MEL CVS. A 40 CFR 1065 approved, AVL PM PEMS 494 system with constant dilution PM filter loading was also attached to the raw exhaust during the Version 1.0 and 1.1 chassis testing, as discussed in Section 6. The AVL PM PEMS 494 system data was not analyzed as part of this report due to the complexities in the test setup, presented issues, and data processing of the other systems discussed in Section 6, however.

4.6 Pre-test

Prior to emissions testing, the PM PEMS (G) system was set up to perform operational checks, such as exhaust flow proportionality, event identification, and valve switching. Proportionality was confirmed with simulated exhaust flow programming controls. The valve switching and event identification checks were performed with simulated exhaust flow and engine control module (ECM) signals. After successfully triggering from simulated exhaust flow, but before testing the system during emissions testing, quick snap and idle tests were performed with measured signals. These tests included the use of a real exhaust flow meter and exhaust flow from a class 8 tractor. The system was able to track the measured exhaust flow well and meet the proportionality specifications of 40 CFR 1065. The next step to testing was setting up the bypass at a desired emission level and then performing emission testing.

4.7 Chassis dynamometer testing

UCR's chassis dynamometer is an electric AC type design that can simulate inertia loads from 10,000 lb. to 80,000 lb. which covers a broad range of in-use medium and heavy-duty vehicles. The design incorporates 48" rolls, axial loading to prevent tire slippage, 45,000 lb base inertial plus two large AC drive for achieving a range of inertias. The dynamometer has the capability to absorb accelerations and decelerations up to 6 mph/sec and handle wheel loads up to 600 hp at 70 mph. The chassis dynamometer was designed to accurately perform the ARB 4 mode cycle, urban dynamometer driving schedule (UDDS), refuse drive schedule, bus cycles such as the central business district (CBD) cycle, as well as any speed vs. time trace that does not exceed the acceleration and deceleration rates. The load measurement uncertainty was 0.05% of full scale and had a response time of less than 100 ms which is necessary for repeatable and accurate transient testing. The speed accuracy of the rolls is ± 0.01 mph and had acceleration uncertainty of ± 0.02 mph/sec.

The chassis dynamometer laboratory testing involved repeats of the standard UDDS driving cycle and a high load steady state cruise cycles to characterize the repeatability and accuracy of the PM system relative to the MEL. The UDDS is a transient test cycle with a short cruise section, and hence exercises both the test vehicle and the PM PEMS (G) system over a fairly wide range of operation. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph and a maximum speed of 58 mph over 1060 seconds. The results from the UDDS cycle provide the PM PEMS (G) ability to compare with the MEL during certification like cycles. For the chassis testing the gross vehicle weights (GVW) used were 58,000 lbs and 28,000 lbs. The 58,000 lbs was designed to simulate a loaded vehicle and the 28,000 lbs was used to simulate an empty tractor trailer.

4.8 In-use on-road

The in-use, on-road testing utilized various routes similar to those designed during the MA test program. This included some routes used in the gas-phase MA program (Miller et al., 2007, 2008) and others used for the PM MA test program (Durbin et al., 2009 and Johnson et al., 2010). The routes were designed to provide differing environmental conditions, elevations, humidity, and ambient temperatures, but at the same time to be conducive to operation in the NTE-zone or applicable to WBW operation. The routes include scale visits, rural driving, and urban driving where traffic congestion can be experienced. The routes included a trip within Riverside and a trip towards San Diego, CA. The on-road, flow-of-traffic tests provided a comparison between the MEL and PM PEMS (G) during real world on-road conditions.

5 Revision Chronology

During the development and testing of the PM PEMS (G) system there were changes made to improve its accuracy. The PM PEMS (G) system went through three major revisions denoted Version 1.0, 1.1, and 2.0 and one minor final revision on Version 2.0, denoted as Version 2.0a and 2.0b. This section describes that chronology and assists with the interpretation of the tests results presented in Sections 6, 7, and 8. Each of the test sequences described in the Sections 6, 7, and 8 represented a unique set of conditions where the description of the tests is provided in the results sections for each of the different testing campaigns. A summary of the PM PEMS (G) versions and the associated testing is provided in Table 1. Versions 1.0 and 1.1 were used during three days of chassis dynamometer testing presented in Section 6. For this testing, varying PM emission levels and compositions were used to characterize the repeatability of the system. Version 2.0a was used during two days of on-road tests with the CRT over various on-road routes designed to capture varying PM emission levels and composition, as presented in Section 7. Two additional days of chassis testing (Section 8) were added to the research program to evaluate pre-DPF vehicles emitting above 0.1 mg/hp-h, and to evaluate a metallic transfer line during passive regeneration events with the CRT re-installed. The first set of tests described in Section 8 were with Version 2.0a with the CRT removed to prevent regeneration PM influences. The final tests were with the CRT reinstalled, but with a metallic transfer line, denoted as Version 2.0b.

5.1 Version 1.0

During emissions comparison testing it was found the PM PEMS (G) flow meter systems utilized were not suitable for proper sample flow, total flow, and dilution calculations. The Version 1.0 system included two TSI MFM for dilute and total flow measurements with a bypass control system design maintain constant flow through the filter. The bypass control valve was to control a minor vacuum trim flow while maintaining a constant filter flow. Issues with exhaust flow pulsations caused the system to not be stable, controllable, or reliable. The bypass trim flow was considered to minimize power by using a smaller vacuum pump as compared to the MFC method. Due to the poor performance, the PM PEMS (G) system was upgraded with a MFC filter flow system and was called Version 1.1. Version 1.0 was utilized for tests 1, 2, and 3, as presented in Section 6.

5.2 Version 1.1

Version 1.1 utilized an upgraded flow control system which included a low cost Sierra MFC, a filter flow TSI thermal mass flow meter, and a TSI MFM for the dilution flow. Unfortunately the TSI flow meters were not suitable for pressure and temperature drift operation as reported by their drift specifications, see Appendix J. During testing the filter MFM was subjected to a pressure difference of 5 inHg pressure change and a temperature change between 20 and 47°C depending on bypass or filter loading conditions. At these conditions, the MFM could report a 5-10% error which could cause a greater than 100% error in the proportionality and dilution ration calculations thus causing for a poor comparison with the MEL. The results from Version 1.1 PM PEMS (G) are presented in Section 6 with corrections made where possible for the actual temperature and pressure of the measured flows. Version 1.1 was utilized for tests 4-13 as presented in Section 6.

5.3 Version 2.0a

Version 2.0 utilized improved flow measurement for proper proportionality and total mass calculation. Specifically, this included the use of an accurate high end for the filter control and measurement and a laminar flow element dilution flow meter made by Alicat. The filter flow and dilution flow represented the best available measurement technologies with least drift specifications see Appendix J.

The results from Version 2.0a are presented in Section 7 and part of Section 8. The proportionality was found to be with-in specifications of the CFR and was well behaved. Unfortunately the PM mass comparison was poor for some points. After further investigation the large relative errors were found to coincide with high sustained exhaust temperatures, see Section 7.5.2. The discussion in Section 7 suggests the cause of the poor comparison for some test points may due to issues with regenerations and sulfate PM loss in the carbon impregnated TSI silicone tubing. The CRT was removed to demonstrate the PM PEMS (G) system could reliably measure PM on transient tests without the sulfate PM source. The tests with the CRT removed are discussed in first part of Section 8.

5.4 Version 2.0b

This version of the PM PEMS (G) system implemented a metallic transfer line to compare how the flexible TSI tubing performs compared to the metallic transfer line during passive regenerations. For Version 2.0b only the metallic transfer line was different where no other changes were implemented. Version 2.0b was only utilized on the final chassis testing and no on-road testing was performed as presented in Section 8.

Table 1 Summary of the PM PEMS (G) Version Designs

Version #	Version Description	Results Section
1.0	Two TSI MFM for dilute and total flow measurements with bypass control system design to maintain constant flow	6
1.1	Upgraded flow control system with a low cost Sierra MFC, a filter flow TSI thermal MFM, and a TSI MFM for dilution flow	6
2.0a	Upgraded flow control system with Red-Y smart series MFCs for the trim flow, a laminar flow element dilution flow meter, and a sample flow venturi meter	7 & 8
2.0b	Same as Version 2.0a with a metallic transfer line	8

6 Results: Chassis Version 1.0 and 1.1

An initial series of transient and steady state cruise tests were performed on the PM PEMS (G) system prior to the arrival of the filter indexer. The goal of these tests was to evaluate the ability of the PM PEMS (G) to sample proportionally and to quantify mass under 40 CFR 1065 conditions.

6.1 Test matrix

Table 2 lists the comparison tests performed on Version 1.0 and 1.1 of the PM PEMS (G) system. The 16 test points took four days to complete and represented approximately three testing days. The first three tests (denoted A, B, and C) were used to configure the setting of the bypass system for 30 mg/hp-h (using real time PM instruments), tuning the proportionality system over the UDDS cycle, evaluating the triggering of the PM systems, and evaluating the temperature controls of the PM PEMS (G) system. The next three tests (denoted 1-3) were comparisons tests between the MEL and PM PEMS (G) Version 1.0 system. The remaining 10 tests (denoted 4-13) were evaluated using the MFC based Version 1.1 system. A more detailed discussion of the PEMS versions can be found in Section 5.

The UDDS tests 1, 2, and 3 showed large variability in the filter flow, as described in the Issues and Resolution section, and poor performance of the partial flow system and PM comparison. These tests were thus not considered in the overall average analysis since the PM PEMS (G) system was modified from this early Version 1.0. The steady state test #7 was also not included in the analysis due to an overheated PM PEMS (G) filter that exceeded 65 °C in average temperature. As such, the results presented in this section are limited to Tests 4 – 6 and 8-13.

The bypass setting of 40% was found to have a fairly high PM emission level exceeding 30 mg/hp-h as determined during real-time assessments of the DMM instruments. Low emission rates were desired to demonstrate the ability for the PEMS to compare well with the MEL where PM composition was less than 90% EC as determined during previous testing with the same bypass. Additionally high emission rates were avoided to prevent filter overloading during sampling with this early version of the PEMS system. During later testing with Version 2.0a the PEMS successfully compared with the MEL at an emission level of 130 mg/hp-h, see Section 8. A setting of 20% was determined to yield a MEL UDDS emission level of approximately 30 mg/hp-h as desired for this phase of the test program. The 30 mg/hp-h at 20% bypass setting is slightly higher than during previous studies which may be a result of the relatively low power UDDS cycle compared to on-road testing. The 20% bypass setting was utilized for the majority of the testing in this study.

The results presented in this section are based on transient and steady state testing with both a moderate emission level (bypass setting of 20%) and then steady state testing with a low emission level (bypass setting of 1%). The bypass setting of 20% is expected to produce mostly elemental carbon (EC) soot, with about 80% EC, 10% organic carbon (OC), and 10% Sulfate (Johnson et al 2010). The 1% bypass setting is the bypass being closed to represent a near zero PM emissions source. The 1% bypass setting is expected to produce a PM composition of mostly sulfate at 50% sulfate, 30% EC and 20% OC (Johnson et al 2010).

Table 2 Testing performed on PM gravimetric system

Test ID	Test cycle	Bypass Setting	Configuration Versions	Ver. #	Est. PM EF (mg/hp-h)	Est. PM composition (EC/OC/Sul)
A	UDDS	40%	System configs [1]		80	90/5/5
B	UDDS	30%	System configs [1]		60	90/5/5
C	UDDS	20%	System configs [1]		30	80/10/10
1	UDDS	20%	Bypass control [3]	1.0	30	80/10/10
2	UDDS	20%	Bypass control [3]	1.0	30	80/10/10
3	UDDS	20%	Bypass control [3]	1.0	30	80/10/10
4	UDDS	20%	MFC control	1.1	30	80/10/10
5	UDDS	20%	MFC control	1.1	30	80/10/10
6	UDDS	20%	MFC control	1.1	30	80/10/10
7 [4]	SS_2% Grade [2]	20%	MFC control	1.1	20	80/10/10
8	SS_2% Grade [2]	20%	MFC control	1.1	20	80/10/10
9	SS_2% Grade [2]	20%	MFC control	1.1	20	80/10/10
10	SS_2% Grade [2]	20%	MFC control	1.1	20	80/10/10
11	SS_2% Grade [2]	1%	MFC control	1.1	5	30/20/50
12	SS_2% Grade [2]	1%	MFC control	1.1	5	30/20/50
13	SS_2% Grade [2]	1%	MFC control	1.1	5	30/20/50

[1] The system was configured on the first three tests which involved proper proportional control setting of the sampling valves and flow calibrations. It also involved setting up the bypass flow percentage based on DMM readings to get close to 40 mg/hp-h over the transient UDDS test cycle.
[2] The SS_2% Grade cycle was a cruise cycle designed to produce enough heat to create sulfuric acid regeneration from the CRT. Past experience showed this happened at 70% load and > 310 ºC at the CRT inlet (Johnson et al 2009).
[3] The "bypass control" design utilized a bypass valve for the control of flow through the filter (Version 1.0). This option was considered in order to minimize power by using a smaller vacuum pump as compared to the MFC method. It was quickly discovered proportionality was not possible with a bypass control valve thus requiring a MFC (Version 1).
[4] Test #7 was invalid due to high filter temperatures and is not included in the analysis.

6.2 PM emissions

This section describes the comparison of the brake specific (bs)PM emissions between the MEL, PM PEMS (G), and the DMM. This section is subdivided into two sections 1) averaged and 2) individual results. The averaged results are compared for bsPM, dilution ratio, and filter weight gain. The individual results are presented for the bsPM percent change between the MEL and PEMS, filter temperature comparison, and flow variability differences between the MEL and the PEMS.

6.2.1 Averaged results

The averaged corrected bsPM results are presented in Table 3 and Figure 10. The error bars represent single standard deviations of triplicate measurements for each category. The UDDS and some SS_2% (2% grade) test points were sampled with the bypass in the flow setting of 20%, while other SS test points were sampled with the bypass setting was closed (1%). The partial flow PM PEMS (G)'s bsPM was higher than the MEL for all the categories tested, this includes both the steady state and transient testing and for the 20% and 1% bypass settings. The PM PEMS (G) was approximately 15% higher than the MEL for all the tests and ranged from 12 to 17%. The PM PEMS (G) showed a relatively similar bias of 13% at the zero bypass condition.

The DMM real-time measurements were well below both the MEL and the PEMS for all the tests which is typical for this instrument at UCR (Durbin et al. 2009a; Johnson et al., 2010). The differences between the DMM instrument and the MEL and PM PEMS (G) were largest for the zero bypass condition where non-soot related PM may dominate the total PM mass. During regeneration testing (sulfate dominated PM) the DMM showed a gravimetric PM correlation with a slope of 0.2 previously (Kahn et al 2012) which agrees with the results for BP1%.

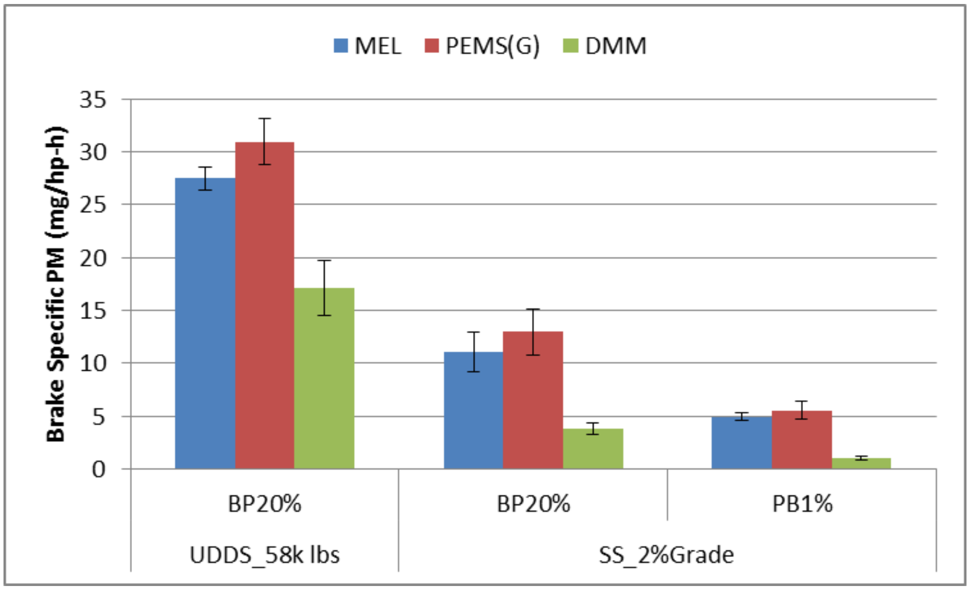


Figure 10. Average bsPM emissions for the MEL, PM PEMS (G), and DMM

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible. The 58k indicates the vehicle's GVW used for the study was 58,000 lbs.

The MEL's PM emission rate for the three UDDS transient tests with a bypass setting of 20% averaged 27.5 ± 1.1 mg/hp-h at one standard deviation with a range from 28.6 to 26.4 mg/hp-h, see Table 3 and Figure 10. The coefficient of variation was low for the UDDS transient tests and averaged 4%. These results agree well with previous studies with the same bypass system and a bypass setting of 20%. The MEL PM emission rate dropped from 27.5 mg/hp-h for the transient tests to 11.1 mg/hp-h for the steady state tests at the same 20% bypass setting. Higher PM emissions were expected for transient tests due to lower loads and more transient fuel injection conditions. The bypass setting of 1% produced the lowest emission results and averaged 4.9 ± 0.4 mg/hp-h for the MEL.

Table 3 Summary of brake specific PM for the MEL and PM PEMS (G) mg/hp-h

Cycle	Bypass	MEL		PEMS(G)	
		ave	stdev	ave	stdev
UDDS_58k lbs	BP20%	27.5	1.1	31.0	2.2
SS_2%Grade	BP20%	11.1	1.8	13.0	2.1
SS_2%Grade	PB1%	4.9	0.4	5.5	0.9

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible. The 58k lbs is 58,000 lbs which is the vehicle's GVW tested on the chassis dyno.

Table 4 and Figure 11 show the filter weight gain for the MEL and PM PEMS (G) filters. The average UDDS filter weight gain was 0.175 mg ± 0.006 mg for the MEL and 0.284 ± 0.005 mg. The MEL filter weight was highest for the steady state tests at the 20% bypass setting and lowest for the steady state testing at the 1% bypass setting. The PM PEMS (G) had the highest filter weight gain for the UDDS transient test. This appears to be a result of low dilution ratio (DR) conditions as discussed below. The standard deviation of filter weights for the MEL and PM PEMS (G) were similar for each test group where the error bars were lowest for the transient tests and highest for the steady state tests, as indicated by the error bars. The larger filter weight variability for the steady state test compared to the transient test may be a result of vehicle test-to-test variability (possibly from passive regenerations) and not measurement variability.

Table 4 Summary of filter weights for the MEL and PM PEMS (G) mg

Cycle	Bypass	MEL		PEMS(G)	
		ave	stdev	ave	stdev
UDDS_58k lbs	BP20%	0.175	0.006	0.284	0.005
SS_2%Grade	BP20%	0.227	0.044	0.186	0.019
SS_2%Grade	PB1%	0.100	0.009	0.164	0.027

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible. The 58k lbs is 58,000 lbs which is the vehicle's GVW tested on the chassis dyno.

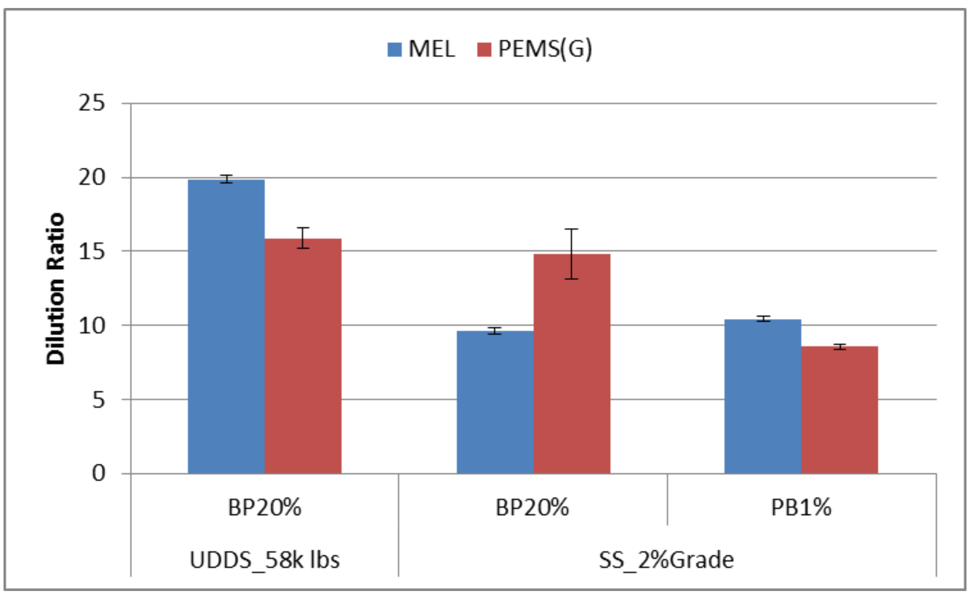


Figure 11 Average filter weights for the PM PEMS (G) and the MEL

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible. The 58k lbs is 58,000 lbs which is the vehicle's GVW tested on the chassis dyno.

Figure 12 shows the comparison between the PEMS and the MEL overall average dilution ratio. The dilution ratio of the MEL was relatively similar for both steady state tests and higher for the transient test, see Figure 12. The higher DR for the transient test is expected because the average exhaust flow is lower compared to the steady state tests. The PM PEMS (G) DR was lower relative to the MEL for the UDDS test and higher relative to the MEL for the first cruise test. The final DR for the final steady state test was the just slightly lower. The improved Version

2.0a system showed a more similar dilution ratio between the MEL and the PEMS for steady state and transient tests as discussed in Section 7. The poor comparison for the dilution ratio in this section may be a result of the issues with flow measurement in Versions 1.1 as discussed in Section 6.5.

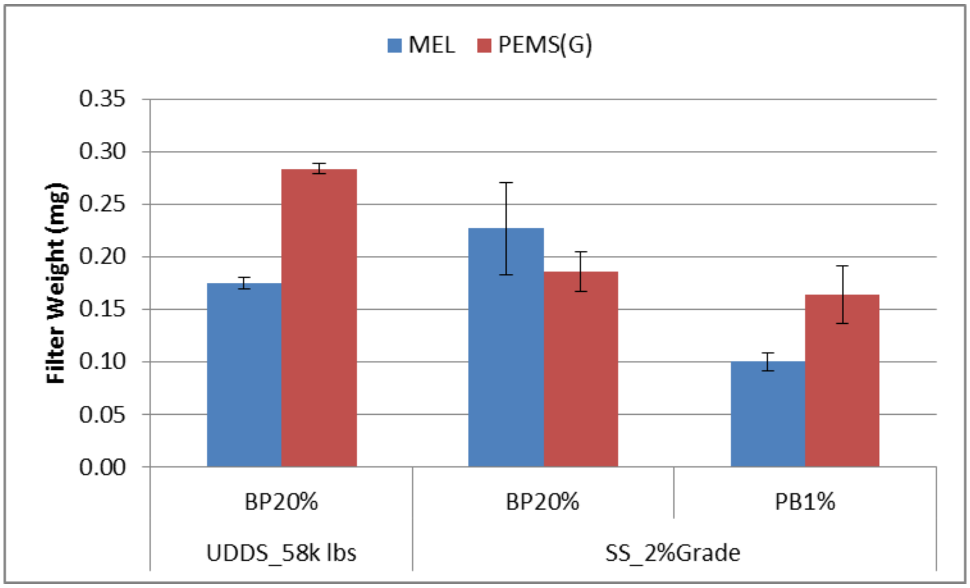


Figure 12 Average dilution ratio for the PM PEMS (G) and the MEL

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible.

6.2.2 Individual results

Table 5 lists the individual bsPM emission results for the PM PEMS (G) and the MEL systems and Figure 13 shows the individual bsPM relative error (PM PEMS (G)-MEL)/MEL. The first three UDDS tests (Tests 1, 2, and 3 in Table 5) show a very large positive relative bsPM error ranging from 35% to 50%. Tests 1, 2, and 3 were not included in the averages presented in the previous section. Tests 1-3 showed poor proportionality where a deeper analysis showed these tests had poor filter flow stability. Figure 14 and Figure 15 show the filter flow standard deviation during the sample period for each individual test. The filter flow instability was around 10 slpm for the first three tests (Tests 1, 2, and 3) and less than 0.2 slpm for the remaining tests. The MEL filter flow standard deviation was much lower at 0.05 slpm.

Test #7, a steady state test, showed a large negative bias, see Figure 13 where filter face temperatures were found to be high. Figure 16 shows the filter temperatures for each test point. Test #7 showed an average integrated PM PEMS (G) filter temperature of more than 65 °C. The other tests showed the PM PEMS (G) and MEL filter temperatures were mostly between 50 and 45. The steady state cycles subjected the engine to significantly higher loads compared to the UDDS (>250 hp vs 73 hp) where the exhaust temperature may have caused the filter temperatures to be over heated. The temperature controller was reconfigured for the higher exhaust temperatures of the steady state tests to prevent the excessive filter temperature on subsequent tests.

Table 5 Individual test results for the chassis Version 1.0 and 1.1 PM PEMS (G) system

Test #	Version #	Cycle n/a	Bypass Setting	Power hp	Work hp-h	Filter Weight (mg) MEL	Filter Weight (mg) PEMS(G)	bsPM (mg/hp-h) MEL	bsPM (mg/hp-h) PEMS(G)	Rel Error %
1	1.0	UDDS58k	BP20%	71.9	21.2	0.190	0.308	30.4	40.9	35%
2	1.0	UDDS58k	BP20%	71.3	21.0	0.166	0.299	26.8	40.1	50%
3	1.0	UDDS58k	BP20%	75.0	22.1	0.186	0.324	28.5	41.3	45%
4	1.1	UDDS58k	BP20%	72.9	21.5	0.181	0.285	28.6	31.3	9%
5	1.1	UDDS58k	BP20%	73.9	21.8	0.170	0.279	26.4	28.6	8%
6	1.1	UDDS58k	BP20%	73.0	21.5	0.175	0.288	27.5	33.1	20%
7	1.1	SS_2%Grade	BP20%	288.5	67.7	0.269	0.170	13.5	12.1	-10%
8	1.1	SS_2%Grade	BP20%	326.7	71.5	0.269	0.203	12.8	15.4	20%
9	1.1	SS_2%Grade	BP20%	290.1	69.1	0.230	0.190	11.3	12.1	7%
10	1.1	SS_2%Grade	BP20%	287.6	67.5	0.182	0.166	9.1	11.4	25%
11	1.1	SS_2%Grade	BP1%	295.1	69.3	0.099	0.139	4.8	4.7	-2%
12	1.1	SS_2%Grade	BP1%	290.4	68.3	0.092	0.159	4.6	5.4	17%
13	1.1	SS_2%Grade	BP1%	296.9	70.3	0.110	0.193	5.3	6.5	23%

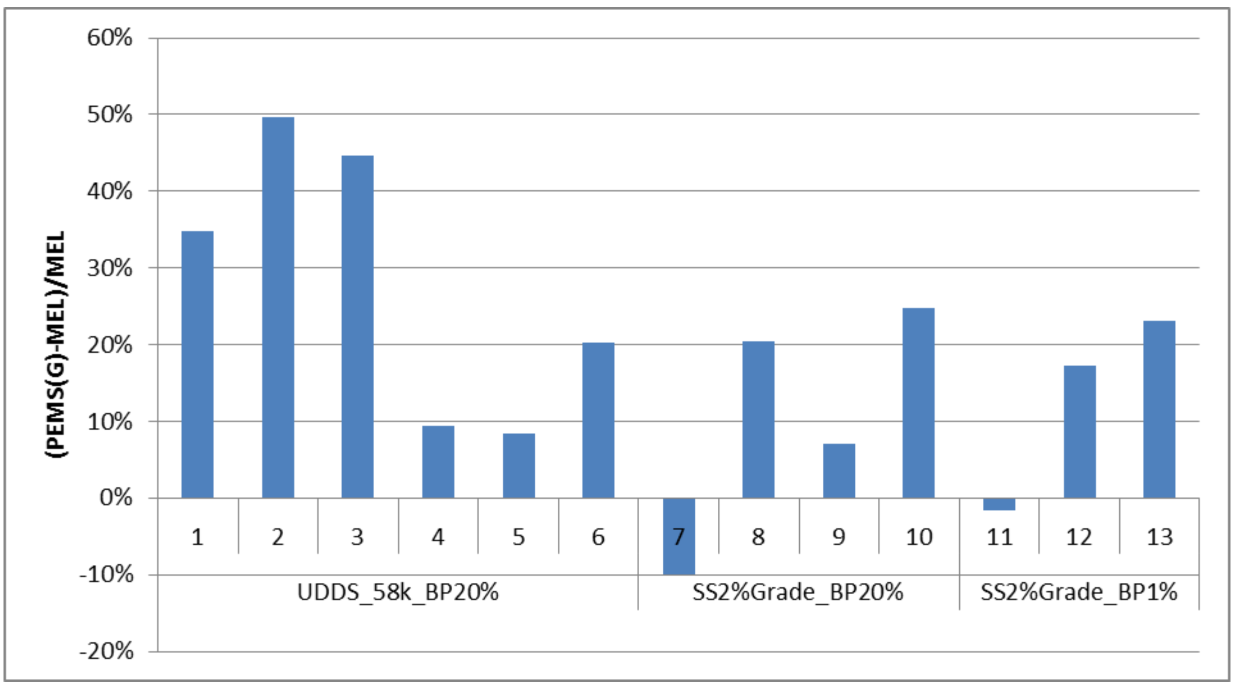


Figure 13 bsPM percent difference by point

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible.

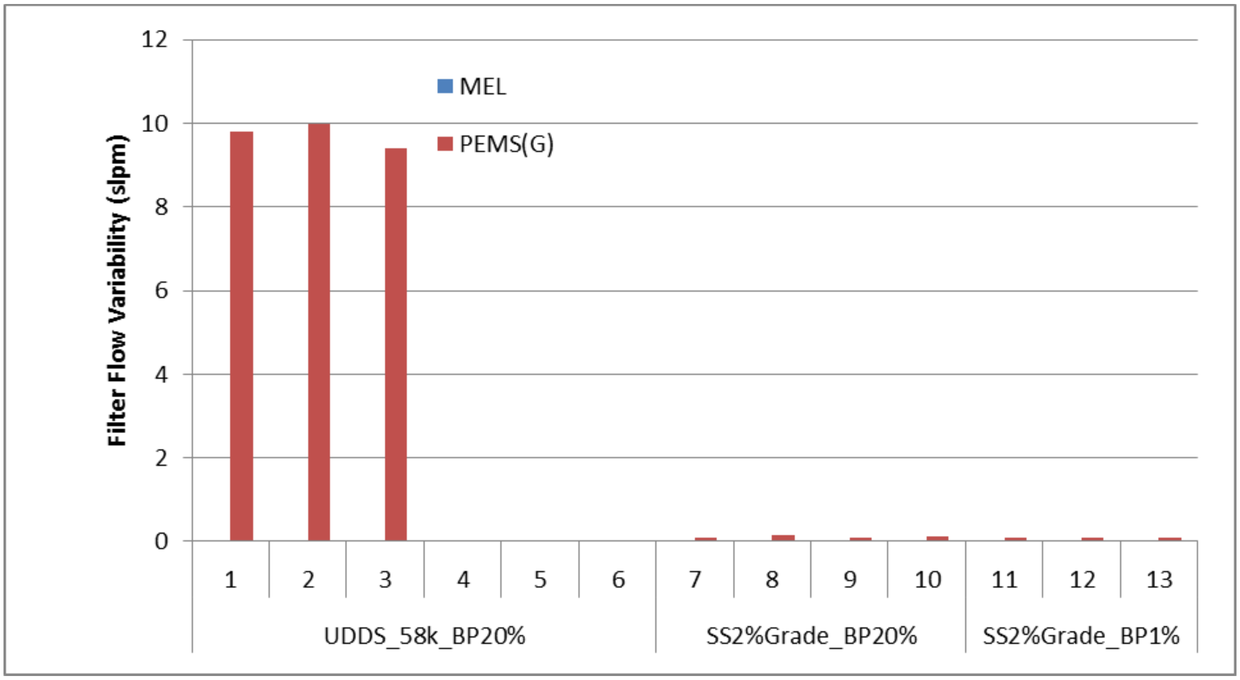


Figure 14 Filter flow variability for the MEL and the PM PEMS (G)

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible.

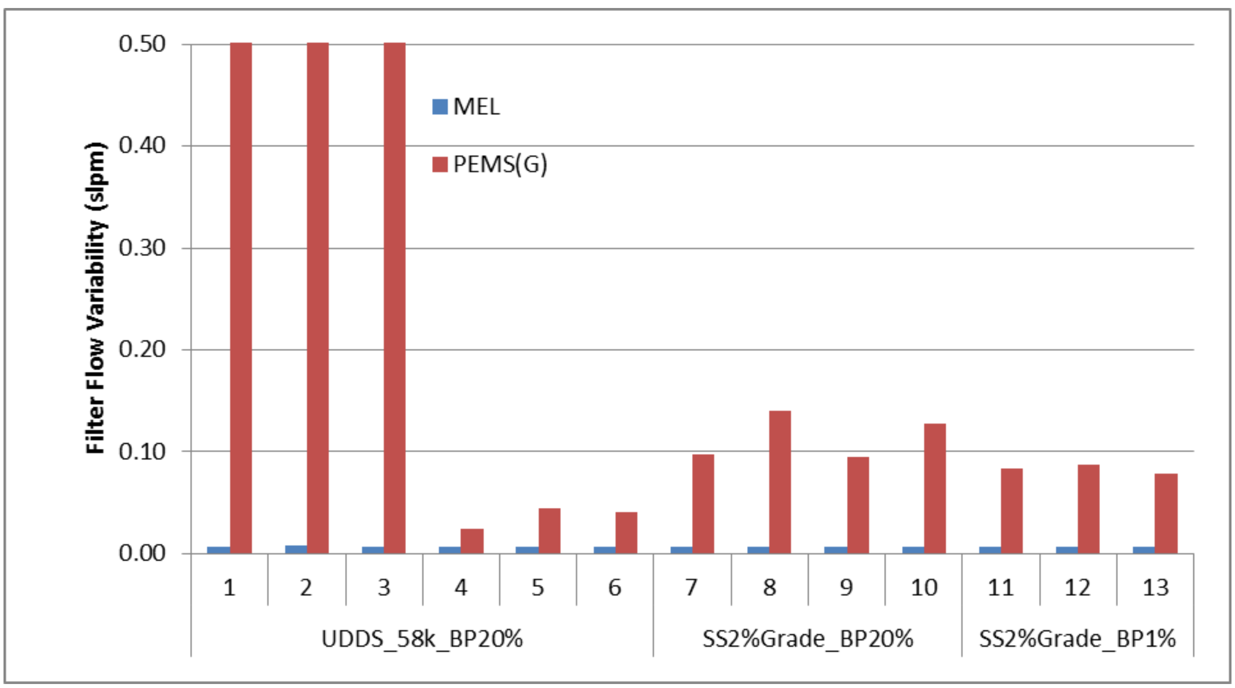


Figure 15 Filter flow variability for the MEL and the PM PEMS (G); zoomed

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible.

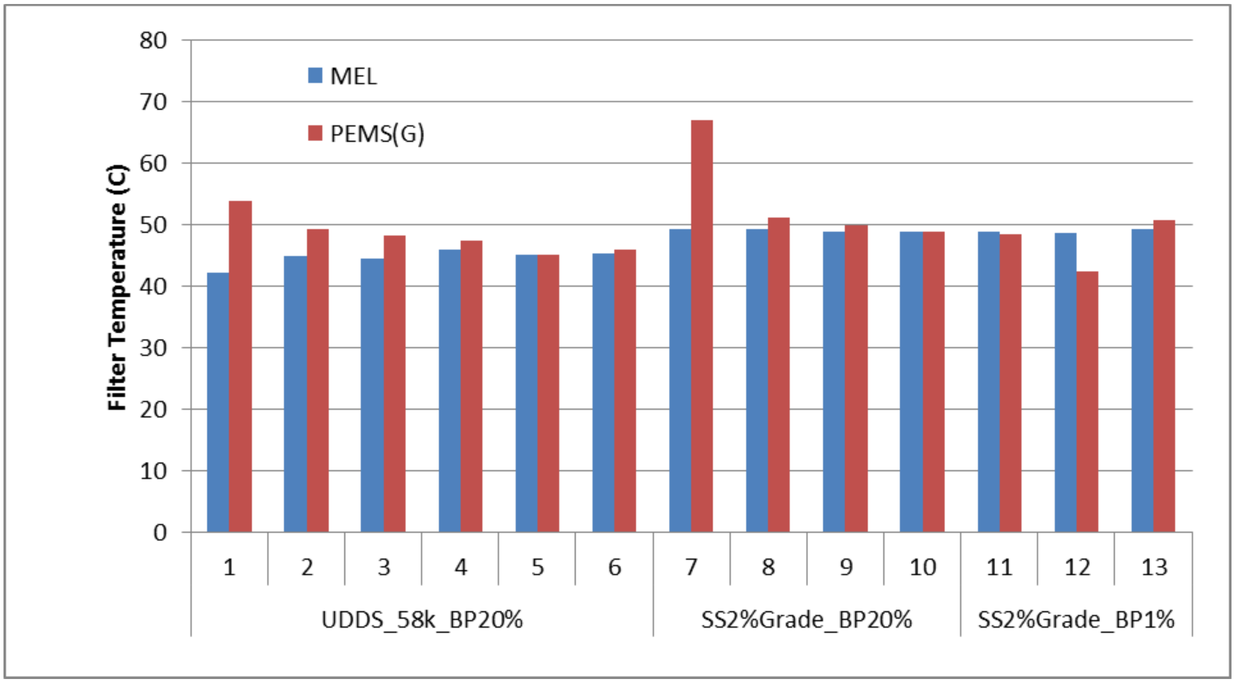


Figure 16 Filter face temperature for the PM PEMS (G) and the MEL

[1] SS_2%Grade is a steady state cycle with the dyno set at a 2% grade. BP stands for bypass where the percent is the approximate percentage of bypass. 1% represents minimum bypass possible.

6.3 Proportionality

Figure 17 shows the PM PEMS (G) exhaust and sample flow proportionality for a selected transient UDDS cycle. The test selected showed a standard error estimate (SEE) over maximum exhaust flow of 3% which meets the specifications of 40 CFR 1065 and ISO, see Appendix A. However, many of the tests did not meet the proportionally requirements and a list of randomly selected tests are presented in Table 6. The proportionally specification varied from 2.6% (SEE/max) to 17.4% and 9.2% (SEE/mean) to 56%, see Table 6. Efforts were taken to correct for proportional issues with daily flow verifications and checks, but it is unclear how well these corrections impacted the overall comparison. Later it was discovered that an issue with flow drift caused a significant amount of these deviations. Ultimately an improved flow control and measurement system was needed for the final system to ensure proportionality was robust. This included replacing the original combination of low cost Sierra MFCs and TSI MFMs with accurate low drift MFC (Red-Y series) and a laminar flow element meter made by Alicat, as discussed in greater detail in Section 6.5.

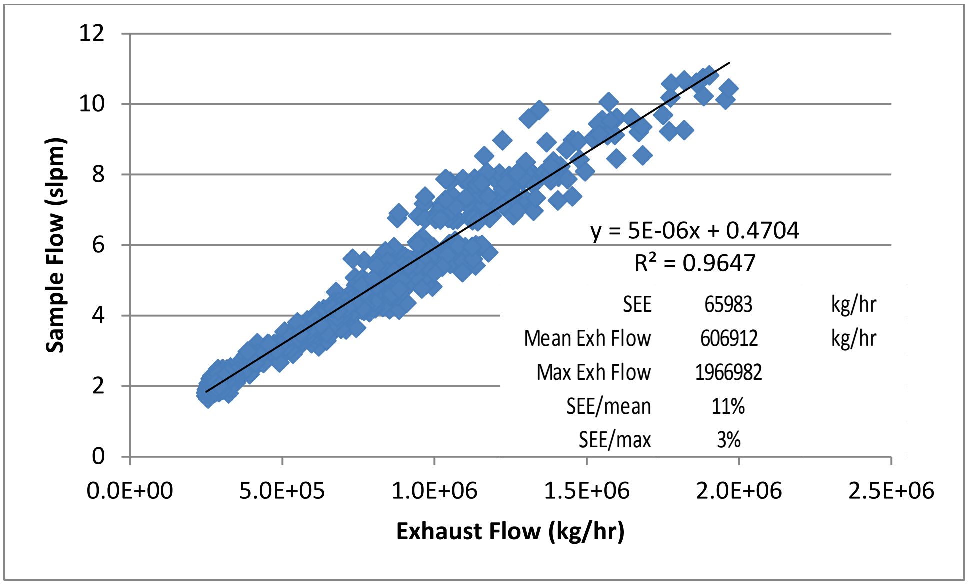


Figure 17 Proportionality correlation for a selected UDDS test

Table 6 Summary of the proportionality statistics for selected the tests

	Version 1						
Statistic	Cruise	UDDS	Cruise	Cruise	UDDS	UDDS	UDDS
SEE	256763	341454	103461	50638	334427	292440	65983
Mean Exh Flow	626526	606912	634229	551215	599591	614451	606912
Max Exh Flow	2001762	1966982	1981591	1969534	2005494	1981315	1966982
SEE/mean	41.0%	56.3%	16.3%	9.2%	55.8%	47.6%	11.1%
SEE/max	12.8%	17.4%	5.2%	2.6%	16.7%	14.8%	3.2%

[1] Randomly selected proportionally results for Version 1.1 of the PM PEMS (G) system.

6.4 Gaseous Emissions

Individual gaseous emissions and selected vehicle performance results are presented in Table 6 and average statistics are listed in Table 8. The CO_2 brake specific emissions showed a COV less than 3% for all the tests and the $bsNO_x$ emissions showed a COV less than 5% for the UDDS and just over 5% for the steady state tests. The data in the tables shows the tests were repeatable and controlled. Additionally the slightly higher variability for the steady state test also suggest more vehicle variability for these tests compared to the transient tests as see by higher PM variability between these same tests.

Table 7 Summary of individual engine and gaseous emissions results

Test ID	Bypass	Ver #	Cycle	Eng. Power hp	Eng. Work hp-h	Emissions Rate (g/hp-h) THC	CH_4	NMHC	CO	NO_x	NO_2	CO_2
201305081236	BP20%	1.0	UDDS58k	71.9	21.2	0.029	0.006	0.024	0.125	4.81	1.45	577
201305081325	BP20%	1.0	UDDS58k	71.3	21.0	0.033	0.010	0.024	0.134	4.51	1.38	560
201305081404	BP20%	1.0	UDDS58k	75.0	22.1	0.027	0.004	0.024	0.102	4.37	1.34	553
201305090950	BP20%	1.1	UDDS58k	72.9	21.5	0.033	0.010	0.025	0.159	4.63	1.35	587
201305091031	BP20%	1.1	UDDS58k	73.9	21.8	0.034	0.012	0.024	0.117	4.35	1.27	565
201305091110	BP20%	1.1	UDDS58k	73.0	21.5	0.031	0.010	0.022	0.138	4.32	1.37	566
201305091335	BP20%	1.1	SS_2%Grade	288.5	67.7	0.011	0.002	0.010	0.041	2.66	0.30	476
201305091422	BP20%	1.1	SS_2%Grade	326.7	71.5	0.011	0.001	0.010	0.028	2.67	0.30	465
201305100841	BP20%	1.1	SS_2%Grade	290.1	69.1	0.010	0.002	0.009	0.026	2.94	0.70	485
201305100923	BP20%	1.1	SS_2%Grade	287.6	67.5	0.010	0.001	0.009	0.025	2.51	0.52	480
201305101006	BP1%	1.1	SS_2%Grade	295.1	69.3	0.007	0.001	0.006	-0.002	2.65	0.61	476
201305101042	BP1%	1.1	SS_2%Grade	290.4	68.3	0.007	0.002	0.006	-0.003	2.67	0.65	472
201305101119	BP1%	1.1	SS_2%Grade	296.9	70.3	0.008	0.002	0.007	-0.004	2.67	0.63	466

Table 8 Average summary of engine and gaseous emission results

Cycle	Statistics	Eng Power hp	Eng Work hp-h	Emissions Rate (g/hp-h) THC	CH_4	NMHC	CO	NOx	NO_2	CO_2
UDDS58k	ave	73.0	21.5	0.031	0.009	0.024	0.129	4.498	1.361	567.9
	stdev	1.3	0.4	0.003	0.003	0.001	0.020	0.191	0.058	12.4
	COV	1.8%	1.8%	9.1%	34.0%	4.2%	15.1%	4.2%	4.2%	2.2%
SS_2%Grade BP20%	ave	298.2	69.0	0.011	0.001	0.010	0.030	2.697	0.456	476.5
	stdev	19.0	1.8	0.001	0.000	0.001	0.007	0.180	0.193	8.3
	COV	6.4%	2.7%	5.3%	34.4%	6.1%	24.7%	6.7%	42.3%	1.7%
SS_2%Grade BP1%	ave	294.1	69.3	0.007	0.001	0.006	-0.003	2.663	0.629	471.2
	stdev	3.3	1.0	0.001	0.000	0.001	0.001	0.008	0.017	4.8
	COV	1.1%	1.4%	9.9%	29.5%	8.9%	-27.5%	0.3%	2.8%	1.0%

6.5 Issues and resolutions

During the testing of the PM PEMS (G) Version 1.1 system a relatively large relative error was found between the MEL and the PM PEMS (G) system. This section discusses the observation of poor flow measurement and possible sulfate sample line losses.

6.5.1 Flow measurement

During the testing of the PM PEMS (G) Version 1.1 system it was discovered that the flow error for the TSI flow meters was much larger than expected for non-standard conditions of 20 °C and 1 atm. The sensitivity of accuracy to flow is discussed in greater detail in Appendix I. A closer look at the uncertainty specifications showed that the drift of the TSI meter is 0.14% per psi and

0.075% per degree C, see Table 9. Additional information on the flow meter errors is also found in Appendix J. The Alicat meter (a laminar flow element) had the lowest drift specification of all the flow meters at 0.0014%/psi and 0.02%/°C. The TSI has a 100 times higher reported drift for pressure and 4 times higher drift for temperature compared to the Alicat meter. Verifications were performed to document the deviations of the sample trim flow to try and correct for this for the results presented. This deviation directly affected the total mass calculation, dilution ratio, and the real-time proportionality. Factors were prepared for each test and applied to normalize the affect, but it is unclear if the factors were properly collected. An estimate of possible uncertainties was calculated in Table 10, where it shows the TSI meter of 3% error may cause a greater than 50% uncertainty in the mass emission rate. As such, the TSI meters were removed from the system and a direct measure of the sample flow with a Venturi was implemented. A summary of the errors and flow methods is provided in Appendix I.

Table 9 Flow meter drift specifications for temperature and pressure

Variable	Alicat	Sierra	TSI	Red-Y
Temp Drift	0.02%/C	0.02%/C	0.075%/C	0.025%/C
Pres Drift	0.02%/atm	0.02%/psi	0.02%/kPa	0.2%/bar
Pres Drift	0.0014%/psi	0.02%/psi	0.14%/psi	0.014%/psi

Table 10 Impact of drift specifications for Version 1.1 PM PEMS (G) system

Pressure	Temperature	Trim Flow		Total Flow 20C1atm		Dilute	Sample	Mass Err	DR Err	
kPa	C	slpm	% err	slpm	% err	slpm	slpm	%	n/a	%
101.3	**21.1**	**8.00**	**0%**	**58.9**	**0%**	**48.1**	**2.80**	**0%**	**21.04**	**0%**
101.3	26.1	7.97	0%	58.7	0%	48.1	2.61	7%	22.49	-7%
101.3	31.1	7.94	1%	58.5	1%	48.1	2.42	14%	24.17	-15%
101.3	36.1	7.91	1%	58.2	1%	48.1	2.23	20%	26.15	-24%
101.3	41.1	7.88	2%	58.0	2%	48.1	2.04	27%	28.49	-35%
101.3	46.1	7.85	2%	57.8	2%	48.1	1.85	34%	31.31	-49%
101.3	51.1	7.82	2%	57.6	2%	48.1	1.65	41%	34.79	-65%
91.2	51.1	7.80	2%	57.4	2%	48.1	1.54	45%	37.27	-77%
82.1	51.1	7.79	3%	57.3	3%	48.1	1.44	49%	39.83	-89%
73.8	51.1	7.77	3%	57.2	3%	48.1	1.35	52%	42.47	-102%
66.5	51.1	7.76	3%	57.1	3%	48.1	1.26	55%	45.17	-115%
59.8	51.1	7.75	3%	57.0	3%	48.1	1.19	57%	47.92	-128%
53.8	51.1	7.74	3%	57.0	3%	48.1	1.12	60%	50.71	-141%
48.5	51.1	7.73	3%	56.9	3%	48.1	1.06	62%	53.52	-154%

The PM PEMS (G) system was revised in Version 2.0 to laminar flow for the trim flow (manufacturer Vögtlin Red-Y model MFC and Alicat M-Series mass flow meter), a calibrated low pressure thermal mass flow controller for the filter flow, and an added inlet sample flow custom machined Venturi.

6.5.2 Sulfate PM

At the time of this testing it was not clear the impact of sulfate PM on the flexible transfer line due to the poor sample flow and proportionality issues for Version 1.1 presented in this section. Later analysis suggests both proportionality and the transfer line sulfate PM loss may have caused some of the differences between the PM PEMS (G) and the MEL. Although it cannot be shown hear that sulfate PM contributed to the bsPM relative error, it is possible sulfate PM may be part of the deviation. A more thorough discussion of sulfate influences is presented in Sections 7 and 8.

7 Results: On-Road Version 2.0a

The on-road testing shows the ability of the PM PEMS (G) to sample proportionally and to quantify mass at 40 CFR 1065 conditions while in a mobile application. At the time of this testing, the automatic filter indexer, ECM interface, and remote control system were implemented. The PM PEMS (G) system was operated remotely from the cab of the tractor trailer utilizing the remote control computer. The PM PEMS (G) system was upgraded with a laminar flow element dilution flow, calibrated mass flow controller for the filter flow, and a custom machined inlet sample flow Venturi. This version of the PM PEMS (G) system was found to be accurate, stable, and robust.

7.1 Test matrix

The in-use tests covered a range of conditions including arterial driving, freeway cruising, congested freeway operation, and freeway cruising with grade, see Table 11. Four bypass conditions were simulated ranging from a minimal 1% bypass to a medium bypass of 20%. The testing involved transient medium and lower power conditions with moderate emission levels (bypass setting of 20%) and a low emission level (bypass setting of 1%). As discussed previously, the low bypass setting should provide PM that has a higher contribution of sulfate to the composition, while the higher bypass levels should provide PM with a higher contribution of elemental carbon (soot). The bypass setting of 20% is expected to produce mostly elemental carbon (EC) soot, with about 80% EC, 10% organic carbon (OC), and 10% Sulfate. The 1% bypass setting is expected to produce a PM composition of mostly sulfate at 50% sulfate, 30% EC and 20% OC.

Table 11 Testing performed on the PM PEMS (G) system

Test ID	Test cycle	Bypass Setting	Route	Proportional Control	Status
1	Arterial/Freeway	1%	Riverside	EFM	EFM frozen
2	Freeway	1%	Riverside	EFM	EFM frozen
3	Freeway	20%	Riverside	EFM	Valid
4	Congested Freeway	20%	Riverside	EFM	Valid
5	Congested Freeway	1%	Riverside	EFM	Valid
6	Arterial/Freeway	1%	San Diego	EFM	Valid
7	Freeway	5%	San Diego	EFM	Valid
8	Freeway	5%	San Diego	EFM	Valid
9	Arterial/Freeway	5%	San Diego	EFM	Valid
10	Freeway	10%	San Diego	EFM	Valid
11	Freeway	10%	San Diego	ECM	Valid

[1] EFM frozen is when the display of the flow meter would stop updating data on the digital interface. This would prevent proper proportionality and invalidate the test point.

Proportionality was controlled by utilizing a commercially available exhaust flow meter for most of the tests. One test was performed utilizing the ECM signals for calculation of exhaust flow to control proportionality as shown in Table 11. Both proportionality control systems performed well although there were some issues with the exhaust flow meter freezing causing invalid tests. Eleven tests were performed where two tests were invalidated due to the freezing of the exhaust flow meter, see Table 11. The flow meter was relocated to the inside of the cab to allow the operator to quickly reset the flow meter if it appeared frozen on the PM PEMS (G) remote control computer (resetting the EFM occurred three times, but did not invalidate the test point since the issue was caught quickly). It is unclear what was causing the issue so further investigation is needed.

7.2 PM Emissions

Table 12 shows the bsPM emission factors for the PM PEMS (G) Version 2.0a and the MEL during on-road driving conditions. The MEL bsPM emissions varied from 197 mg/hp-h to 4.8 mg/hp-h. The very high bsPM emission test (197 mg/hp-h) was well beyond typical behavior for the PM source at a bypass level of 1%. Previously it was shown that a bypass setting of 1% provided a bsPM emission rate of less than 10 mg/hp-h. The substantially high PM for Test 1 is suspicious and suggests that a large passive regeneration may have occurred. See Section 7.5 for a more thorough discussion.

The bsPM relative error between the MEL and the PEMS was low for Tests 4, 5, 7, 8, and 10 as shown in Table 12. The flow corrected brake specific PM relative error ranged from -1% to -14% where the bsPM emission factor ranged from 2 mg/hp-h to 45 g/hp-h. The correlation between the MEL and the PEMS(G) system showed good agreement where an R^2 of 0.99 and a slope of 0.90 were reported for these selected points, see Figure 18 trend line bsPM_reduced.

Table 12 bsPM relative error between UCR's MEL and the PM PEMS (G) Ver2.0a

Test	Ver	Traffic [1]	Bypass	Power	Work	Filter Weight (mg)		bsPM (mg/hp-h)		Rel Error
#	#	n/a	Setting	Hp	Hp-hr	MEL	PEMS(G)	MEL	PEMS(G)	%
1	2.0a	Trans	BP1%	104.9	42.6	2.510		197.0		
2	2.0a	Cruise	BP1%	186.7	69.1	0.074		3.7		
3	2.0a	Cruise	BP20%	85.9	31.3	0.787	0.335	86.1	28.4	-67%
4	2.0a	Congest	BP20%	60.1	18.3	0.223	0.228	41.7	37.3	-11%
5	2.0a	Congest	BP1%	82.8	35.9	0.051	0.039	4.8	3.4	-14%
6	2.0a	Trans	BP1%	159.5	55.1	0.192	0.050	12.1	3.0	-75%
7	2.0a	Cruise	BP5%	141.3	47.6	0.034	0.038	2.5	2.4	-1%
8	2.0a	Cruise	BP5%	133.1	37.9	0.050	0.053	4.6	4.2	-3%
9	2.0a	Trans	BP5%	159.6	65.2	0.179	0.097	9.5	4.5	-50%
10	2.0a	Cruise	BP10%	151.7	51.2	0.092	0.091	6.3	5.4	-9%
11	2.0a	Cruise	BP10%	151.9	48.3	0.151	0.113	10.9	6.6	-43%

[1] The traffic column describes the general conditions during the on-road testing. Trans – is a combination of arterial and cruise conditions, Cruise – is all cruise conditions with speeds over 50 mph, and Congest – is conditions with extended congestion.

The relative error was high for Tests 3, 6, 9, and 11, see the grey coloring tests in Table 12. When all the data points are correlated to the MEL PM emissions the slope reduces from 0.9 to 0.26 and the R^2 reduces from 0.999 to 0.81, see Figure 18 bsPM_all vs bsPM_reduced. It is unclear if these selected test points were biased with sulfate PM from passive CRT regenerations. Additional discussions on the influence of regenerations are provided in Section 7.5. There is some speculation that the TSI flexible transfer line may be an issue for sulfate dominated PM, but further analysis of the filters and testing is needed to verify this. The possible loss of PM from flexible tubing is a significant issue for PEMS testing since most PEMS systems use flexible transfer lines due to logistics of installation and in-use operational needs.

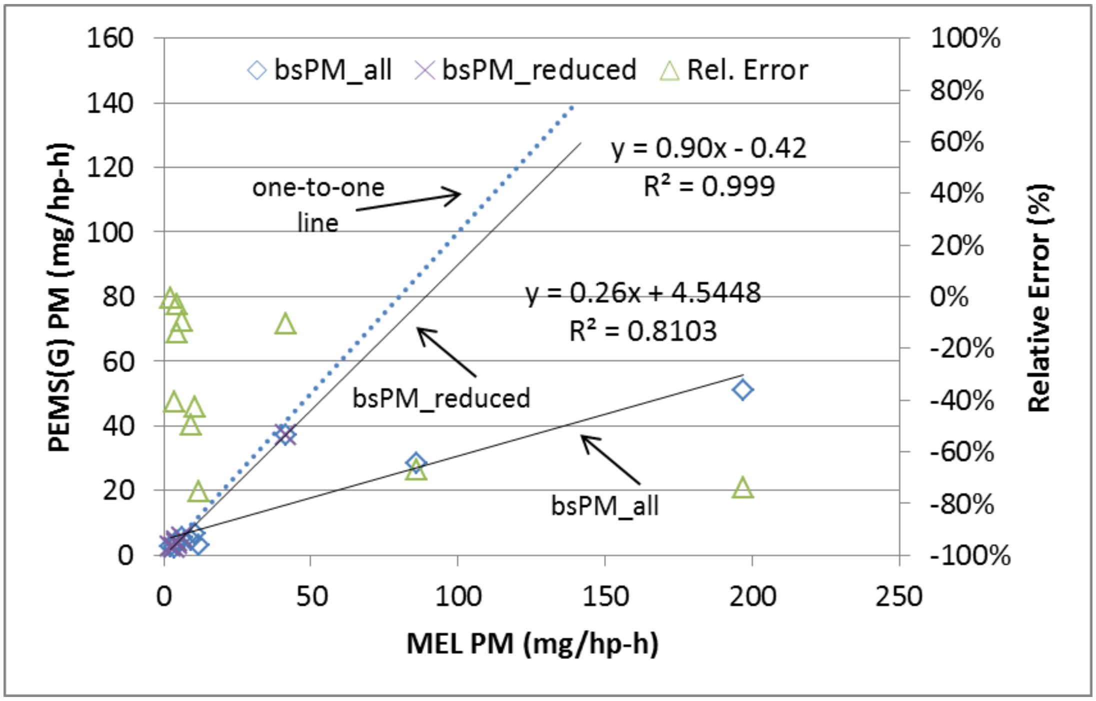


Figure 18 On-road bsPM correlation and relative

[1] The bsPM data represents all the data from the on-road testing and the bsPM reduced is only the data where it is expected that large fractions of sulfate PM was present in the exhaust.

Figure 19 shows the total exhaust volume as measured by the EFM and as calculated by the speed density approach utilizing ECM signals, compared with calculations using the MEL's total and dilute Venturi's. Corrections to the bsPM for flow biases were made to eliminate the bias of the exhaust flow meter, as allowed by 40 CFR 1065 methods 2 and 3 for in-use testing. The magnitude of this correction was 10%, as shown by the slope in Figure 19. The PM PEMS (G) emission results were presented in this section based on the MEL corrected exhaust flow measurements.

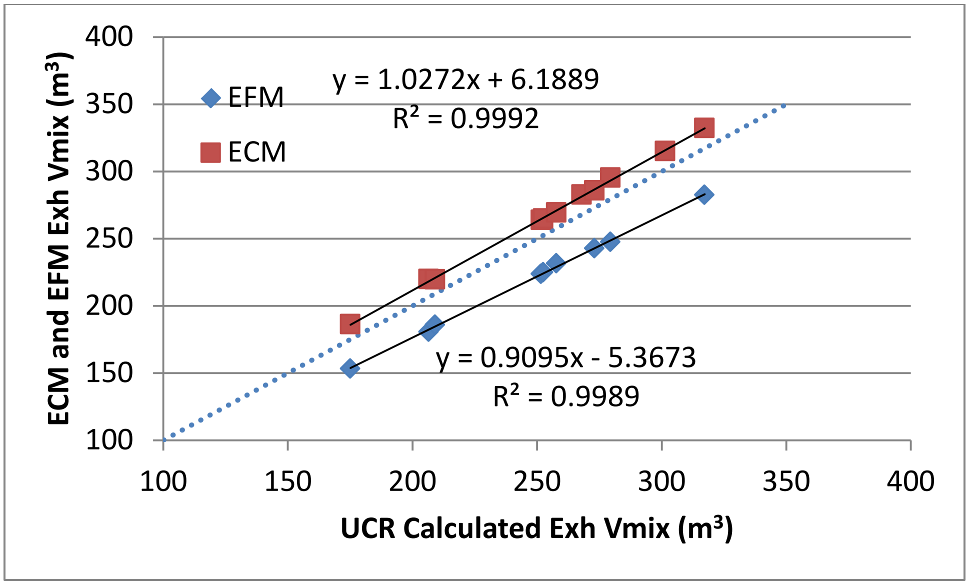


Figure 19 On-road exhaust flow deviations relative to the MEL

The on-road engine loads were similar to the UDDS tests, but were lower than the chassis cruise tests. Figure 20 shows the average power for the on-road and chassis testing. The UDDS cycle compares well with congestion driving and was slightly low compared to arterial driving. The simulated cruise with a grade was about twice the load of what was typically found cruising on-road with local grade changes. The differences in average power for the on-road tests and the chassis tests suggest the PM formation may be different since exhaust temperatures are lower at lower engine loads and exhaust temperatures affect PM formation from a CRT type of after-treatment system.

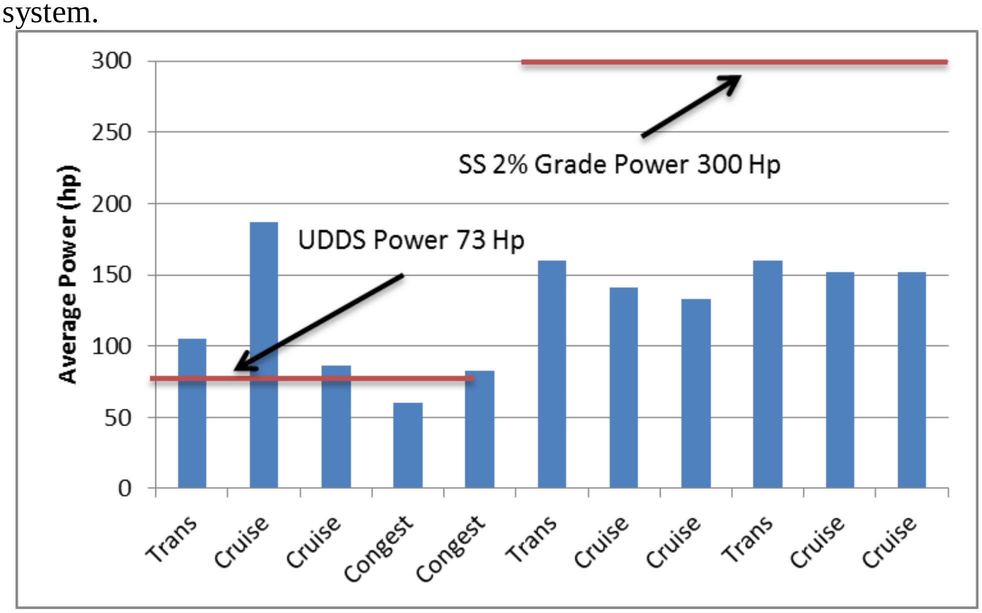


Figure 20 On-road average power and its comparison to the chassis tests

Figure 21 shows the dilution ratios for the MEL and the PM PEMS (G) system. The dilution ratio for the PM PEMS (G) was slightly lower than the MEL with a very consistent bias. These differences are not significant and should not affect the PM formation process of particles. The dilution ratio performance suggests the Version 2.0a system was well behaved and in control.

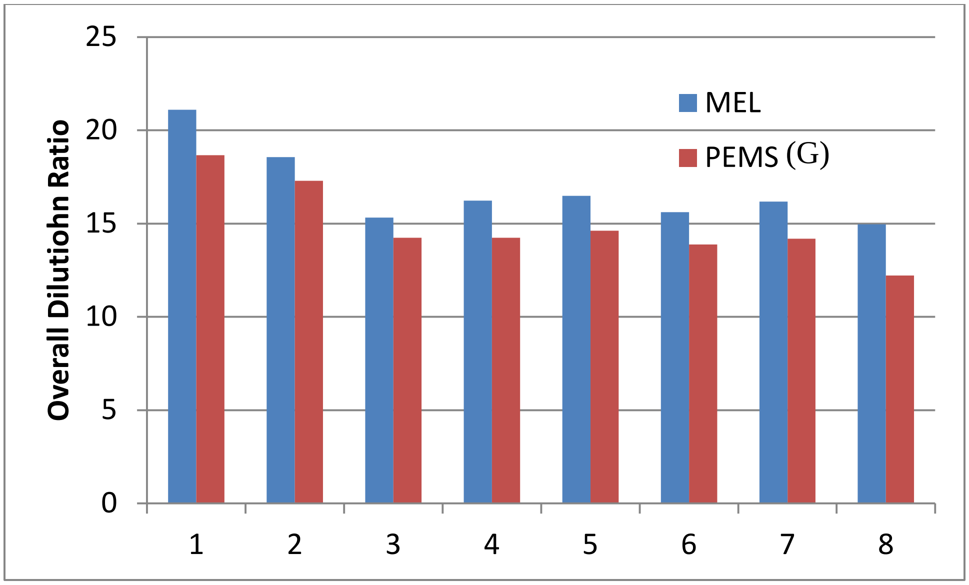


Figure 21 On-road dilution ratios between the MEL and PEMS valid tests

7.3 Proportionality

The Version 2.0a system included an online proportionally analysis feature to provide a check of the flow operation of the system and to provide the operator quick feedback that the test is being conducted within specifications. Figure 22 and Figure 23 show the real-time proportionality feedback during two selected on-road tests. The proportionality for these tests was very good and was typical. The good proportionality suggests proper PM sampling and that a good correlation should be expected between the PM PEMS (G) and the MEL. Table 13 shows the proportionality statistics for randomly selected on-road tests.

The proportionality specification (SEE/max exhaust flow) was well below the 5% and the SEE/mean exhaust was also below 5% for a few tests. The flow control for Version 2.0a system did not require flow validations, corrections, or adjustments. The good proportionality suggests the PM correlation between the MEL and the PM PEMS (G) should be good. Some of the tests did not correlate well, however, suggesting there may be another source of bias between the MEL and the PEMS systems that will be discussed in a later section.

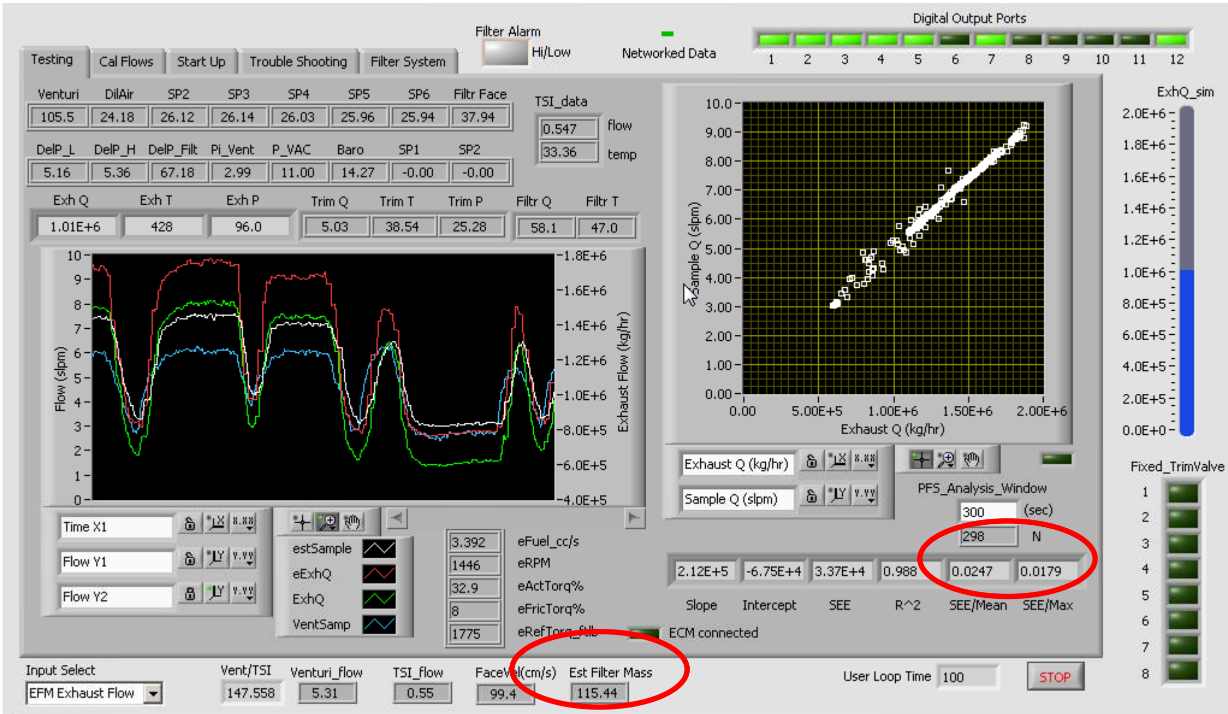


Figure 22 Online real-time proportionality and control screen shot test 2

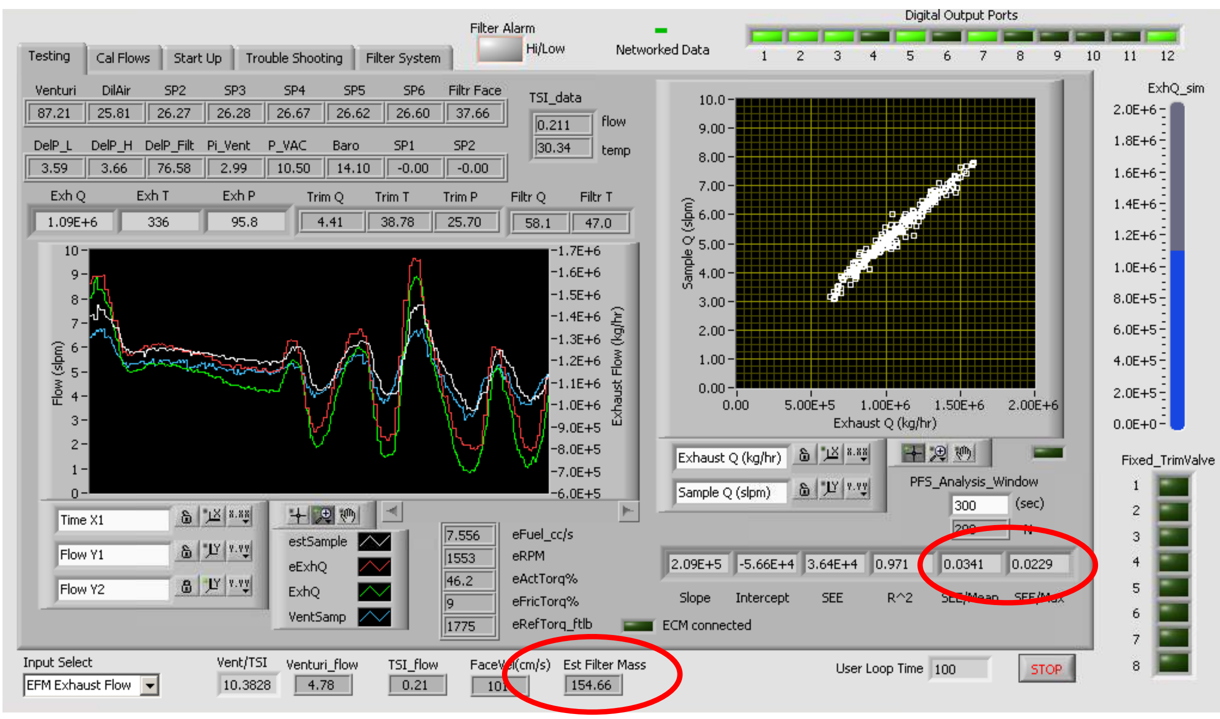


Figure 23 Online real-time proportionality and control screen shot test 3

Table 13 Randomly selected proportionality summary for the Version 2.0a system

	Version 2.0a (kg/hr)						
Statistic	congest	congest	congest	freeway	freeway	freeway	freeway
SEE	43813	24775	36860	41608	35104	61390	34911
Mean Exh Flow	597582	606162	669583	801308	714266	800807	805782
Max Exh Flow	2022938	1785122	1943999	1998804	1980740	1990076	1980025
SEE/mean	7.3%	4.1%	5.5%	5.2%	4.9%	7.7%	4.3%
SEE/max	2.2%	1.4%	1.9%	2.1%	1.8%	3.1%	1.8%

7.4 Online automation

A feature of the automated filter indexing system is the ability to change filters at specific filter loadings. This was implemented by correlating filter loading with filter pressure drop. The base pressure drop across the filter was first measured to record the initial pressure reading (like a tare weight). From this initial pressure drop value the increase in pressure drop was monitored and used to calculate a semi-real-time filter loading value. Figure 24 shows the on-line filter weight during the on-road tests. Prior to testing it was estimated that 1 inHg pressure drop across the filter is equal to 100 µg of filter loading. Initial tests were performed with the factor at 100 µg/1 inHg (13.6 inH_20). The factor was since revised to 100 µg/33 inH_20, as shown in Figure 24. The trend in Figure 24 was consistent for Paul filters. Tests at higher pressure drops were not performed for the Whatman filters, but tests at the lower pressure drops were in the same range as those for the Paul filters.

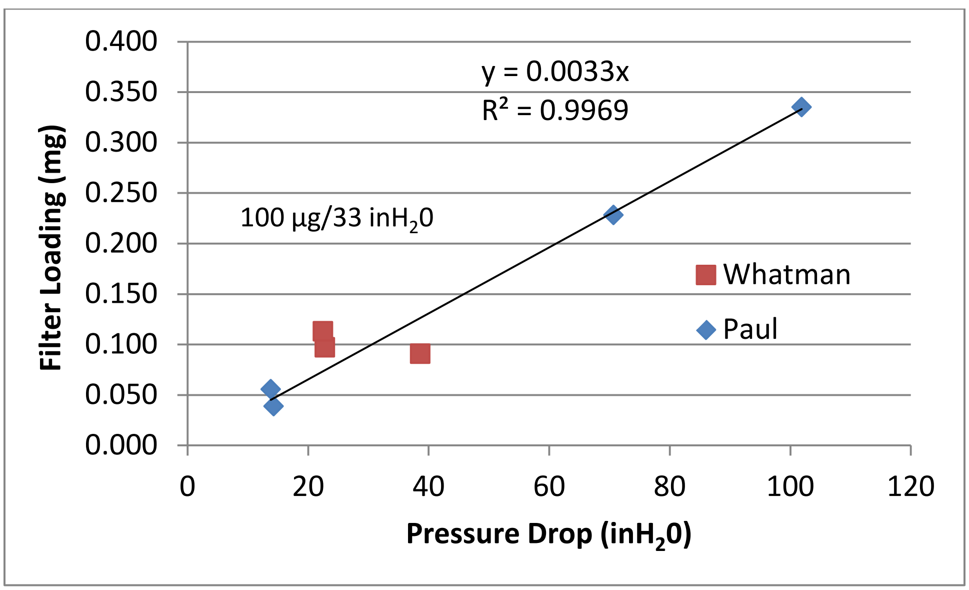


Figure 24 Online filter weight estimation based on Paul and Whatman filters

7.5 Issues and resolutions

During the testing of the PM PEMS (G) Version 2.0a system a relatively large error was found between the MEL and the PM PEMS (G) system for selected test points. Additional analysis was performed that showed these test points coincided with high exhaust temperatures which suggests possible passive regenerations may have influenced the composition of those points.

One hypothesis is that the flexible transfer line for the PEMS may have prevented the sulfate PM from reaching the filter. This section discusses the proposed hypothesis from various observations. Eventually this observation will need to be validated with additional testing to quantify and characterize the impact on transfer line sampling.

7.5.1 Ver 2a PM bias

Proportionality, flow control, and flow accuracy were very good, if not ideal, for Version 2.0a of the PM PEMS (G) system. Still, there were several tests that showed large biases that were eliminated from the correlation plot of Figure 18. The variations were as much as 67% bias, with the PM PEMS (G) bsPM values being lower than those for the MEL, see Table 12. These filters may have influences from sulfate particle formation typical of extended passive regenerations. The difference was not quantified, but could be seen by looking at the varying gray coloration on paired filters and their equivalent masses. Figure 25 shows the three paired filters with the largest relative error. The first pair shows a PM PEMS (G) filter loading of 50 µg, but a MEL loading of 192 µg. The PM PEMS (G) filter looks slightly darker, but is three times lower PM mass. The difference in total weight suggests the difference in the two filter weights may be sulfate particles captured by the MEL, but not the PM PEMS (G) system. Sulfate PM typically is clear or yellowish on Teflon filters. The other filters show a similar trend, but not at the same magnitude.

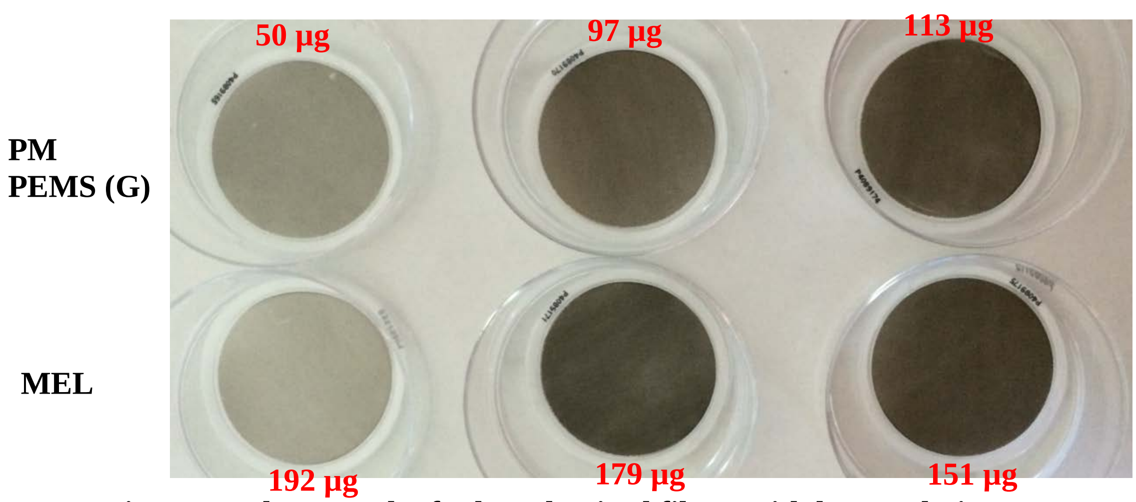


Figure 25 Photograph of selected paired filters with large relative error

7.5.2 Sulfate PM estimates

During previous studies of the same vehicle and CRT system, it was discovered that exhaust temperatures over 300°C resulted in passive regeneration and the formation of nano-sized sulfate particles (Johnson et al 2009, Durbin et al 2006). The particle size distributions showed a large contribution of nano-sized particles peaking at 20 nm, see Figure 26 (Durbin 2006). PM composition analysis (sulfate via ion chromatography and elemental carbon and organic carbon via the NIOSH method) for those tests showed that the PM fraction was dominated by sulfate PM. It was suggested the nucleation mode particles may be attributed to the conversion of SO_2 to SO_3, which is likely aided by the catalytic wash coat on the CRT. This is consistent with previous studies that have shown sulfate makes an important contribution to nucleation particles downstream of an aftertreatment system (Kittelson et al., 2006; Grose et al.2006).

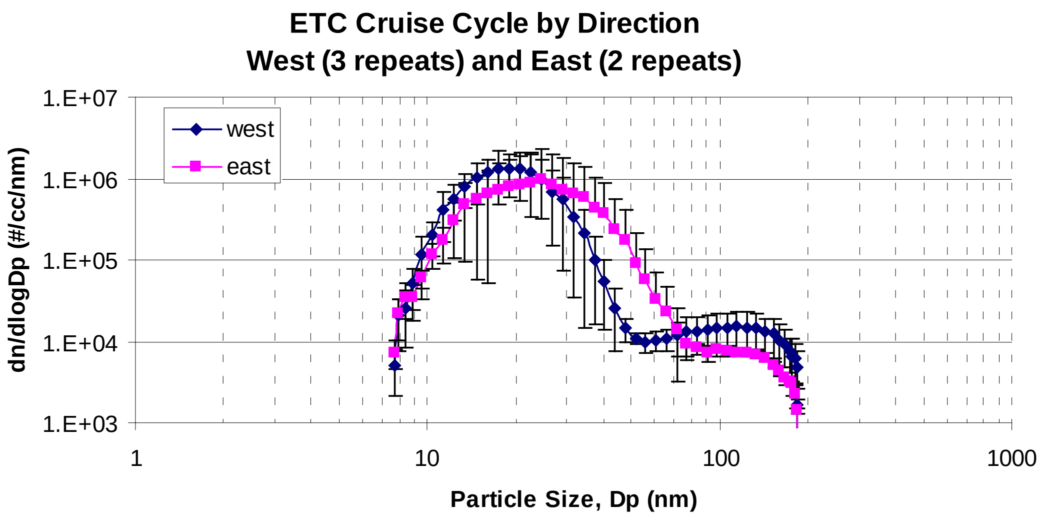


Figure 26 Particle size distribution during regen on the same test vehicle (Durbin 2006)

[1] East and west labels describe different directions on the freeway the data was collected with. The west direction was slightly uphill compared to the east direction.

As a deeper understanding of the influence of regenerations, the exhaust temperature was investigated for each of the on-road tests to investigate a correlation between exhaust temperature and the relative error. The average temperature was first considered, but no correlation could be found. After additional consideration, it was thought that the true metric is not average temperature, but sustained temperature over 300 °C. Figure 27 shows the continuous time during the test the exhaust was over 300 °C on the x-axis (in seconds) with the bsPM relative error between the MEL and the PEMS on the vertical y-axis. The blue dots represent the on-road tests and the red dots represent tests performed with a metallic transfer line as discussed in Section 8. The blue dots show that the longer the CRT was above 300 C the larger the deviation between the MEL and the PEMS (with the PEMS bias being lower than the MEL). This figure supports the fact that the transfer line for the PM PEMS (G) may be considered an important source of loss for sulfate-based PM. PM loss from a transfer line is a significant finding as many PEMS systems employ flexible transfer lines such as the one used during this study. Additional testing needs to be performed to confirm and quantify the impacts of flexible lines.

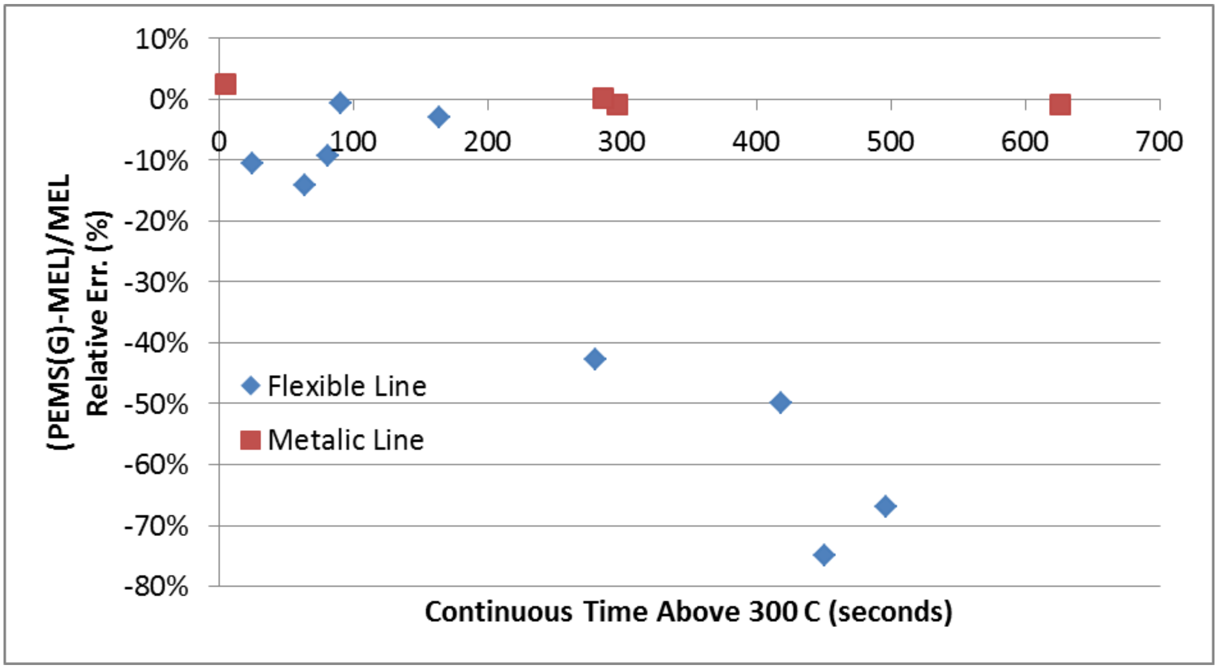


Figure 27 Exhaust temperatures for Ver2.0a (blue) and selected Ver2.0b (red) tests

[1] Version 2.0a and 2.0b are the same except for a metallic transfer line was used on Version 2.0b to evaluate losses due to possible SO_2 formation from the CRT during passive regenerations.

7.5.3 Transfer line

As discussed one possible cause for the difference may be due to the transfer line between the MEL and the PM PEMS (G) system. The PM PEMS (G) system needs to be flexible so that it can be mounted in unusual places that require flexible tubing to transfer the sample from the exhaust to the probe. The MEL uses a conductive stainless steel transfer tube to direct the vehicle's exhaust about 10 feet to the constant volume dilution tunnel. The PM PEMS (G) system utilizes about six feet of flexible silicon conductive tubing manufactured by TSI. This tubing is specially designed to assist with complex test setups while maximizing PM transmission efficiencies similar to that of stainless steel. The line has been shown by others to provide PM transmission efficiencies similar to those of metallic lines when the PM source is predominantly soot, as shown in Figure 28 (Timko et al 2009). Timko et al. (2009) also found that silicon conductive tubing may absorb or desorb gaseous species. Although this study did not specifically address SO_3 gaseous species and sulfate particles, it does suggest that conductive tubing has the capability for water uptake and gas phase interferences. Additional testing and evaluation is needed to evaluate possible sulfate particle losses due to this flexible sample line usage.

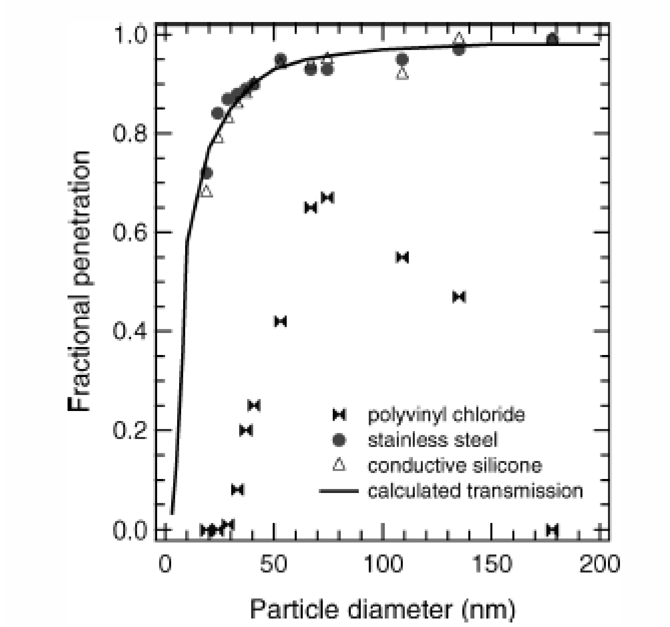


Figure 28 Penetration fractions of soot particles through transfer lines (Timko 2009)

8 Results: Chassis Version 2.0a and 2.0b

The previous on-road test results showed some high relative error for selected filters. This chassis testing was a repeat of the conditions for the on-road testing, but with the CRT removed and with the CRT installed, but with a metallic transfer line.

The operation of the PM PEMS (G) system was the same as during the on-road testing where a minimum dilution ratio of 6 to 1 was used for both the MEL and the PEMS. The minimum dilution ratio of 6 to 1 is based on the measured maximum exhaust flow of 2.6E6 kg/hr (1100 scfm). The PM filter sampling conditions for the gravimetric methods were similar where the filter temperature was targeted to 47 °C with a face velocity of 100 cm/s, and a dilution air temperature of 25 °C as per 40 CFR 1065. The set point filter mass flow was 58.1 slpm (20 °C and 1atm conditions) for both the MEL and PM PEMS (G) system.

8.1 Test matrix

The repeated chassis testing performed in this section covered transient and steady state operation with and without the CRT, see Table 14. The non-CRT tests were designed to evaluate the PM PEMS (G) system with soot dominated PM and the standard Version 2.0a flexible transfer line. The metallic transfer line tests with the CRT were designed to evaluate the ability of PM PEMS (G) Version 2.0b to measure sulfate based PM with a similar transfer line as the MEL. Proportionality was controlled utilizing the same EFM as previously tested in Section 6 and 7.

Ten tests were performed where eight were validated and used in the following analysis. Prior to starting the testing there were issues with the EFM where the reported value changed by a factor of three and involved some delays as the EFM was investigated. The flow error was resolved after calibration with UCR's MEL and some system reconfigurations with in the firmware of the EFM see detailed description in Section 8.5.

Table 14 Testing performed on PM PEMS (G) Ver2a and 2b

Test ID	Test cycle [3]	CRT	Bypass	PEMS(G) Version [1]	EFM Status [2]
1	UDDS 58k	no	n/a	2a-Silicon TL	Valid
2	UDDS 58k	no	n/a	2a-Silicon TL	Valid
3	UDDS 28k	no	n/a	2a-Silicon TL	Invalid
4	UDDS 28k	no	n/a	2a-Silicon TL	Valid
5	UDDS 28k	no	n/a	2a-Silicon TL	Valid
6	UDDS58k	yes	0%	2b-Metalic TL	Invalid
7	UDDS58K	yes	0%	2b-Metalic TL	Valid
8	Trans/Cruise	yes	0%	2b-Metalic TL	Valid
9	Cruise	yes	10%	2b-Metalic TL	Valid
10	Cruise	yes	10%	2b-Metalic TL	Valid

[1] Version 2.0a and 2.0b are the same except for a metallic transfer line was used on Version 2.0b to evaluate losses due to possible SO_2 formation from the CRT during passive regenerations.
[2] EFM prior to testing lost all internal parameters (K factor, tube inside diameter, and others). The cause was unknown. The test day was aborted until the system could be restored. The restored system had a 20% bias from the MEL. This bias was corrected for in the post processed data since full repair would require sending the system out for repair and time was limited. See issues and resolution this section for more details. The EFM was precise and linear so all the collected data is valid.
[1] Two different GVW were used to evaluate the PM PEMS(G) Ver2b system. One was at the same previous 58,000 lbs (denoted 58K) and the other was at a lighter GVW of 28,000 lbs (denoted 28k).

8.2 PM emissions

Figure 29, Figure 30, and Table 15 show the bsPM emission factor results for the chassis testing listed in Table 14. The bsPM between the MEL and the PM PEMS(G) system compared well as shown by the near unity slope (1.016) and R^2 = 0.9998, see Figure 29. The range of emissions varied from 129.7 mg/hp-h to a 3.6 mg/hp-h where the non-CRT tests were above 100 mg/hp-h and the CRT tests were below 50 mg/hp-h, see Table 15. The non-CRT tests with the flexible transfer line showed and the CRT tests with the metallic transfer line showed good agreement see Figure 29. All the tests were with in ± 5% of the MEL regardless of the emission rate.

Analysis of the filters for sulfate PM was not performed but inferred with previous testing of the same CRT and continuous time above 300 °C exhaust temperatures. Figure 27 shows the continuous time above 300 °C for these repeated tests in comparison to other tests performed with the flexible transfer line. The metallic sample line tests showed a relative error less than ±5% from low to high sustained time over 300 °C. The much lower relative error and similar sustained temperatures of 300 °C suggests the metallic line is performing well and the flexible line may have some sulfate PM losses. Further investigation is needed to confirm these results. ARB has agreed to analyses the filters collected in this study to help quantify and characterize the possible impacts of transfer line losses.

The good correlation (within ±5%) both with and without the CRT for the PM PEMS (G) system suggest the system is robust for all PM types. These results also suggest a metallic transfer line may be needed for the best comparison to a CVS laboratory.

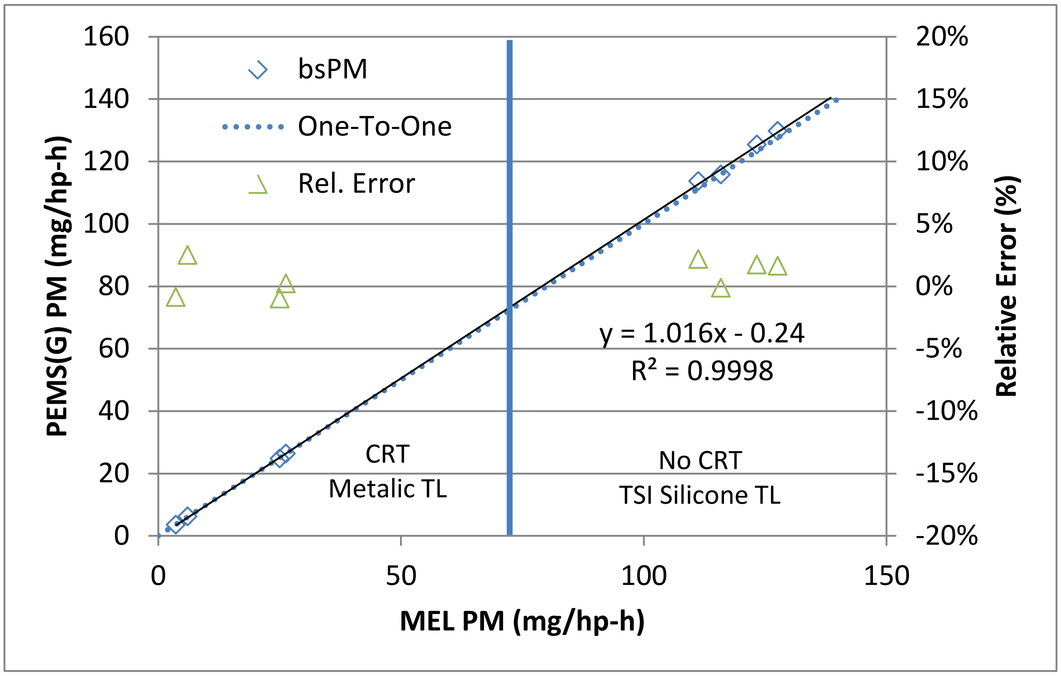


Figure 29 Correlation plot between the MEL and the PM PEMS (G) Ver2a and 2b

[1] Version 2.0a and 2.0b are the same except for a metallic transfer line was used on Version 2.0b to evaluate losses due to possible SO_2 formation from the CRT during passive regenerations.

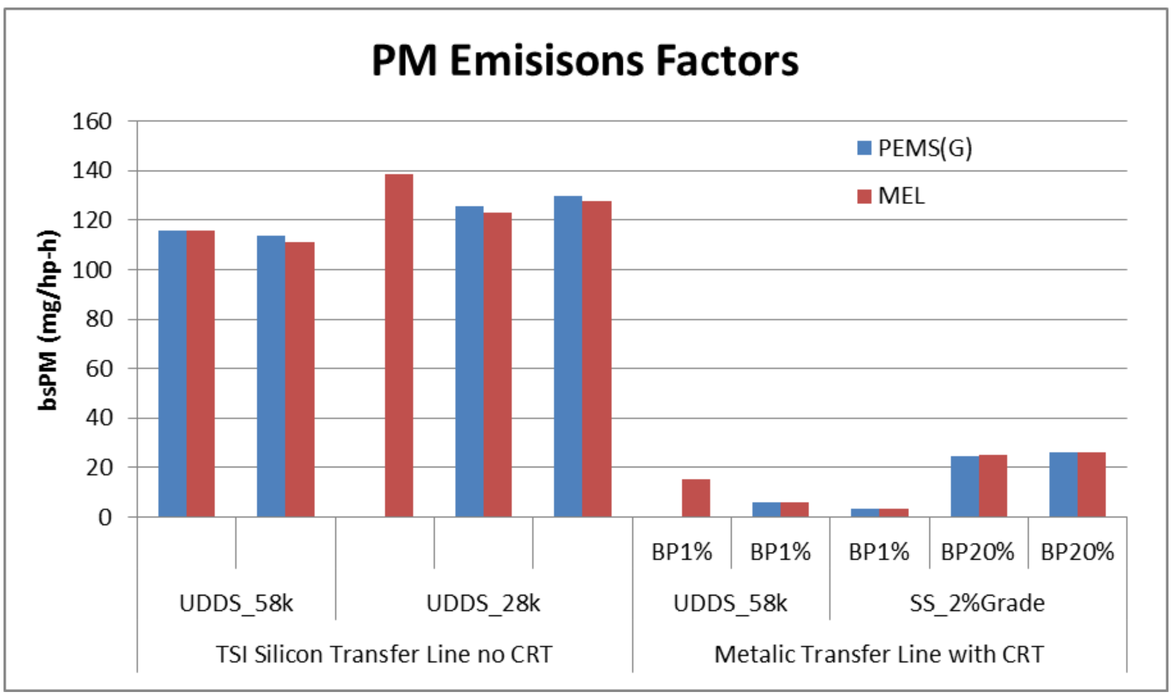


Figure 30 bsPM comparison chart between the MEL and the PM PEMS (G)

Table 15 bsPM results for the MEL and the PM PEMS (G) gravimetric systems

Test #	Ver #	Cycle n/a	Bypass Setting	Power	Work	Filter Weight (mg) MEL	PEMS(G)	bsPM (mg/hp-h) MEL	PEMS(G)	Rel Error %
1	2.0a	UDDS58k	noCRT	66.3	19.6	0.654	0.524	115.9	115.8	0%
2	2.0a	UDDS58k	noCRT	68.7	20.3	0.650	0.567	111.2	113.7	2%
3	2.0a	UDDS28k	noCRT	53.9	15.9	0.636	0.000	138.5		
4	2.0a	UDDS28k	noCRT	53.3	15.7	0.559	0.470	123.3	125.5	2%
5	2.0a	UDDS28k	noCRT	54.1	16.0	0.589	0.507	127.6	129.7	2%
6	2.0b	UDDS58k	BP1%	66.7	19.7	0.088	0.000	15.5		
7	2.0b	UDDS58k	BP1%	69.8	20.5	0.036	0.038	6.0	6.2	3%
8	2.0b	SS_2%Grade	BP1%	190.8	61.5	0.064	0.063	3.6	3.6	-1%
9	2.0b	SS_2%Grade	BP20%	201.2	22.1	0.159	0.156	25.0	24.8	-1%
10	2.0b	SS_2%Grade	BP20%	201.9	26.0	0.197	0.198	26.3	26.3	0%

8.3 Real time bsPM from filter pressure drop

During testing with and without the CRT, the real time estimation of PM emission factors was evaluated to see if one could estimate short 30 second PM emission factors from real time filter pressure drop measurements. As the gravimetric filter is loaded with PM the pressure drop increases across the filter. The amount of pressure drop is related to the mass accumulated on the filter. As such, the filter pressure drop was measured across the filter in real time during testing in to investigate this signal for total filter weight determination and possible NTE and WBW bsPM calculations. The non-CRT tests showed high pressure drop response compared to the test with the CRT. These two different test cases provided a unique opportunity to assess the ability to evaluate short 30 second PM emission factors above and below the in-use compliance specification.

Figure 31 and Figure 32 show the filter pressure drop across the gravimetric filter for the test vehicle equipped without the CRT (Figure 31) and with the CRT (Figure 32). The pressure drop in Figure 31 is initially low because the gravimetric filter is in bypass mode (i.e. flow is going around the filter). Once the sample mode is commanded the pressure increases to the pressure drop of a clean filter. The figure shows as pressure increases on the filter more PM mass is accumulating. The final net pressure increase in Figure 31 was 62 inH_20 and in Figure 32 was 8 inH_20. The pressure increases represented an emission rate of 129.7 mg/hp-h and 6.2 mg/hp-h bsPM respectively.

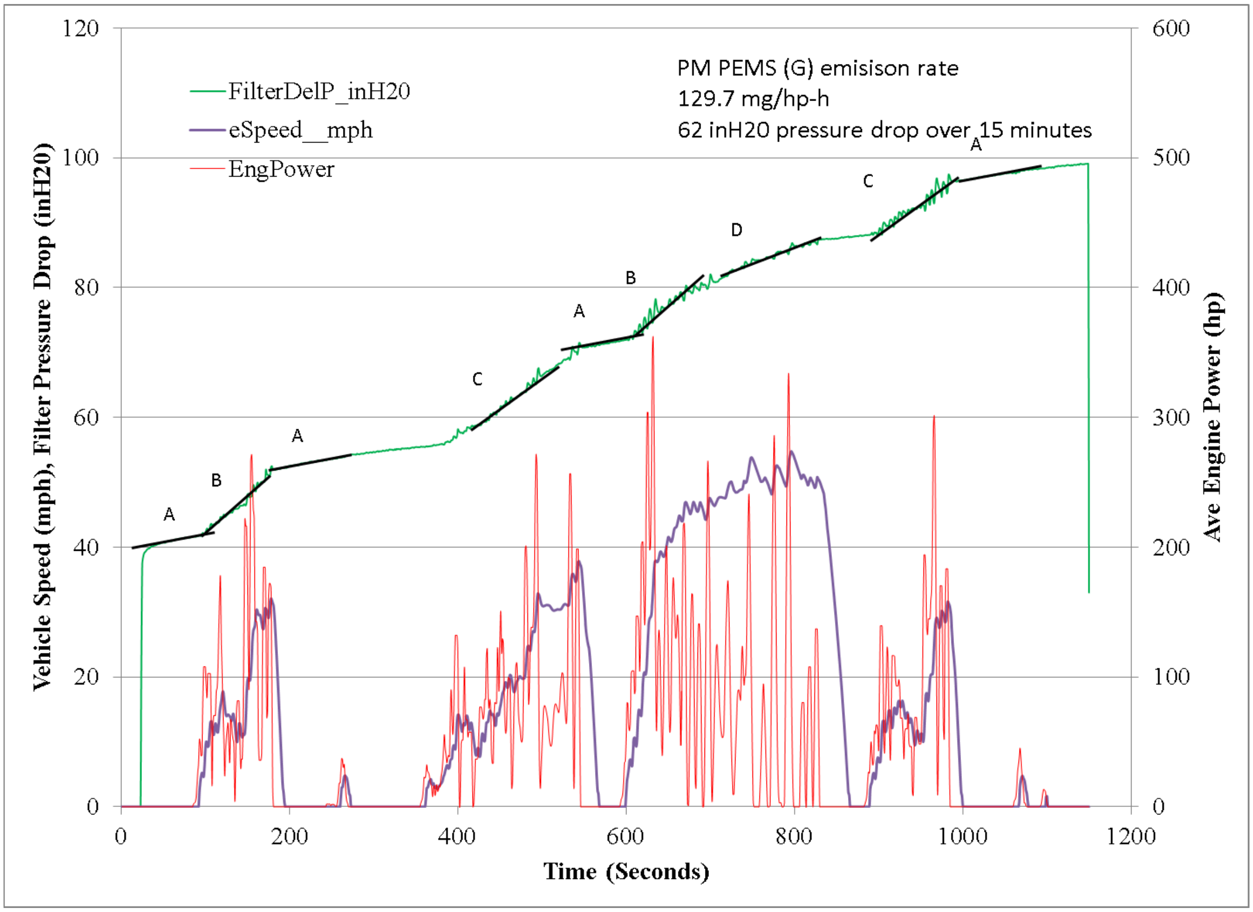


Figure 31 Pressure drop across the filter without a CRT equipped engine

[1] The lines "A", "B", "C", and "D" represent similar pressure drop slops across the filter. The pressure drop slope can be used to proportion the mass emission rate during the test.

Figure 31 shows four different slopes identified where "A" represents the idle condition, "B" represents type 1 acceleration, "C" represents type 2 acceleration, and "D" represents a cruise type of operation (still transient, but relatively stable engine speed). These modes represent different emission rates that could be quantified in bsPM emission factors using the pressure drop measurement.

The slopes were much lower during the CRT test compared to the non-CRT test. Figure 32 shows the pressure drop had one general slope for the full UDDS test. The "A" through "D" lines in Figure 32 are copied from Figure 31 to show a relative difference in pressure drop rates between the two tests. The dotted green line in Figure 32 is the sample pressure drop signal, but scaled to see it easier with in the figure. The pressure drop trend across the CRT filter shows no significant PM loading difference between idle, cruise, and accelerations. If only the cruise section was utilized the emission rate would be approximately 2 mg/hp-h due to the numerator being constant, but the denominator being much larger (i.e. removal of idle and low power conditions).

Both figures show the ability to calculate short 30 second NTE bsPM emission rates using pressure drop over the filter. These results suggest using a gravimetric filter and pressure drop may be a reliable method for quantifying NTE and WBW PM emission rates over a range of operation conditions, fuel sources, and PM composition.

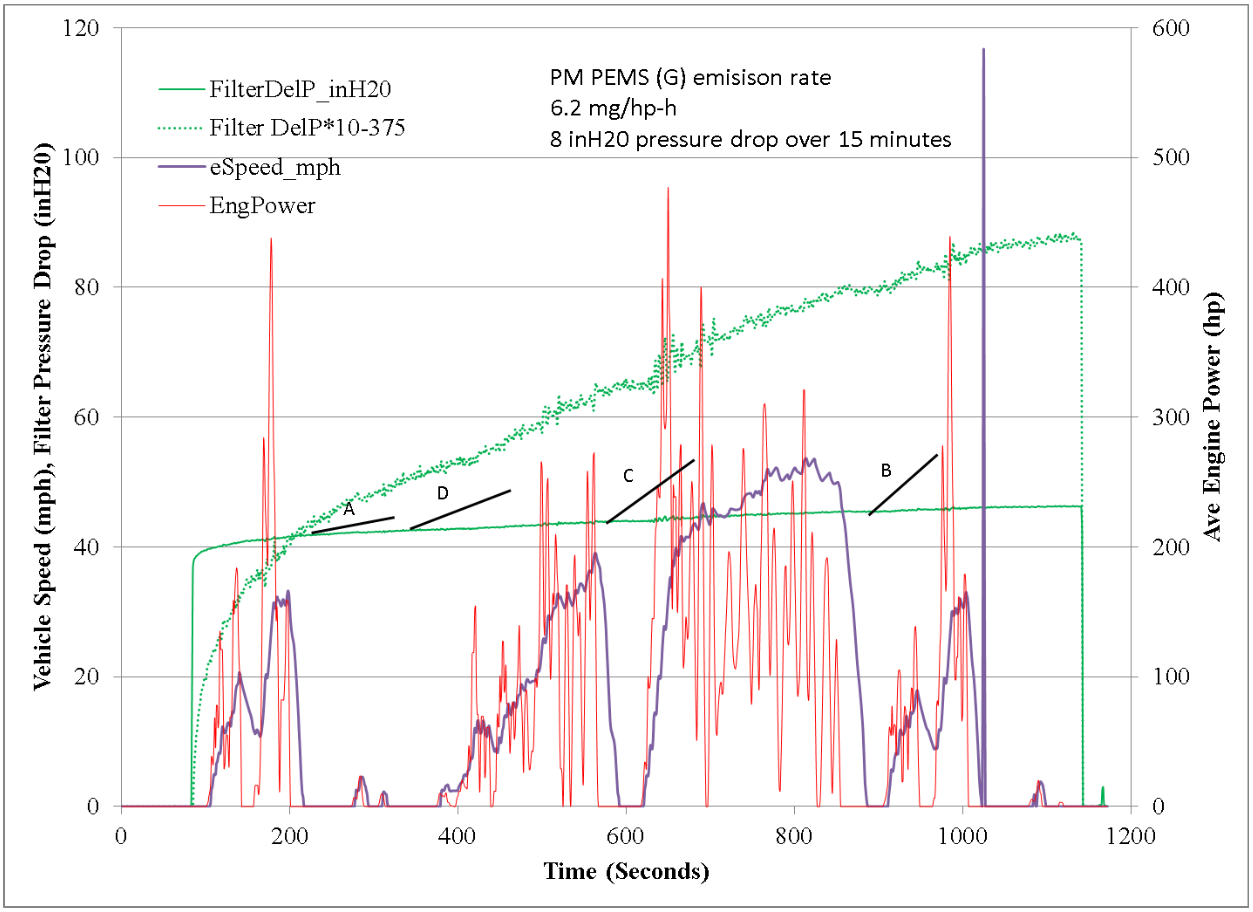


Figure 32 Pressure drop across the filter for a CRT equipped engine

[1] The lines "A", "B", "C", and "D" represent filter pressure drop slopes found during testing of the same vehicle equipped without the CRT, see Figure 31. The measured slopes for the test article with the CRT were much less that with the CRT.

8.4 Proportionality

Proportionality during the Version 2.0a and 2.0b chassis dynamometer testing was found to be similar to the Version 2.0a on-road testing. This can be seen in Figure 33 where the real time proportionality screen shot was captured during testing. The proportionality had an R^2 of 0.994 and a SEE/mean of 2.9% (< 10%). The other tests showed similar performance for proportionality.

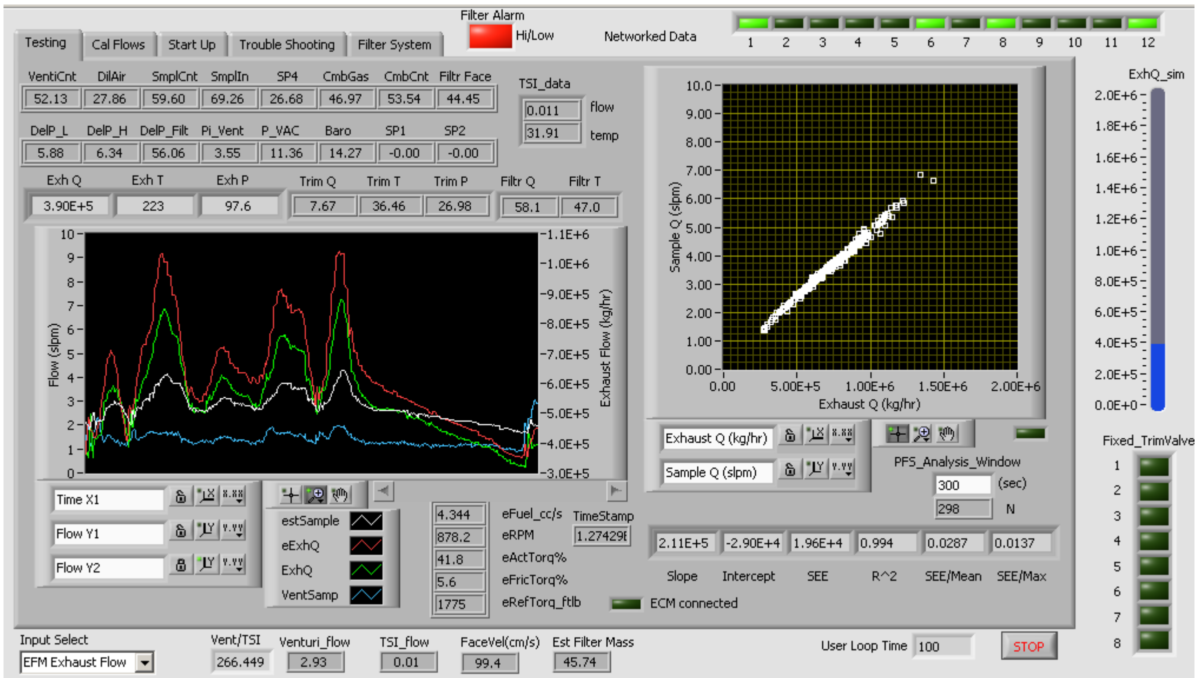


Figure 33 Proportionality screen-shot during transfer line chassis testing

8.5 Issues and resolutions

The issues and resolutions during this final set of testing was limited to the exhaust flow measurement system and staff not following the procedures for operating the PM PEMS (G) Version 2.0a system.

8.5.1 Exhaust flow bias

The exhaust flow meter was freezing during the on-road testing and during the first chassis testing as described previously. During the second chassis testing campaign, the exhaust flow meter was noticed to be reporting very low exhaust flows and proportionality was only reach 30% of maximum exhaust flow. This was unusual since during typical accelerations exhaust flow would go to about 70% of maximum. Testing was immediately paused and the exhaust flow meter was investigated.

It was found that the local EFM LCD screen was reporting erroneous information. It appeared the controller managing the EFM's systems was damaged. After several power cycles the system was restored. After restarting it was noticed though the flow was still very low. Further investigation identified that the EFM had lost its control parameters such as the calibration "K" factor, tube ID setting, and possibly other internal settings. We called the manufacturer and discussed resolutions. We were instructed to simply connect the EFM to a computer to update the embedded micro controller. UCR had experience doing this during the measurement allowance program with the same manufacturer (Johnson et al 2009). UCR was able to restore the parameters and verified the correct outputted units.

8.5.2 Exhaust flow calibration

UCR noticed there was still a large negative bias between the reported EFM value and the measured value by UCR's MEL after completing the micro controller update discussed previously. During the on-road testing the bias was -10%, but after the electrical issue the bias in this test session was as large as -20%. During previous usage of three other EFM's the bias ranged from ±10%. It is unclear what may be causing the -20% negative bias in this testing, but in order to complete the research, the EFM was verified for linearity and repeatability using UCR's MEL.

Figure 34 shows five steady state load calibration points with UCR's MEL measurement on the x-axis and the EFM flow meter on the y-axis. The tests were performed under steady state stabilized test points and represent real world conditions. The high R^2 and low SEE of 2800 kg/hr suggest the EFM reliable for proportionality, but not for total mass calculation. The data in this section is based on the proportionality of the exhaust flow meter, but the mass based emissions are based on the MEL corrected exhaust flow calibrations shown in Figure 34.

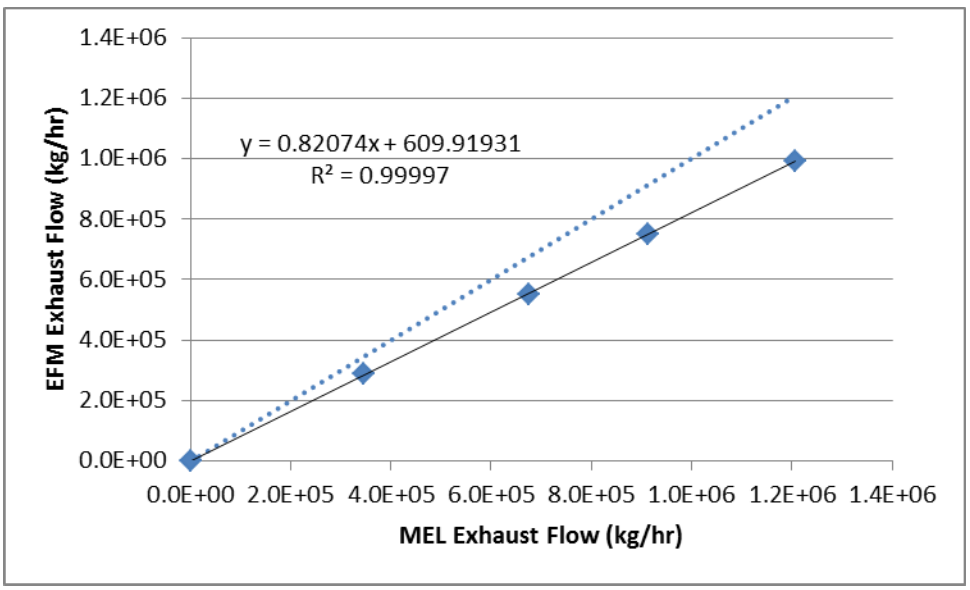


Figure 34 EFM calibration during a steady state flow check with the MEL

9 Summary and Conclusions

This report describes the development and evaluation of a high quality, robust, multi-filter indexing gravimetric PM measurement system (referred to as a PM PEMS (G) in this report). The PM PEMS (G) was designed for autonomous, all day in-use operation, for up to 30 gravimetric PM events in a single shift while following 40 CFR part 1066 and 1065 sampling specifications. The developed system was designed to quantify PM mass for in-use confirmatory testing on gasoline, alternative fuels, bio diesels, and diesel sources (on-highway, non-road, and marine) while utilizing the gravimetric reference method.

The main observations of this research are summarized below:

- The multi-filter operation was successfully compared against UCR's MEL during chassis and in-use on-road operation.
- Accurate, robust, and responsive flow measurements are critical for the accurate determination of dilution ratio and overall mass calculations. Improved 1% flow measurement devices were utilized with ultra-low drift specifications.
- Filter face velocities matching that of the reference method were implemented into a portable system using high sample flows.
- Fast acting solenoid valves combined with orifices provided a 10 ms control response time of the proportional flow system. The response time exceeds the specifications of 200 ms.
- On-road proportionality meets the specification requirement of <5% of SEE/Max exhaust flow and typically met this for SEE/Mean exhaust flow for the revised system. An earlier version showed poor proportionality that exceeded the 5% SEE/Max exhaust flow specification.
- Sample flow estimation by difference of dilution and total flow requires better than 2% flow accuracy to minimizing deviation during variable conditions and is thus not recommended.
- A custom made sample venturi was implemented for the determination of sample flow and to prevent sample flow estimates by the difference of dilution and total flow.
- The PM PEMS (G) system agrees well with a CVS reference method for soot and organic PM dominated sources.
- The PM PEMS (G) system showed a poor comparison to the MEL for tests with high sustained exhaust temperatures with a CRT equipped engine. The relative error was greatly minimized by the use of a metallic transfer line. It is believed the error may be from losses of sulfate forming species to the walls of the flexible transfer line. The high sulfate PM formation is typical of DPF regenerations found on most heavy duty diesel engines and thus the results is an important finding for in-use testing.
- Additional testing of a PEMS transfer line for regenerating type PM is needed to fully characterize and quantify the impact PEMS may have on in-use PM emissions from modern diesel engines with aftertreatment.
- The version of the PM PEMS (G) system with a metallic line agrees well with a diesel engine equipped with a CRT that is operated with sustained temperatures over 300C.
- Real time estimation of filter loading was determined using on-line differential pressure measurements across the sample filter. The real time assessment appears to work on 30

second windowed events and was able to identify emission rates above and below 30 mg/hp-h NTE compliance threshold.

- Pressure drop across the filter may be a suitable metric for quantifying short 30 second PM emission factors. This approach could be applied to the NTE, W, and other sub filter sampled events. Additional analysis is needed to confirm these results.
- Having numerous filter based samples during a day of testing can be used for later laboratory analysis to help investigate unique events identified during posttest analysis. As such, the PM PEMS (G) gravimetric filters additional expand the significance of this tool for PM research from in-use sources where posttest analysis hypothesis is common.
- The commercially available exhaust flow meter failed once on each of the testing campaigns. A reliable exhaust flow measurements are needed in order to reliably control the PM PEMS (G) system.

10 Future Work

The PM PEMS (G) system was shown to be a successful in-use PM measurement system for a wide range of conditions. During its development issues were identified and successes were noted, but not fully developed. This section summarizes some additional work that could be performed to complete the analysis and approach of a in-use PM PEMS (G) system.

- Repeat the metallic line tests with the non-CRT case. This was not performed during the main study and it would provide a direct comparison to the sulfate tests
- The EFM was shown to be an unreliable yet critical element of the PM PEMS (G) system. Only one test was performed with the ECM based exhaust flow meter operation. As such repeating additional tests with the ECM system would help demonstrate the accuracy of this system over a range of conditions.
- The PM PEMS (G) demonstrated potential NTE application with pressure drop over a filter. Additional testing and analysis is needed to investigate the benefit and applicability of this for NTE compliance testing. Questions to answer are what is the uncertainty in gravimetric filter back pressure PM mass prediction? What detection limits could be quantified? How practical is it for various emissions sources?

References

AVL 494 product manual for the PM PEMS 2010

ATI multi-filter indexing system product manual 2013

Bergmann, M., Scheer, V., Vogt, R., Benter, T., 2007. Instrumentation for Vehicle Exhaust Measurements, SAE 2007-24-0116

Cocker, Shah, Johnson, Miller and Norbeck, 2004. "Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines I. Regulated Gaseous Emissions," Environ. Sci. Technol., 38, 2182-2189.

Cocker, Shah, Johnson, Miller and Norbeck, 2004. "Development and Application of a Mobile Laboratory for Measuring Emissions From Diesel Engines. II. Sampling for Toxics and Particulate Matter," Environ. Sci. Technol., 38, 6809-6816.

Durbin., T.D., Johnson, K.C., Heejung J., and Cocker, D.R., 2009a. PM PEMS Pre-Measurement Allowance On-Road Evaluation and Investigation, Final Report to the Measurement Allowance Steering Committee, January.

Durbin., T.D., Johnson, K.C., Heejung J., and Cocker, D., R., 2009b. PM PEMS On-Road Investigation – With and Without DPF Equipped Engines, Final Report to the Engine Manufactures Association, July.

Durbin, T.D., Johnson, K.C., Cocker, D.R and Miller, J.W., 2007. Evaluation and Comparison of Portable Emission Measurement Systems and Federal Reference Methods for Emissions from a Back-Up Generator and a Diesel Truck Operated on a Chassis Dynamometer, Environ. Sci. Technol., 41, 6199-6204.

Durbin, T.D., Jung, H., Cocker R.D., Johnson, K.C., Chaudhary, A., 2008. Evaluation of the Proposed New European Methodology for Determination of Particle Number Emissions and its Potential in California for In-Use Screening, Final Report to the California Air Resources Board.

Grose, M.H. Sakurai, J. Savstrom, M.R. Stolzenburg, W.F. Watts, Jr., C.G. Morgan, I.P. Murray, M.V. Twigg, D.B. Kittelson, and P. H. McMurry, 2006. "Chemical and Physical Properties of Ultrafine Diesel Exhaust Particles Sampled Downstream of a Catalytic Trap," Environ. Sci. Technol., 40, 5502 – 5507.

Johnson, K.C., Durbin,, T.D., Heejung J., Cocker, D.R., and Khan, M.Y., 2010. Validation Testing for the PM-PEMS Measurement Allowance Program, Final Report to California Air Resources Board Contract # 07-620, November.

Johnson, K.C., Durbin, T.D., Heejung J., Cocker, D., R., Miller W.J., Bishnu D.K., Maldonado, H., Moynahan, N., Ensfield, C., and Laroo, C., 2009. On-road comparison of a portable emission measurement system with a mobile reference laboratory for a heavy-duty vehicle, Atmospheric Environment, 43, 2877-2883.

Johnson, K.C., Durbin, T.D., Jung, H., Chaudhary, A., Cocker III, D.R., Herner, J.D., Robertson, W., H., Huai, T., Ayala, A., and Kittelson, D., 2009. Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy-Duty Diesel Vehicles, Aerosol Science and Technology, 43, 962 – 969.

Johnson, K., 2009. Metrolink Verification and In-use Activity Assessment, Final Report.

Khan, M. Yusuf, Kent C. Johnson, Thomas D. Durbin, Heejung Jung, David R. Cocker III, Dipak Bishnu, Robert Giannelli, 2012. Characterization of PM-PEMS for in-use measurements conducted during validation testing for the PM-PEMS measurement allowance program, Atmospheric Environment 55, 311-318.

Kittelson, D.B., W.F. Watts, J.P. Johnson, C. Rowntree, M. Payne, S. Goodier, C. Warrens, H. Preston, U. Zink, M. Ortiz, C. Goersmann, M. V. Twigg, A. P. Walker, and R. Caldow. 2006. On-Road Evaluation of Two Diesel Exhaust Aftertreatment Devices, Journal of Aerosol Science, 37, 1140-1151.

Kittelson, D.B., Hands, T., Nickolaus, C., et al., 2004. Mass Correlation of Engine Emissions with Spectral Instruments JSAE Paper 20045462.

Lehmann, U., Niemela, V., and Morh, M., 2004. New Methods for Time Resolved Diesel Engine Exhaust Particle Mass Measurements, Environ. Sci. Technol., 38, 5704-5711.

Maricq M.M., Xu N., Chase R.E., 2006. Measuring Particulate Mass Emissions with Electrical Low Pressure Impactor, Aerosol Science and Technology, 40, 68-79.

Maricq, M.M., Chase, R.E., Podsiadlik, D.H., Xu, N., 2004. Time-Resolved Measurements of Exhaust PM for FTP-75: Comparison of LII, ELPI, and TEOM Techniques. SAE 2004-01-0964.

Miller, J.W., Durbin, T.D., Johnson, K., D.R. Cocker III, D.R., 2007. Measurement Allowance Project – On-Road Validation. Measurement Allowance Steering Committee, August.

Miller, J.W., Durbin, T.D., Johnson, K., 2002. Airport Ground Support Activity Assessment and Characterization, Final Report.

Podsiadlik, D.H., Chase, R.E., Lewis, D., Spears, M., 2003. Phase-Based TEOM Measurements Compared With Traditional Filters for Diesel PM, SAE 2003-01-0783.

Sensors High Speed Exhaust Flow Manual, 2011 March.

Smallwood, G.J., Snelling, D.R., Gülder, Ö.L. Clavel, D., Gareau, D., Sawchuk, R.A., and Graham, L., 2001. Transient Particulate Matter Measurements from the Exhaust of a Direct Injection Spark Ignition Automobile. SAE Technical Paper No. 2001-01-3581.

Timko, Michael T., Yu, Zhenhong, Kroll, Jesse, Jayne, John T., Worsnop, Douglas R., Miake-Lye, Richard C.,Onasch, Timothy B., Liscinsky, David, Kirchstetter, Thomas W., Destaillats, Hugo, Holder, Amara L., Smith, Jared D. and Wilson, Kevin R. 2009. 'Sampling Artifacts from Conductive Silicone Tubing', Aerosol Science and Technology, 43, 855 – 865.

Appendix A. System specifications and compliance

Table D-1 ISO 16183 and 40 CFR 1065 Specifications for Partial flow systems

Item	ISO	40 CFR 1065	Parameters	Current ISO Limit	40 CFR 1065 Limit	PM PEMS (G) System
1	6.3	205	Flow meter accuracies	2% of reading	2% of reading, 1% noise, 1.25% of pt repeatability	meets
2	6.4	140(d)(3)(i)	Response time	=< 0.5 second	≤ 0.2 second	100 ms
3		140(e)(3)	Residence time		1 to 5 seconds	2 seconds
5	6.4.1 6.4.2 6.4.3 6.4.4		Exhaust flow measurement method	• Direct exhaust method • Air and fuel method • Tracer method • Air flow and air to fuel ratio method		
6	6.6.1		Proportionality	Correlation coefficient R^2 linear regression between Qsample and Qexhaust ≤ 0.9.		Verified
7	6.6.1		Prop. Verification	The standard error of estimate SEE of Qsample on Qexhaust shall < 5% of Qexhaust max.		Verified
8	6.6.1		Prop. Verification	Qexhaust max intercept of the regression ≤ ± 2% of Qsample maximum.		Verified
9	8.1.1.2		Filter size	PM filters must have a minimum diameter of 47mm. Larger diameter filters are acceptable.		47mm
11	8.1.1.4	170(c)(1)(vi)	Filter face velocity	A gas face velocity through the filter of 35 to 100 cm/s	Target 100 cm/s with max 5% of points over 100 cm/s	Meets
12				The filter pressure drop should be limited to 300 mbar at 100 cm/sec face velocity.		300 mbar
16	8.1.3		Qsample accuracy	Absolute accuracy of Qsample ≤ 5% at a dilution ratio of 15.		Meets
17	8.1.4		Additional specifications	Minimize particle deposition or alteration of the particulates.		Utilized
18	8.2.3		Sampling probe	The minimum I.D. shall be 4mm.		Meets
20			Type of probe	Open tube facing to upstream or downstream, or Multiple hole or hatted probe facing to upstream		Hatted probe facing upstream
35			Temperature	May be heated to no greater than 52degC.	47 ± 5 deg C	meets

41	8.3.2.1	Sample flow calibration check and verification	Qsample is calibrated for at least 5 points. a)Direct connection of two flow meters. b)Using calibrated massflow device for calibration. c)Directly calibrate the Qsample, by disconnect the transfer tube d)A tracer gas method		Recmd. c
42	8.3.2.2	Pre-test check	Pre-test check shall be performed within 2 hours before the test run.		Meets requirement

Appendix B. Hardware documentation

This Appendix includes a summary of the parts utilized for the PM PEMS (G) system, see Table B-1 and Figures A-1 through A-6. Additional information on the system parts are provided with the system. Many of these documents are hard copies and are provided in a binder to accompany the final report and are not scanned as part of this electronic copy of the final report.

Table B-1 Parts List for PM PEMS(G) system

Description	Quant	Manufacturer	Vendor	Part #
Pall HEPA filter	2	Pall	Pall	12144
Data logger PC	1	Stealth	Stealth	LPC-125LPFM
Date logger TC	1	MCC	Measurement Computing	USB-TC
Date logger A/D and I/O	1	MCC	Measurement Computing	USB-1608G
Date logger RS232	2	USB Gear	USB Gear	USBG4U3ML
Date logger GPS	1	Garman		18X
Temperatures sensors	10	Omega	Omega	KMQSS-125U-4
Barometric Pressure Transducer	1	Omega	Omega	PX2760-600A5V
Stack Pressure Transducer	1	Omega	Omega	PX309-002G5V
Diluter	1	UCR machine shop	UCR	DIL01
Cal Flow meter		TSI	TSI	4040
SSR relays		Crydom	Crydom	DRA-1-CXE240D5R
Heater controller				TM4
USB hub				
USB to serial 4-port	2	Serial Gear		4USBRS232
Filter changer				
Plumbing				
Mounting box		Armando Cases		
Red-Y MFC pressure		Vogtlin	Meas. And Control	GSC-D3SA-BB12
Red-Y MFC vacuum		Vogtlin	Meas. And Control	GSC-D3SA-BB99
Solenoid valve		ASCO	Mc Master Carr	8215G2
Tygon tubing			Mc Master Carr	various
Stack pressure				
Venturi dif pressure				
Alicat flow meter				
Micro valve + manifold				
Precisions pres regulator				
Valve manifold				

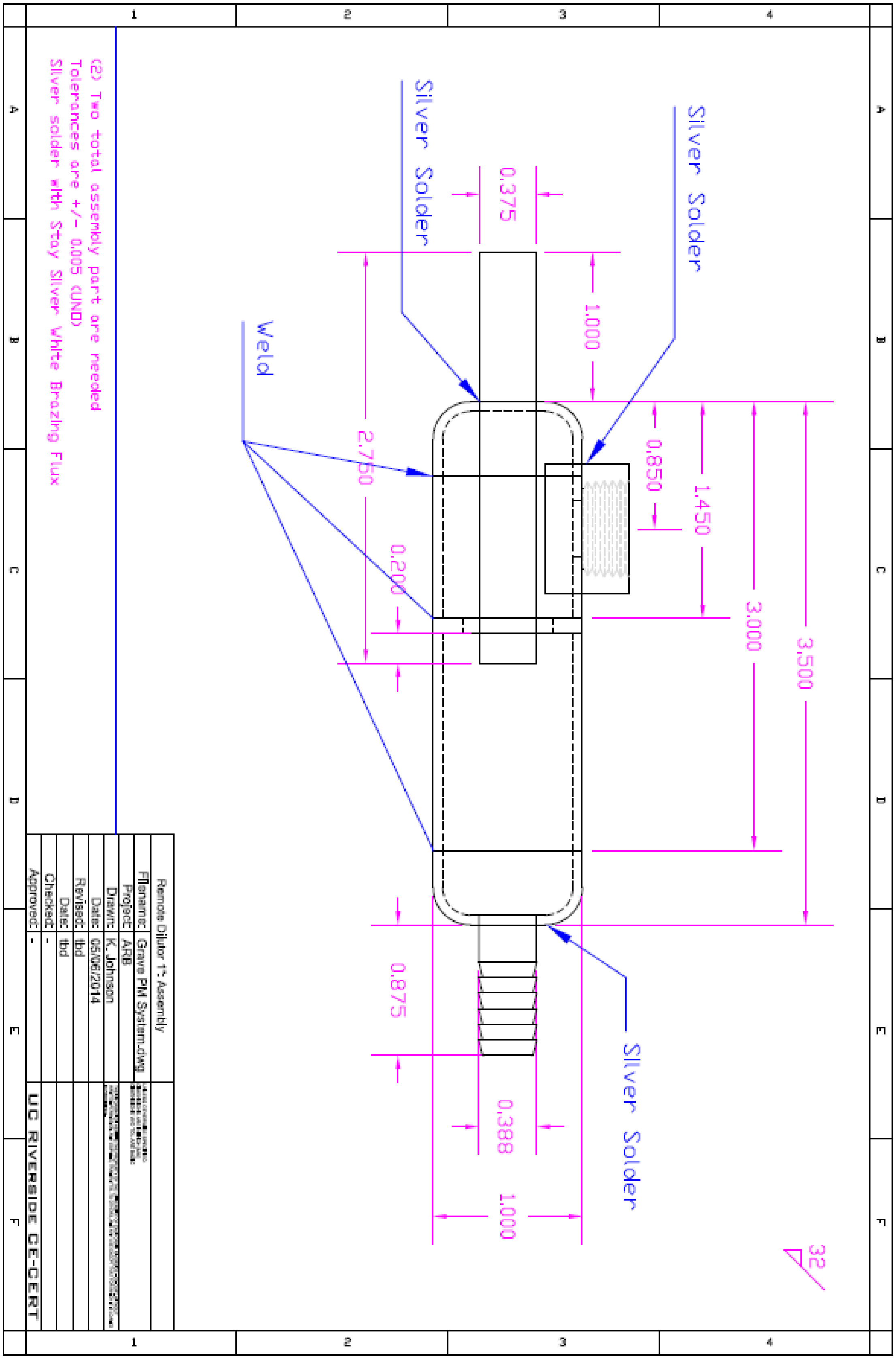


Figure B-1 Dilutor assembly drawing

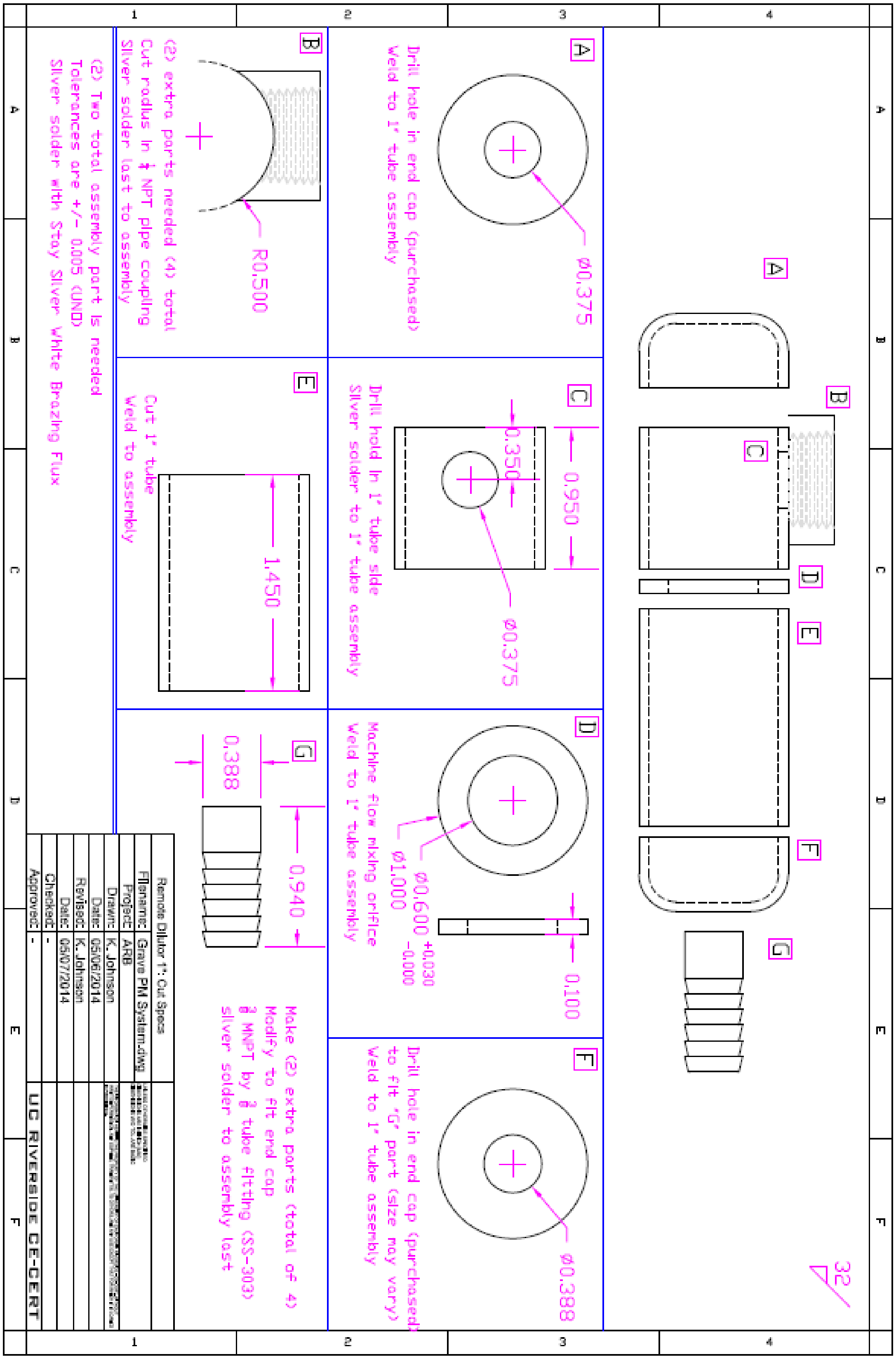


Figure B-2 Dilutor assembly drawing details

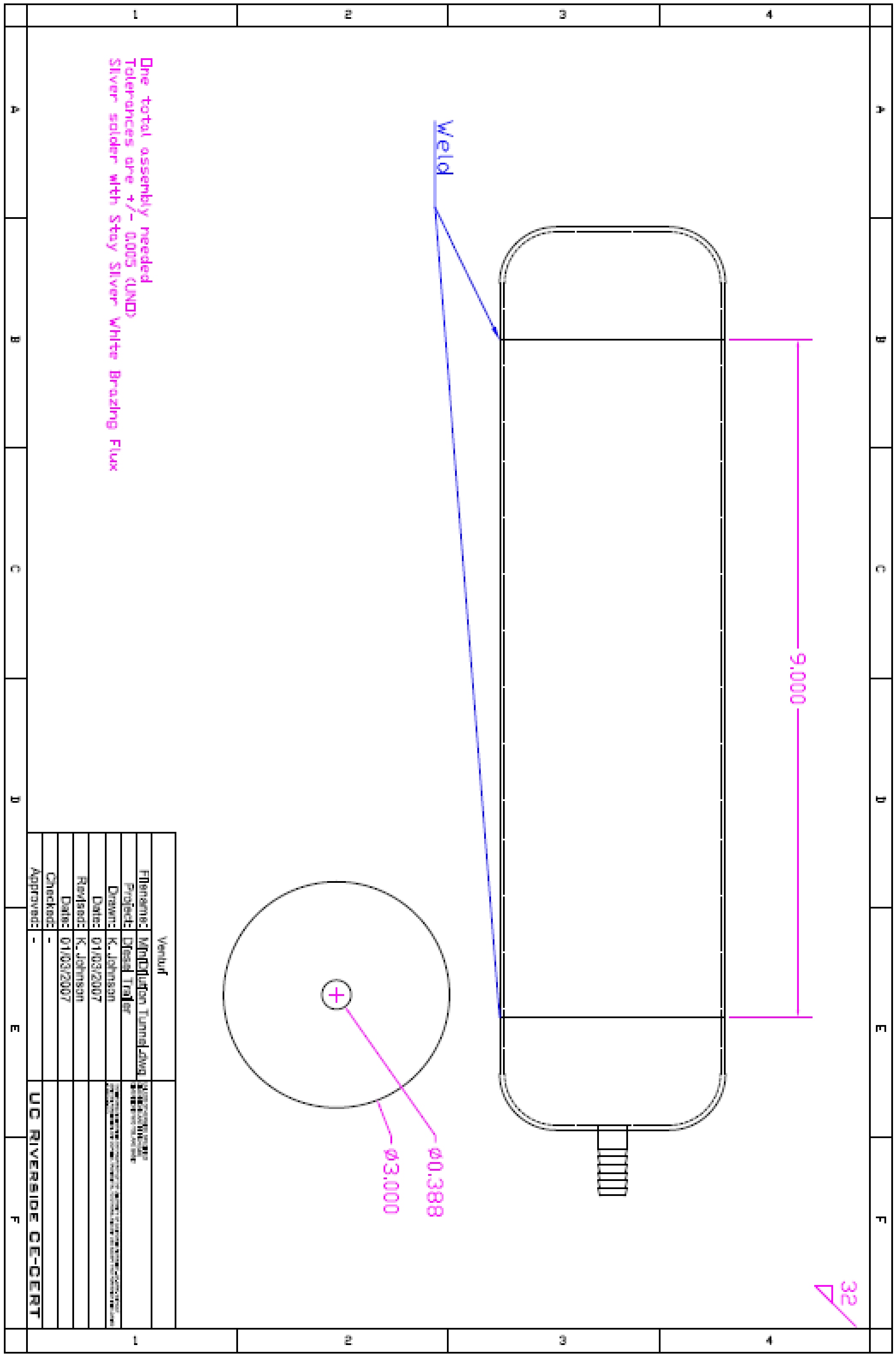


Figure B-3 Residence chamber assembly drawing details

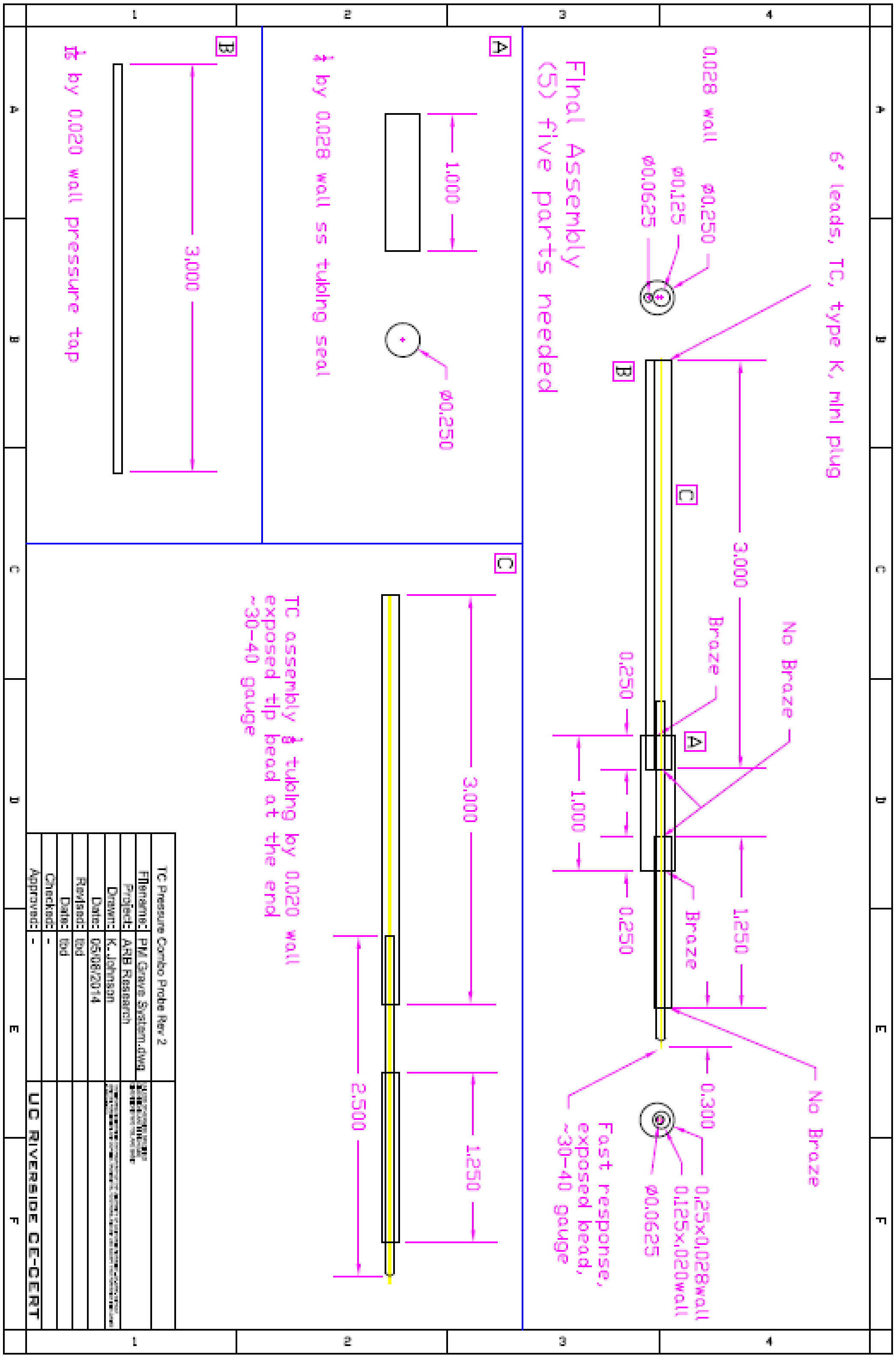


Figure B-4 Thermocouple and pressure tap assembly: to Wilcon Inds.

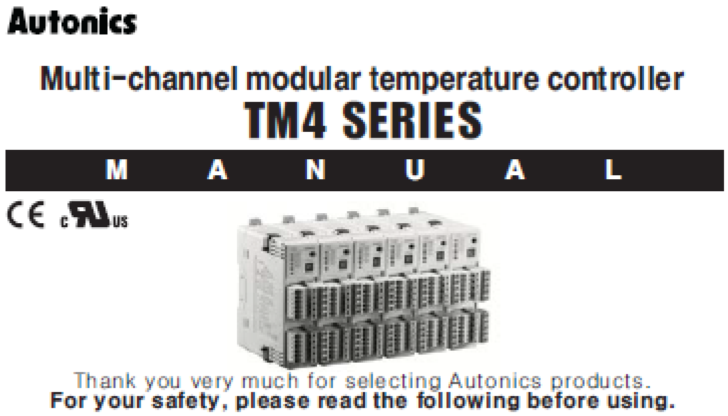
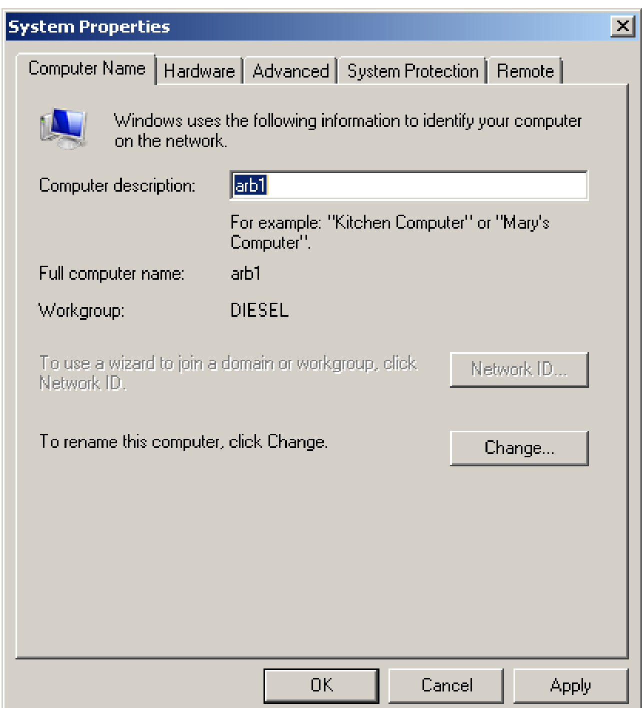


Figure B-5 TM4 temperature controller

Computer control systems, memory,case,drive,cpu,Windos os. Jetway HBJC600C99352W-BWM Mini-Top/OS Atom Dual-Core 525 Intel NM10 NVIDIA ION2 WiFi Remote Control with 320G HD Mini Barebone. Intel Atom D525 (1.8GHz, Dual-Core)
http://www.newegg.com/Product/Product.aspx?Item=N82E16856107080

G.SKILL 4GB 204-Pin DDR3 SO-DIMM DDR3 1066 (PC3 8500) Laptop Memory Model F3-8500CL7S-4GBSQ http://www.newegg.com/Product/Product.aspx?Item=N82E16820231265



System control computer name and workgroups

Metal Orifice Air Flow – SLPM

Orifice Diameter Inches		0.004	0.005	0.006	0.007	0.008	0.009	0.010	0.011	0.012	0.013	0.014	0.015	0.016	0.017	0.018	0.019	0.020	0.021	0.022	0.023	0.024	0.025	0.026	0.027	0.028	0.029	0.031	0.032	0.033
Size Number		**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**31**	**32**	**33**
C_v		0.00035	0.00061	0.00086	0.0012	0.0015	0.0019	0.0025	0.0028	0.0034	0.0038	0.0043	0.0050	0.0055	0.0067	0.0073	0.0080	0.0088	0.0096	0.011	0.012	0.013	0.014	0.016	0.017	0.018	0.019	0.022	0.024	0.025
Supply Pressure – psig	1	0.035	0.064	0.086	0.127	0.170	0.226	0.280	0.308	0.398	0.45	0.52	0.61	0.66	0.77	0.86	0.96	1.05	1.13	1.29	1.41	1.54	1.67	1.91	1.95	2.21	2.39	2.65	2.88	3.03
	5	0.09	0.16	0.21	0.30	0.40	0.52	0.65	0.71	0.92	1.06	1.21	1.41	1.54	1.76	1.98	2.22	2.47	2.65	2.97	3.24	3.53	3.83	4.34	4.44	4.94	5.31	5.86	6.42	6.80
	10	0.12	0.22	0.31	0.43	0.57	0.74	0.93	1.01	1.29	1.48	1.68	1.95	2.01	2.26	2.54	2.83	3.16	3.53	4.33	4.75	5.18	5.55	6.15	6.43	7.18	7.83	8.63	9.40	9.98
	15	0.16	0.28	0.39	0.54	0.72	0.93	1.17	1.26	1.62	1.85	2.10	2.44	2.50	2.85	3.23	3.57	4.01	4.41	5.35	5.93	6.43	6.95	7.58	7.95	8.78	9.58	10.6	11.6	12.3
	20	0.19	0.33	0.46	0.65	0.85	1.10	1.38	1.49	1.92	2.19	2.49	2.87	2.97	3.40	3.86	4.26	4.84	5.22	6.35	6.95	7.58	8.15	8.90	9.28	10.3	11.2	12.4	13.5	14.3
	25	0.22	0.39	0.53	0.75	0.98	1.27	1.59	1.71	2.20	2.50	2.86	3.28	3.42	3.92	4.45	4.91	5.59	6.01	7.30	7.95	8.65	9.38	10.2	10.7	11.7	12.8	14.2	15.4	16.3
	30	0.25	0.44	0.60	0.85	1.12	1.43	1.80	1.93	2.47	2.82	3.21	3.69	3.87	4.43	5.03	5.56	6.33	6.81	8.23	8.98	9.75	10.6	11.5	12.0	13.2	14.4	15.9	17.3	18.4
	40	0.30	0.54	0.74	1.05	1.38	1.77	2.21	2.37	3.04	3.45	3.93	4.51	4.78	5.47	6.21	6.85	7.81	8.42	10.1	11.0	12.0	13.0	14.1	14.7	16.1	17.5	19.4	21.1	22.5
	50	0.36	0.65	0.88	1.26	1.65	2.10	2.62	2.80	3.58	4.07	4.64	5.31	5.70	6.51	7.40	8.15	9.26	10.0	11.9	13.0	14.2	15.4	16.6	17.3	19.0	20.7	22.9	25.0	26.6
	60	0.42	0.75	1.02	1.46	1.91	2.42	3.02	3.23	4.13	4.70	5.34	6.13	6.61	7.56	8.58	9.46	10.7	11.6	13.8	15.0	16.4	17.7	19.2	20.0	21.9	23.8	26.4	28.8	30.7
	70	0.48	0.86	1.16	1.67	2.17	2.75	3.43	3.66	4.68	5.32	6.05	6.96	7.53	8.61	9.77	10.8	12.2	13.2	15.6	17.0	18.5	20.1	21.7	22.7	24.8	27.0	30.0	32.7	34.9
	80	0.54	0.96	1.30	1.87	2.43	3.08	3.83	4.09	5.23	5.95	6.77	7.79	8.46	9.67	11.0	12.1	13.7	14.9	17.5	19.0	20.7	22.5	24.2	25.3	27.7	30.2	33.6	36.7	39.0
	90	0.60	1.07	1.44	2.08	2.69	3.40	4.23	4.51	5.78	6.58	7.49	8.62	9.38	10.7	12.2	13.4	15.2	16.5	19.3	21.0	22.9	24.9	26.8	28.0	30.7	33.5	37.2	40.6	43.2
	100	0.66	1.17	1.58	2.28	2.95	3.72	4.63	4.94	6.33	7.22	8.21	9.46	10.3	11.8	13.4	14.7	16.6	18.0	21.1	23.0	25.1	27.4	29.4	30.8	33.7	36.8	40.9	44.6	47.5
Vacuum Level In. Hg.	5	0.053	0.096	0.129	0.191	0.253	0.332	0.406	0.450	0.582	0.661	0.773	0.899	0.977	1.14	1.28	1.41	1.55	1.70	1.90	2.10	2.30	2.48	2.74	2.83	3.16	3.41	3.78	4.12	4.32
	10	0.069	0.124	0.168	0.246	0.324	0.421	0.519	0.564	0.730	0.834	0.972	1.12	1.24	1.41	1.58	1.79	1.96	2.18	2.44	2.68	2.89	3.13	3.44	3.58	4.00	4.30	4.77	5.16	5.43
Choked Flow	15	0.075	0.134	0.185	0.268	0.351	0.455	0.566	0.614	0.792	0.902	1.07	1.22	1.35	1.55	1.75	1.94	2.19	2.32	2.61	2.85	3.12	3.34	3.65	3.78	4.20	4.51	5.05	5.45	5.72
	20	0.075	0.134	0.185	0.268	0.351	0.455	0.566	0.614	0.792	0.902	1.07	1.22	1.35	1.55	1.75	1.94	2.19	2.32	2.61	2.85	3.12	3.34	3.65	3.78	4.20	4.51	5.05	5.45	5.72
	30	0.075	0.134	0.185	0.268	0.351	0.455	0.566	0.614	0.792	0.902	1.07	1.22	1.35	1.55	1.75	1.94	2.19	2.32	2.61	2.85	3.12	3.34	3.65	3.78	4.20	4.51	5.05	5.45	5.72

Orifice Diameter Inches		0.035	0.037	0.038	0.039	0.04	0.041	0.042	0.043	0.047	0.052	0.055	0.06	0.063	0.067	0.07	0.073	0.076	0.079	0.081	0.086	0.089	0.094	0.096	0.1	0.104	0.109	0.113	0.12	0.125
Size Number		**35**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**47**	**52**	**55**	**60**	**63**	**67**	**70**	**73**	**76**	**79**	**81**	**86**	**89**	**94**	**96**	**100**	**104**	**109**	**113**	**120**	**125**
C_v		0.028	0.031	0.032	0.033	0.036	0.038	0.039	0.041	0.048	0.059	0.068	0.081	0.088	0.1	0.11	0.12	0.13	0.14	0.15	0.17	0.18	0.2	0.21	0.23	0.25	0.27	0.31	0.34	0.37
Supply Pressure – psig	1	3.48	3.83	4.13	4.46	4.6	4.67	4.99	5.36	6.43	8.04	9.4	11.2	12.2	14.2	15.9	16.9	18.5	20.3	21.7	23.5	25.4	28.4	30.1	32.9	35.5	39.6	43.1	47.8	50.1
	5	7.67	8.48	9.09	9.7	10.2	10.6	11.3	12.1	14.2	17.6	20.3	23.9	26.1	30.3	33.8	36.1	39.4	43.1	46	51.1	54.9	61.9	65	70.8	76.6	84.8	92.1	102	108
	10	10.6	11.8	12.5	13.6	14.4	14.8	15.6	16.8	19.4	24.5	27.1	32.2	35.2	40.7	45.6	48.5	52.9	57.3	61.6	67.9	72.3	81	85.5	92.3	102	112	118	135	148
	15	13.1	14.5	15.4	16.7	17.7	18.2	19.1	20.4	23.6	29.7	32.9	39	42.6	49.3	55.3	58.8	64	69.4	74.5	82.1	87.3	97.8	103	111	123	135	143	163	178
	20	15.3	17	18.1	19.6	20.9	21.4	22.5	24	27.7	35	38.7	45.9	50.1	58	65	69	75.3	81.4	87.3	95.6	102	114	121	130	144	158	167	190	210
	25	17.7	19.6	20.8	22.6	24	24.7	25.9	27.6	31.9	40.3	44.6	52.8	57.7	66.7	74.7	79.3	86.4	93.5	100	110	117	131	138	149	164	180	191	219	241
	30	20	22.2	23.6	25.6	27.2	28	29.4	31.3	36	45.6	50.4	59.7	65.2	75.4	84.3	89.5	97.4	105	113	125	132	148	156	168	185	204	216	248	273
	40	24.8	27.4	31.7	31.6	33.6	34.6	36.3	38.7	44.5	56.3	62.2	73.6	80.3	92.7	104	110	120	129	139	153	162	181	191	207	228	251	267	306	337
	50	29.5	32.6	34.8	37.6	40.1	41.3	43.3	46	52.9	66.9	74	87.4	95.4	110	123	131	142	153	164	181	192	215	227	247	272	299	317	364	401
	60	34.3	38	40.6	43.8	46.7	48.1	50.3	53.5	61.5	77.7	85.8	101	110	127	142	151	164	177	189	210	223	250	264	286	315	347	368	422	465
	70	39.2	43.3	46.3	50	53.3	55	57.4	61	70	88.4	97.6	115	126	145	162	171	186	202	216	240	254	285	301	327	360	396	421	482	531
	80	44	48.7	52.1	56.2	60	61.9	64.5	68.5	78.6	99.1	109	129	141	162	181	191	209	227	242	269	285	320	338	367	404	445	472	541	596
	90	50	54.2	57.8	62.4	66.7	68.9	71.5	76	87.2	109	121	143	156	179	200	211	231	251	268	298	316	354	374	406	447	492	522	598	660
	100	53.9	59.6	63.7	68.7	73.5	77.3	78.6	83.5	95.8	120	133	156	171	196	221	234	255	277	296	329	349	392	413	449	494	544	578	662	729
Vacuum Level In. Hg.	5	4.92	5.4	5.81	6.29	6.76	6.82	7.29	7.67	9.08	11.3	12.4	14.8	17.1	20	22.5	23.9	26	28.3	30.2	33.2	35.9	40.1	41.8	45.3	49	53.9	57.9	65.3	70.9
	10	6.18	6.78	7.29	7.85	8.31	8.5	9.08	9.58	11.1	13.9	15.4	18.2	21.2	24.4	27.2	29.9	32.5	35.3	37.7	41.5	44.8	50	52.1	56.6	61.2	67.2	72.2	81.4	88.4
Choked Flow	15	6.5	7.17	7.63	8.22	8.66	8.87	9.46	10	11.6	14.4	15.9	18.6	22.1	25.5	28.4	31.2	33.9	36.8	39.4	43.3	46.7	52.1	54.4	59	63.8	70.1	75.3	84.9	92.2
	20	6.5	7.17	7.63	8.22	8.66	8.87	9.46	10	11.6	14.4	15.9	18.6	22.1	25.5	28.4	31.2	33.9	36.8	39.4	43.3	46.7	52.1	54.4	59	63.8	70.1	75.3	84.9	92.2
	30	6.5	7.17	7.63	8.22	8.66	8.87	9.46	10	11.6	14.4	15.9	18.6	22.1	25.5	28.4	31.2	33.9	36.8	39.4	43.3	46.7	52.1	54.4	59	63.8	70.1	75.3	84.9	92.2

Standard Conditions 70°F, 14.7 psia

SCFH – Standard Cu. Ft. Per Hour
SLPM – Standard Liters Per Minute

Above data obtained with Type B restrictor. Flow rates for other metal restrictors are essentially the same as for Type B. Above data supercedes previous publications.

Appendix C. Variable Flow Pump Method

Another low power approach could be used to control the filter sample flow with a high capacity variable flow pump system integrated with a feedback mass flow meter. This approach is used by Control Sistem in their micro-PM system, and this system is able to achieve recommended filter face velocities of Part 1065 and ISO (100 cm/sec). The pressure fluctuations do not cause instabilities and the system has been demonstrated by Control Sistem to be capable of meeting Part 1065 and ISO specifications. The system uses a Thomas variable flow pump as shown in Figure C-1. The pump is capable of 75 lpm flow at ambient conditions and approximately 55 lpm at 300 mbar of pressure drop due to the gravimetric filter. This pressure drop is equivalent to approximately 400-300 μg of filter weight, depending on the filter manufacturer selected.

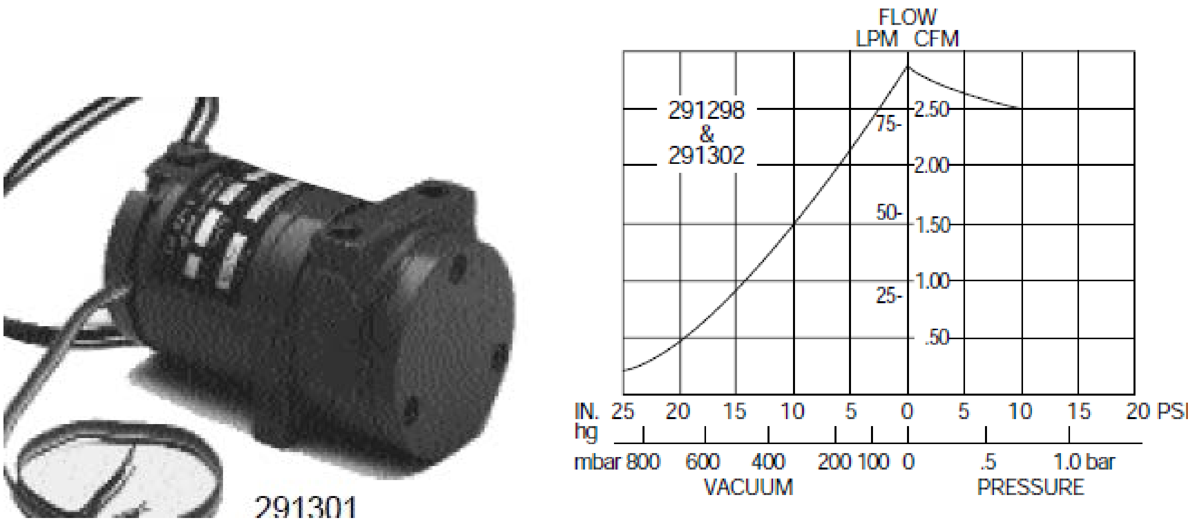


Figure C-1 Variable flow pump and associated performance curve.

Appendix D. Software documentation

The Lab View program is open source so it can be modified and updated as needed. The main program "Grave_PM_V01" contains the main program and calls the sub vi's. The program is divided into three stacks called "stack sequences". Each one is utilized for a specific purpose. On execution the first "sequence 0" is initializes all the hardware, variables, and other details of the program, see Figure C-1. The next sequence executes the main program in real time and allows the user to make updates to the operation of the system. The last sequence is for closing and terminating all the details before the system is ended.

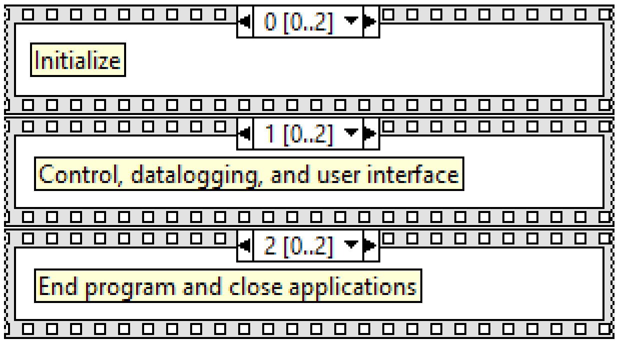


Figure C-1 Main program stack sequences

The main loop is executed in sequence 1 and is described in more detail here. The main loop has four timed while loops designed for specific purposes. The top three loops are the fastest at 10Hz and the bottom loop is the slowest at 1 Hz. The top loop "Control" has the highest priority where all the high speed control activities are performed and data is acquired. The next loop "Data Logging High Speed" has the next highest priority where all data is acquired from the hardware, average, and save 10Hz data to a file. The next loop "User Interface" has the lowest priority for the 10Hz loops, but fast enough for seamless operation. The last loop "Data Logging Low Speed" performs the low speed data logging and performs real time analysis and displays that information to the operator.

Each of these loops and sequence blocks perform specific functions. To add to this PM control system is easy and only requires an understanding of where to place the different pieces. To add a new device, place all the initialize routines in sequence "0". To add control and display put these in the different timed loop in sequence "1". And make sure all housekeeping is performed by putting proper hardware termination as you exit this control program.

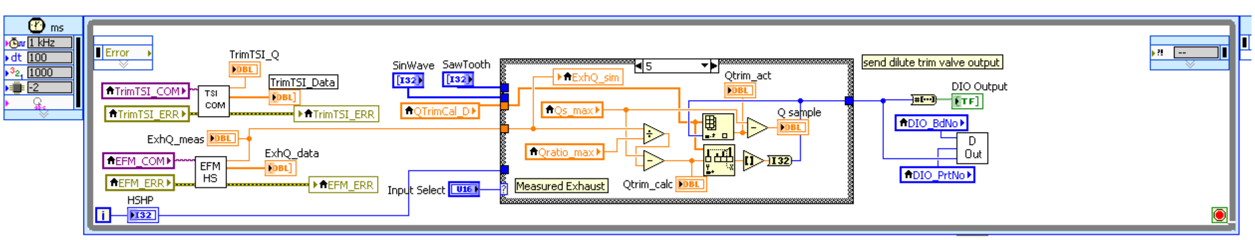


Figure C-2 Main control loop showing highest priority for control

Lable	Description (ref cond. 20c 1 atm)
ave_Sample_Q	calculated flow where Qsample = Qfilter - Qdilute.
Qdilute	Qtrim+Qbase
Qtrim_calc	Qs_max-ExhQ_meas/Qratio_max
ExhQ_meas	measured exhaust flow
Qratio_max	184600 kg/hr
Qs_max	10.83 slpm

Figure C-3 Main control loop constants and details for Beta V-01

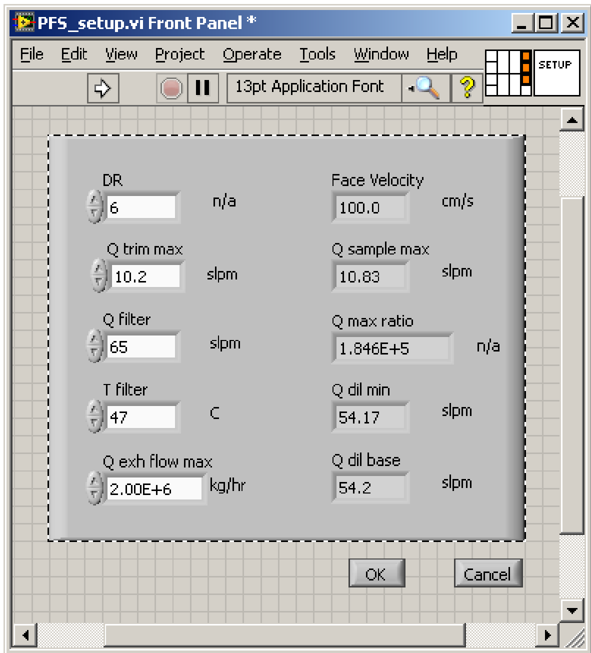


Figure C-4 Input table for PEMS operating details; Version 2

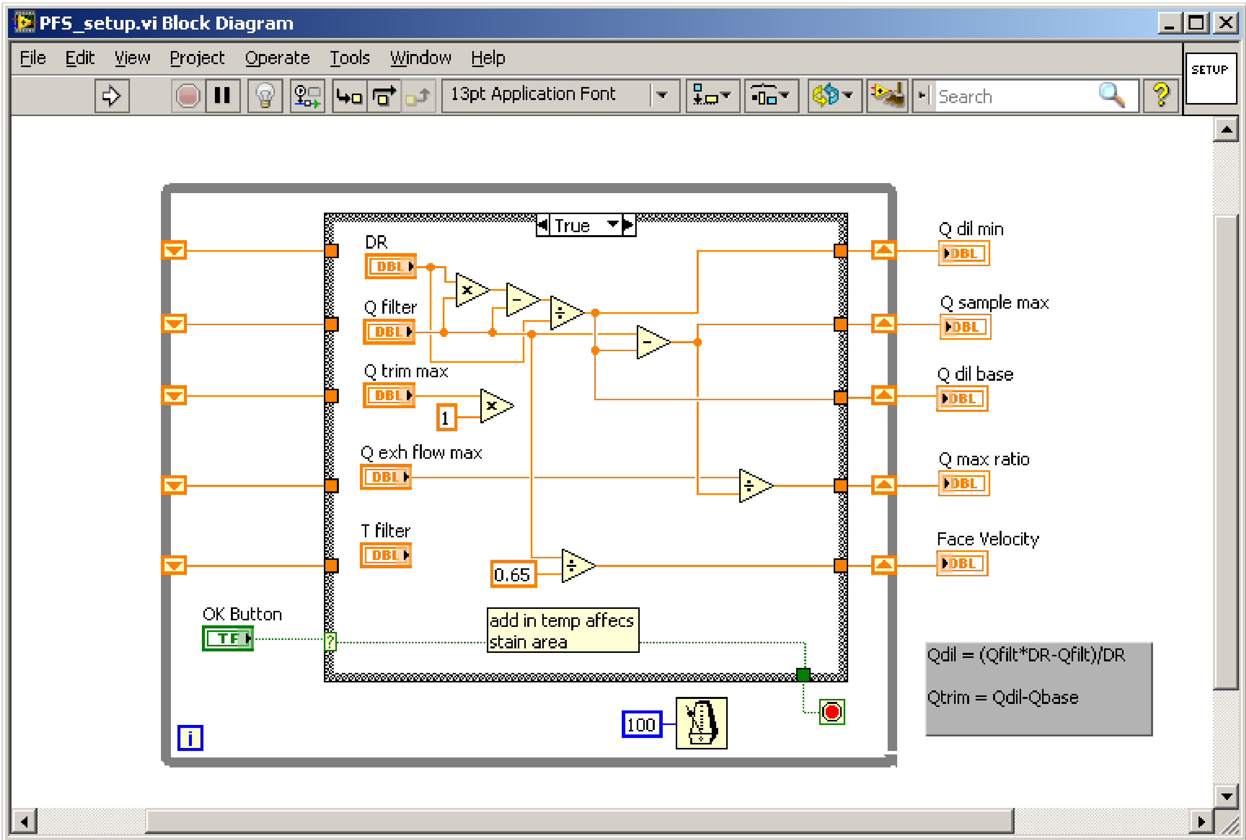
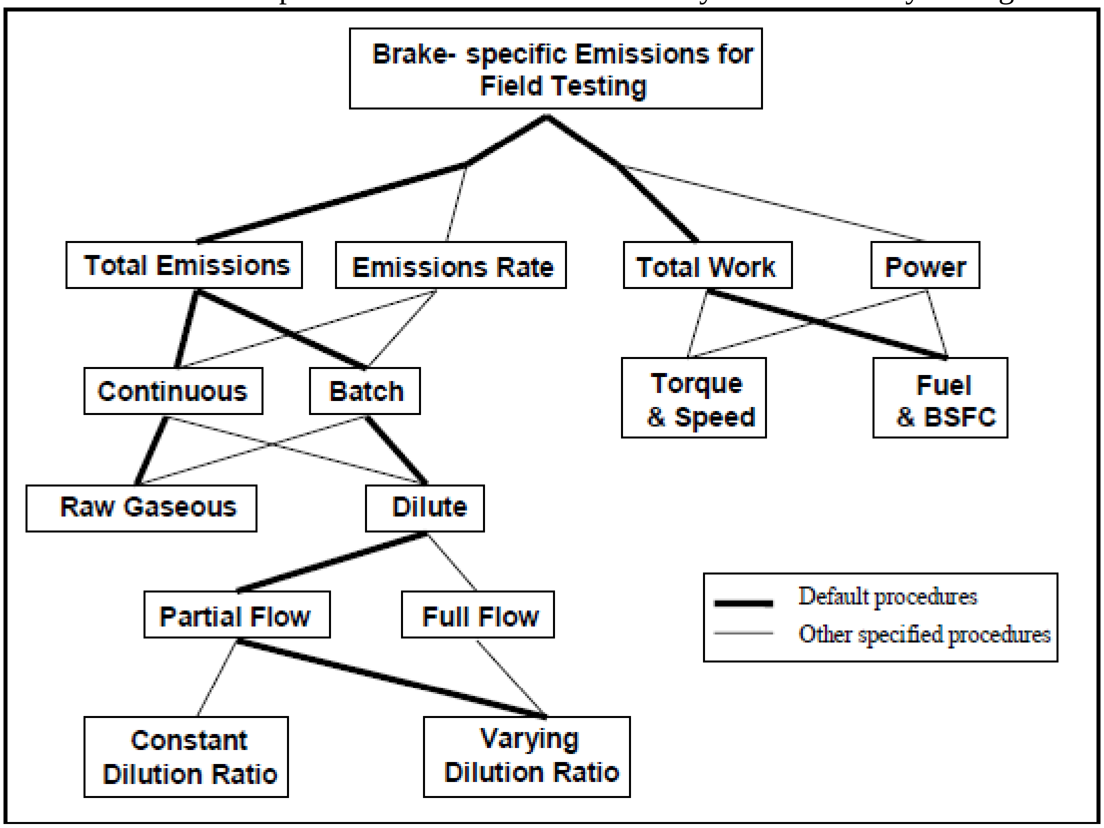


Figure C-5 Input code view for the input features; Version 2

Appendix E. 40CFR 1065 and 1066 Selected Reference Calculations

This appendix summarizes selected 40CFR Part 1066 and 1065 calculations utilized for partial flow dilution (PFD) PM mass calculations and references.

Figure 1 of §1065.15—Default test procedures and other specified procedures.
Also alternate procedure for transient and steady state laboratory testing



Dilution factor is calculated as:

$$DF = \frac{V_{\text{PMstd}}}{V_{\text{exhstd}}}$$

Eq. 1066.620-3

Where:

V_{PMstd} = total dilute exhaust volume sampled through the filter over the test interval at standard reference conditions.

V_{exhstd} = total exhaust volume sampled from the vehicle at standard reference conditions.

Example:

$V_{PMstd} = 170.9\ m^3$

$V_{exhstd} = 15.9\ m^3$

$$DF = \frac{170.9}{15.4} = 11.1$$

(i) Varying flow rate. If you collect a batch sample from a changing exhaust flow rate, extract a sample proportional to the changing exhaust flow rate. We consider the following to be examples of changing flows that require proportional sampling: raw exhaust, exhaust diluted with a constant flow rate of dilution air, and CVS dilution with a CVS flow meter that does not have an upstream heat exchanger or electronic flow control. Integrate the flow rate over a test interval to determine the total flow from which you extracted the proportional sample. Multiply the mean concentration of the batch sample by the total flow from which the sample was extracted. If the total emission is a molar quantity, convert this quantity to a mass by multiplying it by its molar mass, *M*. The result is the mass of the emission, *m*. In the case of PM emissions, where the mean PM concentration is already in units of mass per mole of sample, $\overline{M}_{PM}$, simply multiply it by the total flow. The result is the total mass of PM, m_{PM}. Calculate *m* for batch sampling with variable flow using the following equation:

$$m = M \cdot \overline{x} \cdot \sum_{i=1}^{N} \dot{n}_i \cdot \Delta t$$

Eq. 1065.650-6

Appendix F. Post processor description

The PM PEMS (G) post processor can be used two ways. The main program automatically processes all the data based on each filter sampled. This data is stored in a accumulated in an ASCI text file called “PM PEMS cycle info.txt”. The post processor can also be used on the raw data to make corrections for in-use issues resolved after testing is completed as typically occurs. The post processor for these data files is in a separate file accumulating each test run called “PM PEMS cycle info post.txt”.

These two methods allow the operator to maintain the database of information and to append unique data sets to different testing operations.

Appendix G. Recommended operating procedures

Version 2.0a & b

These operating procedures were developed during testing and evaluation of the PM PEMS (G) Version 2 system. These SOP represent the latest version of the procedure. These represent recommendations and are not necessarily comprehensive. These procedures represent a good starting point for in-use testing using the MultiFilter PM PEMS (G) system.

Startup Pre Test SOP

1. Time align your PM PEMS (G) clock with other computers being used
2. Calibrate the trim flow by running the “Trim Cal” program
3. Verify systems are operational
    a. ECM signal working (perform with engine key on)
    b. MFC communication
    c. Filter indexer communication
4. Turn on VAC pumps
5. Turn on Compressed air
6. Turn on heaters (verify temps increasing)

Prepare for test

1. Load filters (record ID’s loaded)
2. Update log books and notes

Starting a testing

1. Perform leak check (always perform just before testing)
2. Set proportionality mode
    a. ECM flow
    b. Measured exhaust flow
3. Start logging
4. Test is running

Testing

1. Set filter trigger mode
    a. Filter weight
    b. Work based window
    c. Time
    d. Manual
2. Start driving
3. Allow trigger mode to load PM on filter. If in Manual mode perform as needed.
4. Verify the following while testing
    a. Verify filter pressure drop is less than 400 inH20
    b. Verify filter temperatures are within 47C

c. Verify proportionality
d. Verify EFM flow (note EFM is known to drop out during testing)
e. Verify other data values are non-frozen

End testing SOP

1. Turn of auto mode
2. Turn off filter flows and systems
3. Remove the filter holders used (count and verify all accounted for)
4. Prepare for next test or shut down

Shut down SOP

1. Turn off heaters
2. Close all valves
3. Shut down programs
4. Remove pressure
5. Archive data to server
6. Process data files

Version 1.1

These operating procedures were developed during testing and evaluation of the PM PEMS (G) Version 1.1 system. These represent recommendations and are not necessarily comprehensive. These procedures do represent a good starting point for in-use testing using the MultiFilter PM PEMS (G) system.

Startup Pre Test SOP

3. Time align with MEL, AVL and PM PEMS
4. Verify all com ports working (two Sierra MFC's and TSI instruments)
5. Verify 1hz data is a full array (strange problem in Queue VI requiring multi restarts.)
6. Veriac setting (40%) and 20% Filter holder added one.
7. Target pressures (Ptrim 20, Pmain 30, P MFC 10 (when flowing 50)
8. Verify filter flow
    a. Blank filter (non tared)
    b. Turn on VAC pump
    c. Open flow valve
    d. Set base flow to 49.2
    e. Trim flow should be running at ~9slpm (auto tracking)
    f. Set filter flow to 59 ish
    g. Close flow valve
    h. Turn off VAC pump
9. Set base flow to 10 (to prevent sample contamination) trim flow still on also
10. Load filter (10 min before testing)

Start testing with/out MFC filter flow SOP

5. Turn on Vac pump
6. Start logging
7. Set base flow 49.2
8. Start test (truck 1st, 5 seconds later PM valve)
9. Immediately open valve and adjust filter flow targeting 59 (CW increases)
10. Continue to trim flow while testing

Ready Pre Test SOP

5. Verify in "auto exhflow mode"
6. Verify loaded filter
7. VAC pump on

Start testing SOP with MFC and bypass flow

8. Set MFC filter flow to 57
9. Start logging
10. Set base flow 49.2
11. Start test (truck 1st, 5 seconds later PM valve)

12. Switch valves at 5 seconds (slowly to prevent pressure spike)
13. Trim flow is automatic. Verify all operating
    a. Trim flow
    b. Filter temperature
    c. Filter flow

End testing SOP

5. Close filter valve
6. Reduce base flow to 5 slpm leave trim flow in auto mode
7. Leave trim flow on (auto is ~10)
8. Stop data logging
9. Remove filter and ready for next test

Shut down SOP

7. Close all valves
8. Shut down programs
9. Remove pressure

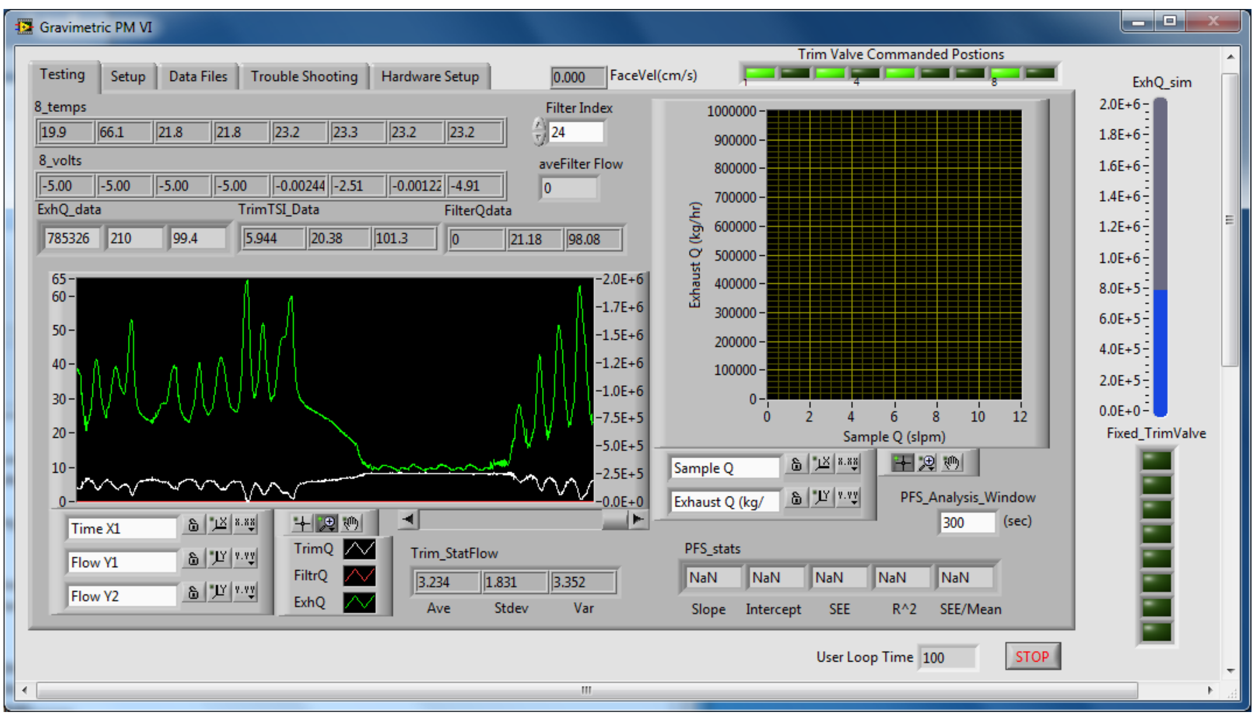


Figure F-1 Testing with dilution trim flow showing good stabilized response during small cruise section. No filter flow

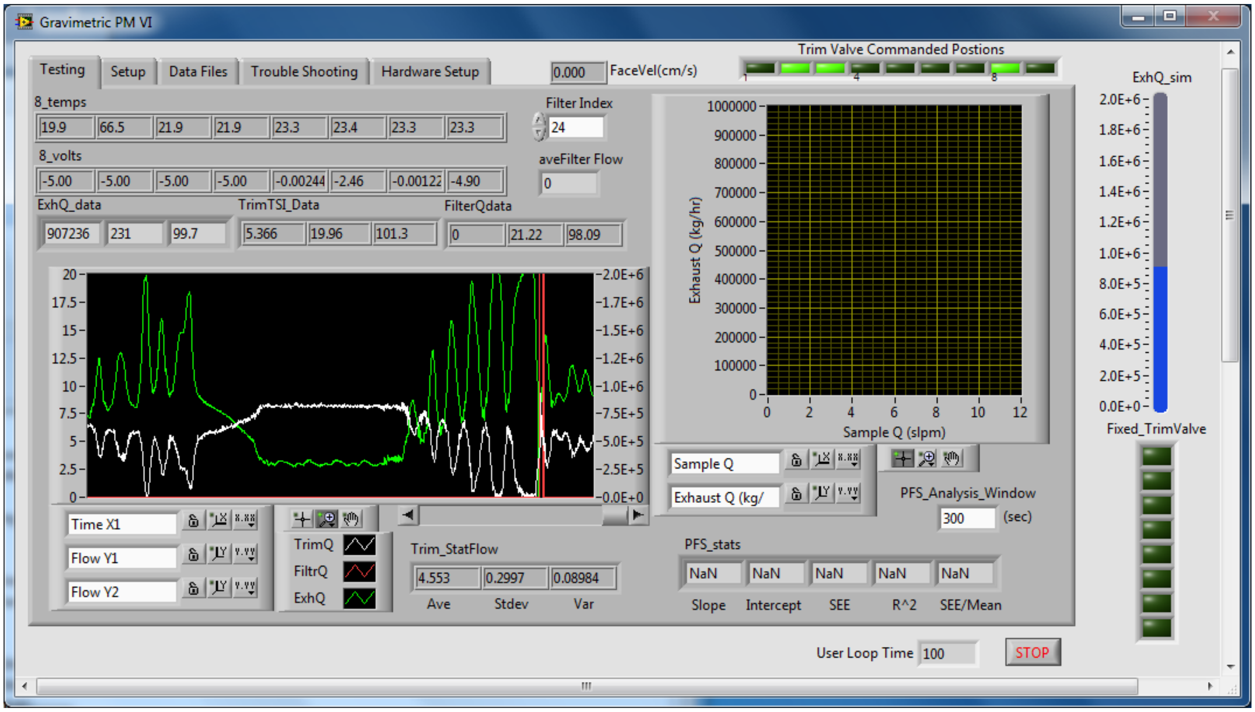


Figure F-2 Testing with dilution trim flow showing good stabilized response during small cruise section. No filter flow

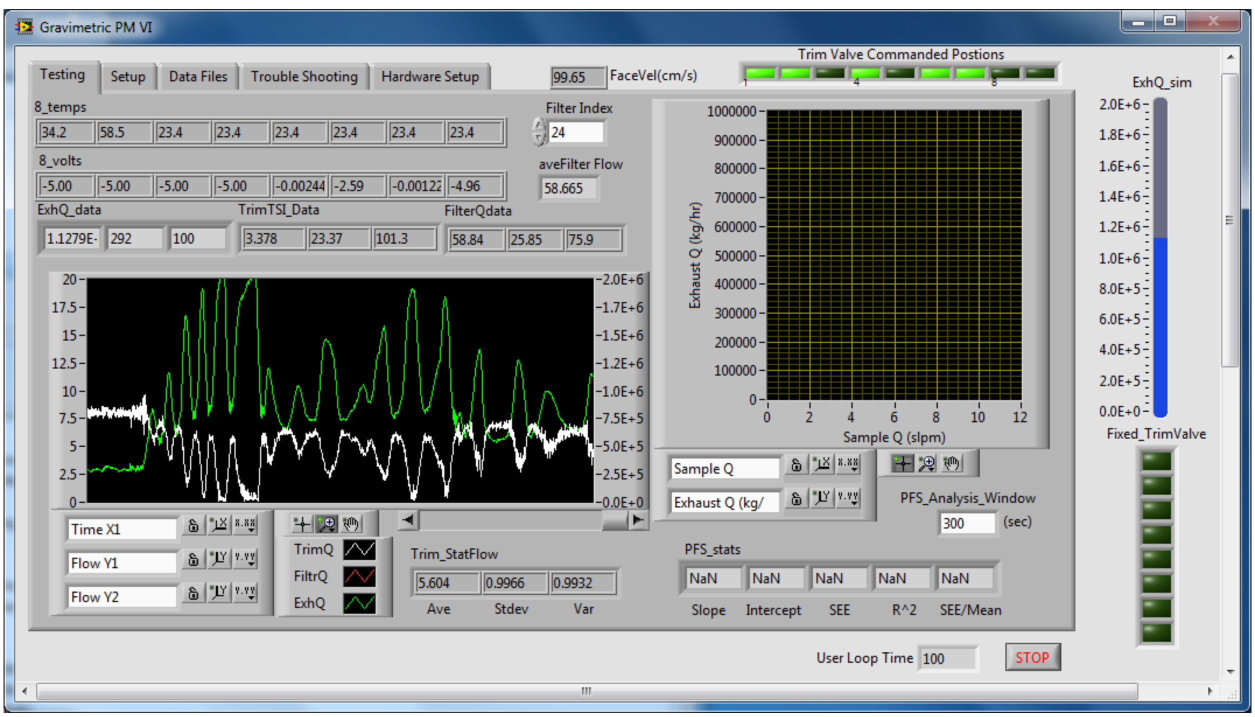


Figure F-3 UDDS testing with dilution trim flow showing good transient response to the dynamic exhaust flow with filter flow

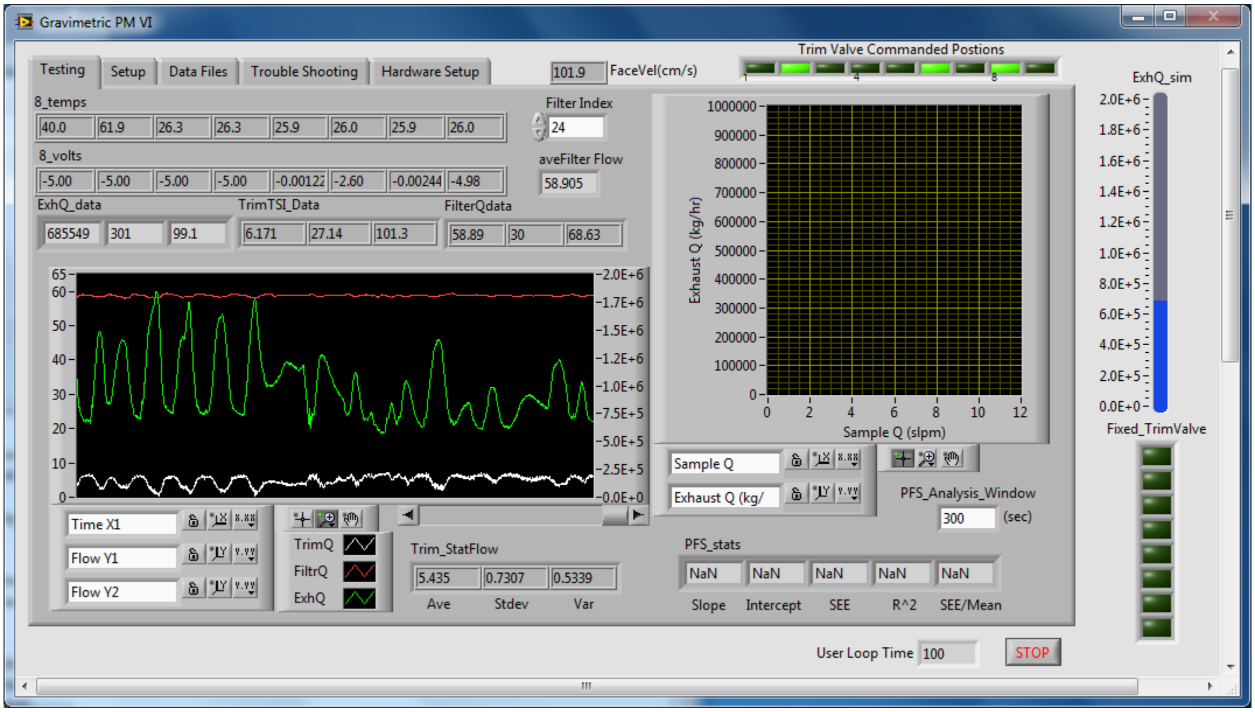


Figure F-4 UDDS Screen shot while testing. Stable filter flow and good transient response

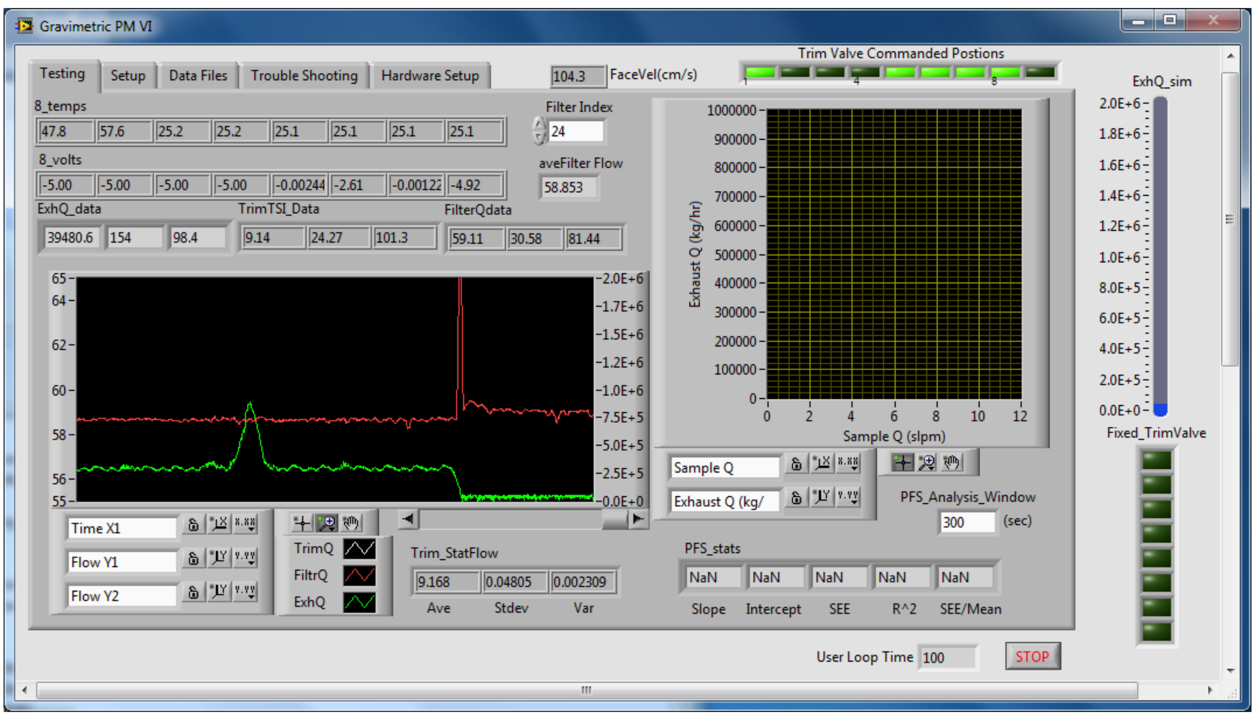


Figure F-5 End of test with the UDDS running. See the change in filter flow at the end of the test.

Appendix H. Test Logs

This appendix describes the details of all the tests performed on the system with explanation, comments, and changes made to improve the system. There are three groups the Ver-2b, Ver2a, and Ver1. The Ver1 was the first set of tests performed on the PM PEMS (G) system. Ver1 had manually controlled bypass valves, heaters, and no sample flow measurement, The V2a was the second set of tests with the modified system including the filter indexer. The final V2.0b was the on-road tests performed with the final controlling system.

PM PEMS (G) Ver1.0

Version 1 of the PM PEMS (G) system represents the first set of tests performed on the PM PEMS (G) system. Below are the typical Operational Settings Normal **Ptrim** = 20+, **Pmain** = 30, P_**MFC** = 10+ when flowing and 15 when off, **Max EFM** = 2.0×10^6, **Variac** = 35%, **Changing/removing filters SOP**: leave base flow on at 15 lpm, close vacuum flow, set trim flow to zero, and remove filer.

201305070902dIag – 1st preliminary test attempt.
201305070905Diag – UDDS attempt: EFM over ranged variable and MFC and trim flow pressure issue due to re-plumbing. Undid and put back to original. Fixed over ranged by increasing format identifier.
201305070949Diag – UDDS attempt #2. EFM max is 2×10^6. Looking good started with out of spec value fixed at about 9:50.
201305070955Diag – Full UDDS test #1. Trim pressure low at 17 psi not 20 psi as calibrated. Actual flows may be low by a little. MFC pressure at 15 psi inlet (facing gauge not 0-200)
201305071054Diag- Fixed minimum flow to 8 bits (10 slpm), updated pressures to 20 psi on trim and 25 on main (to MFC). Ideally use lower pressure on MFC. See if Kurt can come up with something. Kurt came up with a MFC regulator. Set pressures to Ptrim 20+, Pmain 30, P_MFC 10+ (when flowing at 50). Look into inverting signal to watch the trim flow track the exhaust flow in real time. Evaluated flow from UDDS test (looked good) see file SEE Evalu 1054.xlsx
201305071318Diag – Setting up filter probe with filter flow and bypass. FilterQ is now filter flow and not total dilute flow like in previous tests. Previous tests can be used to measure FilterQ = TrimQ+BaseQ vs adding of measured values. Tried manual adjustment at start. Didn't seem too effective. Left alone after mid of main hill. Seemed to be more stable this way. Bypass setting 0% (installed all the way closed). Filter ID T130116 (it was sampled with some ambient as we got things going and during the full UDDS test). Variac set to 25% and line was 43°C changing. Filter got reverse flow. Change end process.
201305071354Diag - Bypass setting 45% on bypass and 35% on main. Increased variac setting, new filter had less drop and had to adjust the bypass valve slightly, Not touching except for overall trim needs. **About 2-3 slpm variation in total flow** (how much will this affect proportionality?) Consider using an MFC or fast valve system. Verified pressures inputs, filter bypass flow needs to be zero when changing filters (back flowing). **Decelerations with EFM do not look real.** Look at this for the fuel flow comparison EcoStar and fuel flow. This test required a lot of bypass adjustment. MFM sure stabilizes near the end of the test (more delta P? reason)
201305080819Meas – fixed running average program. Calibration data. One valve at a time method. Trim Flow calibration only.

201305080823Meas – Calibration data main valves in order leaving on
201305080826Meas - Calibration data all valves LSB to MSB. (note last data point in data file is the filter flow. Fixed for future ones.
201305081245Meas – Test #4 UDDS. Data file header correct with data. Found leak with MFC flow due to extra valves on trim system. Filter ID T130115. Bypass 1. Start pressure on post filter TSI P indicator 80 kPa end. Tried measuring bypass flow (it was over 20 scfh). base flow at 10 first 2 seconds
201305081327Meas – Test #5 UDDS. Bypass 1, base flow at 10 first 2 seconds. Filter ID T130117.
201305081411Diag – Test #6 UDDS. Bypass 1, base flow at 49.2 at start. Start filter flow was 80. Open filter trim valve wide open to fix. Wow. TSI pressure at 82 kPa. Filter ID T130119.
201305090824Diag – Calibration run with Saw Tooth program. Use for TSI trim flow setting with filter flow set point at 57 slpm (59 slpm at 20°C) which is the actual conditions. Base flow is 49.2 slpm. Also did Sin wave program. Add control valve position to data log file for today.
201305090953Meas –UDDS test #7 with MFC added on filter control and bypass flowing startup process. Warm up, setup bypass flow with about same pressure drop. T130121 Filter flow 60, base flow 49.2,
201305091030Diag – UDDS test #8. Filter ID T130123, MFC 57, Use bump in flow data or EFM to find start of filter data logging. MFC inlet pressure was slightly low at 8 instead of 10. Adjusted after first 10 seconds. Interesting flow difference on MFC with and without vacuum drop from filter. Look at end of test when truck turned off and filters switched
201305091112Meas - UDDS test #9. Filter ID T130126, added extra filter heating on the filter holder using same variac. Dropped varic from 45% to 38% started cooling. Back to 45%. Strange at the end of the test the filter holder heater started to burn up the lines. Not sure why it got so hot. The filter temp shot up also (60 °C at the end) mostly conducting temperature. The filter was warm though so it is real.
201305091337Meas – Cruise Test #1. Filter ID T130127. Cruise control cruise. Increased older Variac to 28% from 25%. Filter was up to 70°C at end of continuous cruise. Could not cool down. Retest due to excessive heat. MFC lower flows actually at 55
201305091414Meas – Cruise Test #2. Moved away from engine heat, added fan to keep ambient temp cooler (below 30°C. Need to measure dilution air temperature. **Aborted test.**
201305091424Diag - Cruise Test #2b Filter ID T130131, base flows lower than expected at 55.
201305100844Meas – Cruise Test #3. 2% grade at 45 mph (with grade ~2%). Filter ID T130113. AVL sample had a leak in the first 60 seconds (keep this in mind for the correlation). KJ fixed. Also on Grav system noticed a small change in filter TSI flow at end of test (hotter flow). When it cools it goes back to starting flow. TSI meters don't seem to be as stable as MFC flow set point flows5. Interesting. It is expected the TSI flow is less robust than the MFC flow. Think about. That is a big difference on the sample flow.
201305100925Meas - Cruise Test #4. 2% grade 20% bypass. Filter ID T130134, filter heaters off and exposed.
201305101009Diag – Cruise test #1. 2% grade 0% bypass. Filter ID T130136, filter temps looked good. MFC set at 60 for today
201305101046Meas – Cruise Test #2. Cruise 2% grade 0% bypass. Filter ID T130138, Temps looked great.
201305101122Meas – Cruise Test #3. Cruise 2% grade, 0% bypass. Filter ID T1300140, Temps look great.

201305101141Diag – TrimFLow calibration. Post test (didn't have time pre tests). Sawtooth and Sin Wave.

PM PEMS (G) Ver2.0

Fully automated system with integrated robotic 30 filter changer, integrated ECM interface, inlet sample flow measurement, upgraded trim flow measurement, and integrated filter and base mass flow controllers. Integrated heater controls and updated software for real time assessment of proportionality and filter bypass control.

7/12/2014 – Test preparation data files and information.
201407122328Meas – Simulation test with the 0.080 venturi orifice and TSI flow meter. Goal was to evaluate the upgraded sample flow system. Desired pressure drop was 30 inH20 at 10 slpm. Actual delP was only 10 inH20 at 10 slpm. Fabricate a second venturi at 0.055 in orifice.

7/18/2014 - All the tests performed today were at the following conditions. Filter Q = 58.1, Base flow 47.0 (20°C and 1 atm standard conditions). The robot was controlled through its embedded system for test simplicity. The ECM interface was not functioning properly and thus not used. Data was shared for this from the MEL. MFCfilter flows was set at 57.6 (? Std conditions) as determined by an in house TSI meter. There was concern that the flows tables in the MFC were incorrect. Later is was discovered that the MFC was actually at 0°C and 1 atm. The correct value should have been 54.1 slpm (0°C 1 atm) to achive 58.1 slpm (20°C and 1 atm).
201407181551Meas Bypass closed to simulate a 2007 and 2010 PM certified engine. Route was freeway congested driving. EFM working. T130002
201407181522Meas Bypass opened to simulate a higher pre-2007 certified engine. Route was freeway congested driving. EFM working. T130001
201407181441Meas – Bypass opened to simulate a higher pre-2007 certified engine. Route was freeway congested driving. Exhaust flow was frozen, but was fixed before the test started. T130218
201407181403Meas – Bypass closed to simulate a 2010 and 2007 PM certified engine, route was on a freeway with light congestion. Test invalid. EFM frozen the full test (noticed during testing at the end of the test). T130216
201407181321Meas – Bypass closed to simulate a 2010 and 2007 PM certified engine. Route was in-town and on a congested freeway. EFM was frozen, working, frozen, working, frozen for this test as identified from the data. T130202.

7/21/2014 - All the tests today performed today were at the following conditions. Filter Q = 58.1, Base flow 47.0 (20°C and 1 atm standard conditions). This required a QMFCsetpoint of 54.1 (0°C and 1 atm) and 43.79 on MFCtrim (0°C 1atm). The ECM was setup and working for these tests. The robot was controlled through the main control program through a serial interface. While data processing I noticed column AC and AD labels are backwards AC should be Bypass Flag and AD should be CalcSample. I fixed the 1Hz data, but not the 10 Hz data.
201407211207Meas 2 bypass, ECM control, CVS and exhaust disconnected. Sampled ambient to evaluate noise on the Venturi system.
201407211143Meas 2 bypass, ECM control, freeway, T140316
201407211108Meas 2 bypass, EFM control, freeway, T140314
201407211026Meas 1 bypass, EFM control, surface and freeway, T140312

201407210952Meas 1 bypass, EFM control, freeway, T140310
201407210916Meas 0 bypass, EFM control, freeway (from 914 test). There was an issue with the data file and the program was stopped and started to fix. Data valid. T140305, 5 data glitches and one large one that shifted out the logged EFM flows. It is coming from the EFM. Fix the logging program to save previous values to prevent glitches.
201407210835Meas 0 bypass, EFM control, data logging error, surface and freeway, filter ID T140270

PM PEMS (G) Ver 2.

The tests performed were based on the same PM PEMS (G) system as version 2.01. These tests investigated the PM emissions without the CRT (minimize sulfate formation) and a metallic transfer line with the CRT. The non CRT with flexible transfer tube tests were performed first followed by the CRT + metallic transfer line.

8/11/2014 – Startup testing for Ver 2.0b of the PM PEMS (G) system. The exhaust flow meter failed to start. Strange readings on the display. Investigation revealed all the parameters were lost and the bias in the measurements were off by 200%. Stop testing and repair the system.

8/12/2014 – All the tests today performed today were at the following conditions. Filter Q = 58.1, Base flow 47.0 (20°C and 1 atm standard conditions). This required a QMFCsetpoint of 54.1 (0°C and 1 atm) and 43.79 on MFCtrim (0°C 1atm). The ECM was setup and working for these tests. The robot was controlled through the main control program through a serial interface. While data processing I noticed column AC and AD labels are backwards AC should be Bypass Flag and AD should be CalcSample. I fixed the 1Hz data, but not the 10 Hz data.

201408120939Meas T140353
201408121016Meas T140459
201408121111Meas T140360
201408121142Meas T140362
201408121211Meas T140366

8/13/2014 All the tests today performed today were at the following conditions. Filter Q = 58.1, Base flow 47.0 (20°C and 1 atm standard conditions). This required a QMFCsetpoint of 54.1 (0°C and 1 atm) and 43.79 on MFCtrim (0°C 1atm). The ECM was setup and working for these tests. The robot was controlled through the main control program through a serial interface. Column AC and AD labels were fixed. AC is Bypass Flag and AD is now the CalcSample.

201408130925Meas T140354
201408131001Meas T140355
201408131032Meas T140356
201408131104Meas T140357
201408131123Meas T140358

Appendix I. Partial flow sensitivity analysis

While testing with the partial flow system it became evident there was some issues with the accuracy of the system. An evaluation of the major components making up the flow system were developed to characterize the major contributors to the overall uncertainty of the partial flow system. This appendix describes that analysis and some results.

Figure I-1 shows the accumulated uncertainty of a PM measurement at different filter weights. For example the expected PM uncertainty based on specified measured uncertainties is 20% at filter weights from 150 µg to 300 µg and beyond. Assumptions are the dilution air flow and filter flows are accurate to 2% as specified in the CFR. Typical in-use operation and thermal loads may suggest wider actual uncertainties. The exhaust flow from UCR's experience and from discussions with others is typical 8% high relative to CVS reference methods. The filter weight uncertainty is expected to be around 5% or 5 µg whichever is greater. As the filter weight drops the PM uncertainty increases.

Additional calibrations and checks can be performed to reduce these uncertainties. Such as cross calibrating the dilution and MFC flows to estimate a sample flow. Verify the exhaust flow by carbon balance, and minimizing contamination on the gravimetric filter. It is the responsibility of the user to verify the accuracy of the system to ensure proper PM mass measurements in order to achieve PM within 10% of the reference method which should be practical at more than 80 µg loading.

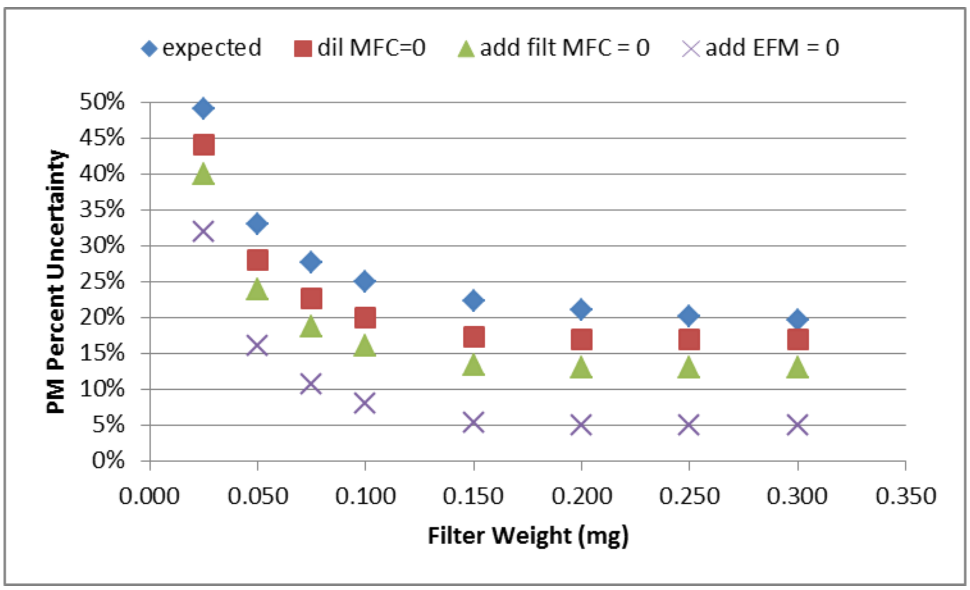


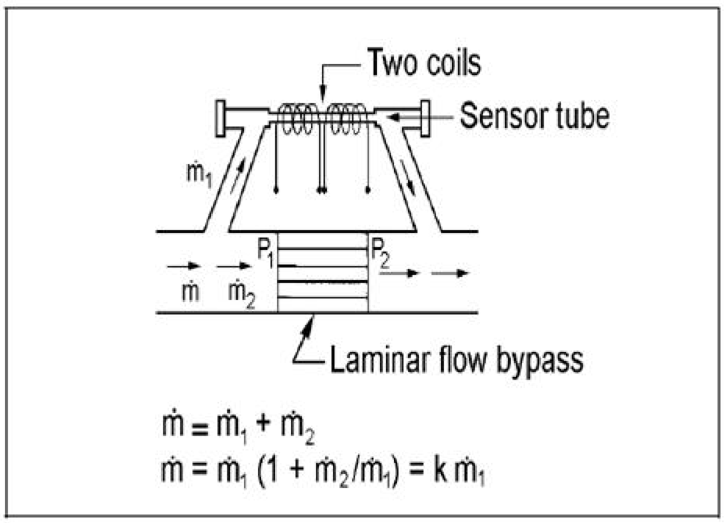
Figure I-1 Uncertainty analysis for the partial flow system

If the flow accuracy of the filter or sample flow are large this will greatly impact the overall performance as shown. The first version of the PM PEMS (G) system utilized a sample flow by difference estimate which was found to vary by 5-6% with an impact of 50-70% on the overall PM mass system. These uncertainties were well beyond what was expected and thus the system was modified with more stable flow meters that varied less than 2% during in-use testing. For an explanation on the flow uncertainty see Appendix J.

Appendix J. Flow meter errors

Not all flow meters are the same. Note the Alicat (laminar flow delP technology), Sierra (heat transfer capillary flow technology like UNIT, and many other MFCs), and TSI (thermal hot wire different than Sierra capillary) use very different measurement approaches, see Figures 1, 2 and 3.

Each of the meters has a similar specification on accuracy for flow 1 or 2% of point/FS. The main difference is shown in Table 1. Table 1 describes how the error grow with different conditions. Alicat shows the lowest drift with conditions and TSI is much higher. Subtle changes in ambient (20 °C and some loss in pressure) can result in 10 or 15% uncertainty in TSI where Sierra and Alicat are around 2-3%. This lead to a switch from a Sierra MFC coupled with a TSI MFC for trim in the initial version of the PM PEMS (G) to a red-y smart series MFCs with an Alicat meter (laminar flow element) for trim in the second version of the system.



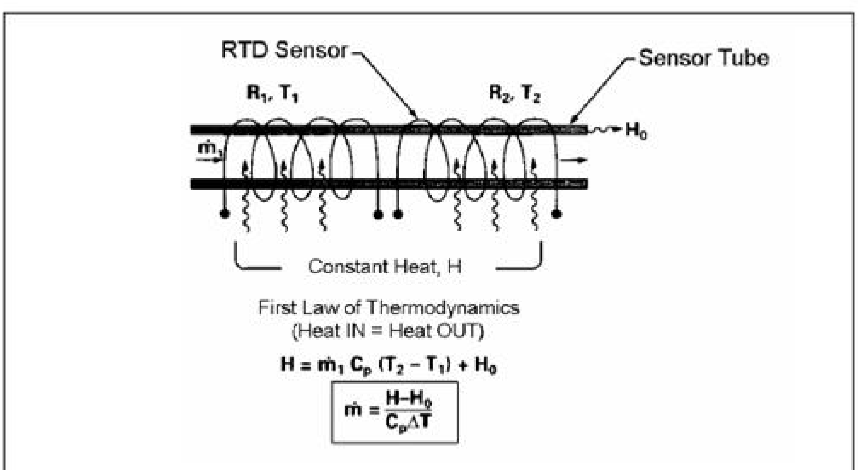


Figure I-1 Sierra and other MFC's (UNIT) use heat balance over a controlled minor (capillary type) flow element within MFC

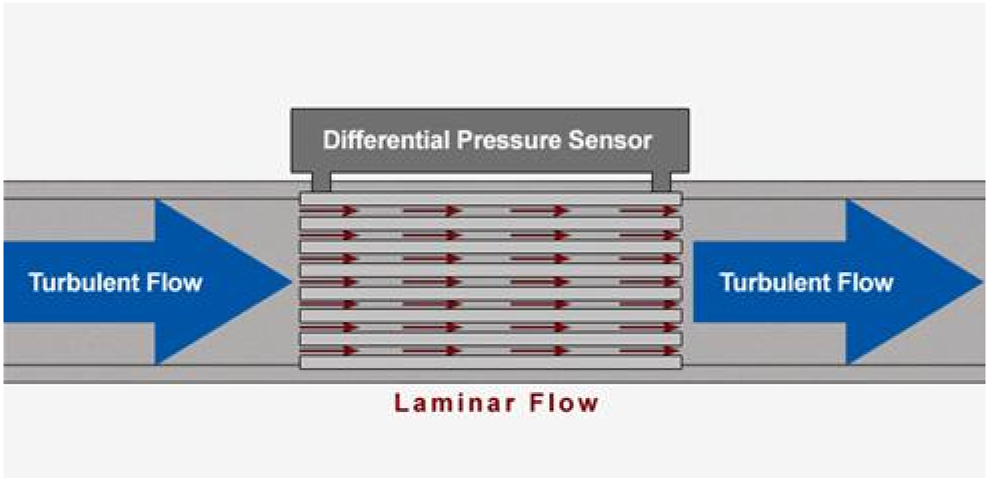


Figure I-2 Alicat Laminar flow and venturi's are based on differential pressure for flow and Pres + Temp measurement for density to mass corrections.

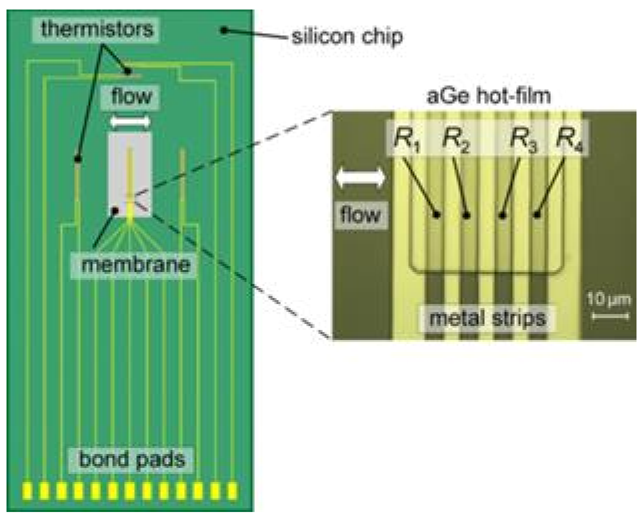


Figure I-3 TSI example of a thin film thermal flow meter (Different from Sierra and other MFCs) Thermal anemometers for turbulent designs