Final Report

Development of a Simplified Field Test Method for PM Compliance Screening of Stationary and Portable CI Engines

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Abstract

In 1998 the California air Resources Board (CARB) identified diesel exhaust particulate matter (PM) as a toxic air contaminant (TAC) and since then the ARB has been implementing Air Toxic Control Measures (ATCMs) to reduce public exposure to diesel PM. The current method to measure PM emissions from stationary sources is ARB Method 5. However, this method is very time consuming, costly and may not be appropriate for diesel sources with controls. Thus CARB and the University of California, Riverside (UCR) tried to develop a simpler, faster and less expensive field test method for measuring PM emissions from stationary and portable diesel engines; one that local districts could afford and use for enforcement. The research proposal considered a Simplified Field Test Method (SFTM) using: a single port sampler of raw exhaust, CO_2 emissions as the surrogate of load, and basing total PM mass on the filter catch. Additionally, the research tested two real time PM instruments, including an inexpensive (~$6K) non-filter-based PM measurement method based on laser light scattering photometry (LLSP) and an expensive (~$60K) instrument.

Tests of a number of diesel engines compared the PM mass measured with CARB M5, federal reference methods and the proposed Simplified Field Test Method. Results showed the SFTM and the federal reference methods were statistically the same and the M5 was biased high because of the impinger catch. Results showed that field measurements of the PM from a diesel engine with an efficient diesel particulate filter (DPF) installed is difficult for all methods to measure. Further work is needed to improve the precision of the SFTM and the real time PM monitors.

Executive Summary

Background

In response to the 1998 designation of diesel exhaust particulate matter (PM) as a toxic air contaminant (TAC), the CARB has implemented Air Toxic Control Measures (ATCMs) to reduce public exposure to diesel PM. However, the current method to measure PM is very time consuming, costly and may not be appropriate for sources with PM controls. Thus the CARB and UCR tried to develop a simpler, faster and less expensive filter-based field test method for measuring PM emissions from stationary and portable diesel engines; one that local districts could afford and use for screening and enforcement. Additionally, the research project explored the use of real time PM monitors and explored the reasons for the high mass bias for ARB Method 5.

Methods

The primary research effort focused on developing a Simplified Field Test Method (SFTM) consisting of a single port sampler of raw exhaust, the measured CO_2 emissions as the surrogate of load, and mass on a Teflon filter as representative of the PM mass. In addition some research effort used pure compounds and impingers to explore the reasons for why the PM mass measured with the CARB Method 5 is biased high as compared with other reference methods. In a secondarily and limited undertaking, the research tested two real-time PM measurement methods; one inexpensive (~\$6K) and the other expensive (~\$60K).

Results

The SFTM provided a good correlation with reference methods based on filter mass but not with methods based on condensable PM, like the total mass measured in ARB Method 5. The simplified filter mass based method seems to offer real promise as it can be developed with equipment in the current Method 5 apparatus. While the correlation is good, the results are adequate for screening but more testing is needed to develop the understanding that is normally associated with compliance methods. Research showed the acid and organic gases in the diesel exhaust transform in the impingers and cause the PM mass to be biased high.

The limited results with two non-filter, real-time PM monitors suggested the possibility of instantaneously determining whether a diesel engine is operating within its certification limit and a lead for a PM Continuous Emission Monitors (CEMs).

Conclusions

There is a need for ARB to provide a "Smog-Check like Program" for diesel engines to assure the public that in-use diesel engines are operating within their PM limits. Monitors for such a program should be field friendly, affordable and provide data quickly. This research examined in detail the current compliance approach, ARB Method 5, and the basis of the bias for high measurement of PM mass form CI sources. In addition, a

primary effort was directed toward the development of a Simplified Field Test Methods; one based on filter mass and others based on real-time electronic signals. Further, except for the ultra low PM levels when diesel engines have Diesel Particulate Filters (DPFs), the methods provide a very fast look at the PM emissions. Preliminary scoping measurements with real time, electronic monitors indicated that a DustTrak unit provided an affordable and an instantaneous reading on whether the diesel engine was complying with the standard. For raw diesel exhaust, the real time monitors offer great promise and there is a need for more research with them.

1   Introduction

1.1   Background

As defined in 40CFR51.100, "Particulate matter emissions means all finely divided solid or liquid material, other than uncombined water, emitted to the ambient air as measured by applicable reference methods, or an equivalent or alternative method, or by a test method specified in an approved State implementation plan." Meyers[1] of the US EPA points out that unlike gaseous criteria air pollutants, the amount of particulate mass (PM) in ambient air or release from an emission source is determined by the conditions under which it exists and the method used to collect the material. The conditions that have the greatest effect on mass concentration of particulate include temperature, humidity and pressure. For ambient particulate sampling, the differences between the ambient conditions and sample collection conditions are minimal. However, for other sources, like stationary or portable units, the flue gas conditions soon after release to the ambient air and the sampling conditions may be significantly different and greatly affect the result.

According to EPA, the most precise method of determining the mass concentration of PM from a source is to collect the entire volume of gas: however, this approach is not very practical for many sources. Accordingly, "extractive" methods, which remove a small portion of the gas stream, have been developed to sample representative portions of the gas stream to allow an estimate of PM mass emission rate. The more common methods for collecting and analyzing particulate emissions from stationary sources are found in Title 40 of the Code of Federal Regulations (CFR) and use an apparatus like in Figure 1-1.
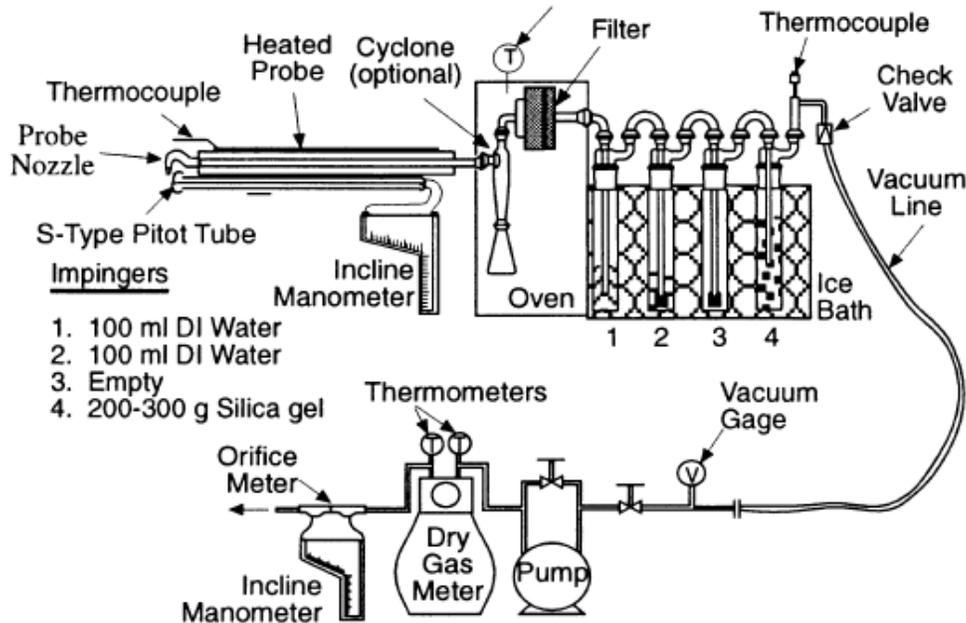
Figure 1-1 Complex Sampling Train of EPA Methods 5/202 & CARB Method 5

Developers of the test method have shown that care must be taken during the analysis to achieve the desired precision. Thus the analytical methodologies used to quantify PM emission factors control the sampling temperature, the temperature and humidity levels for analyses and make adjustments to analytical results to achieve consistency. PM is withdrawn isokinetically from the source and collected on a glass fiber filter maintained at a temperature in the range of l20 ± l4°C. The PM mass includes any material that condenses at or above the filtration temperature and is determined gravimetrically after removal of uncombined water. During extractive methods, the gas must be sampled isokinetically, meaning that the gas velocity within the sample probe equals the gas velocity at the sample point in the source. Doing so allows the concentration and size distribution of the PM in the sample probe to be the same as in the source. Sampling at velocities less than isokinetic will lead to an overestimation of larger-sized particles and a higher than actual PM mass concentration; conversely, sampling at velocities higher than isokinetic will lead to an overestimation of smaller particles with a lower than actual PM mass concentration

1.2   Multiple Source Test Methods Exist for PM Mass

There are several accepted source test methods for measuring the mass of PM from a stationary source. However, these measurement methods are set up differently and do not give the same PM mass. For example, while EPA's Method 5 requires only the filterable PM to be weighed, CARB's Method 5 requires both the filterable PM and the PM that passes through the filter and is captured in the impinger solutions to be weighted. The later fraction is known as the condensable PM (CPM). Meyers[Error! Bookmark not defined.] indicates that EPA only weighs the filterable PM as their method was designed to evaluate the performance of add-on control devices operating over 121°C to control particulate emissions. As a result, vapor state particulate is not controlled or measured. Thus, although the California test method appears similar to the EPA Method 5 method, the total mass of PM for CARB Method 5 is significantly higher based on what is considered to be particulate.

Another compliance or reference source test method is based on full dilution of the exhaust, with details found in either 40CRF86 or ISO-8178. The CFR/ISO method does not necessarily correlate well with CARB's Method 5 as shown in Figure 1-2 below. Figure 1-2 compares the PM emission factor for a number of power generators using both the ISO and CARB methods to measure emissions. One of the generators has a diesel particulate filter (DPF). While the ISO filter-based test methods for diluted exhaust are standard for mobile and off-road engines, CARB's stationary source method has been the reference for new source review, compliance and permitting of stationary engines. Research into the cause of the differences between the two methods showed that most of the increase was due to the CPM as stationary source test methods include filterable and condensable components from undiluted exhaust. As a result of such comparisons, CARB's Stationary Source Division (SSD)[2] recognized and addressed the differences in PM measurement methods during the development of the Air Toxic Control Measure for the stationary and portable sources.
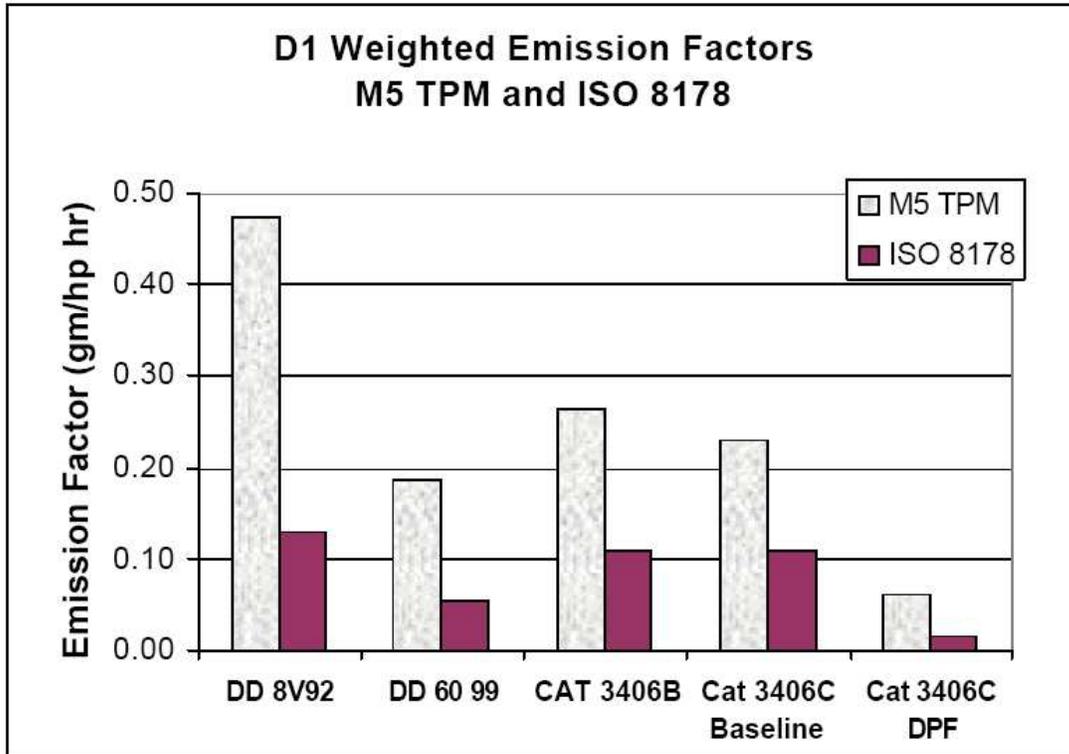
Figure 1-2 PM Comparative Emission Factors: ISO-8178 Method vs. CARB Method 5

To better understand the technical issues, CARB created a Test Method Working Group (TMWG) of key stakeholders including: district staff representing California Air Pollution Control Officers Association (CAPCOA/District), Engine Manufacturers Association (EMA), Manufacturers of Emission Controls Association (MECA), engine manufacturers including Caterpillar and Cummins, Air Resources Board (ARB) and UC Riverside's Center for Environmental Research and Technology (UCR CE-CERT. The workgroup addresses the technical issues and the detail can be found in the staff report[2].

As a consequence of the research and analysis, new information became available and the results are plotted in Figure 1-3. Emissions factors for the same power generators of Figure 1-2 are now calculated with more reliance on the filterable and front half catch of CARB's method. As can be seen in the Figure the agreement between the methods is quite satisfactory. We expect the TMWG members to be supplemented by EPA and possibly others and that together they would become the Advisory Group for this project
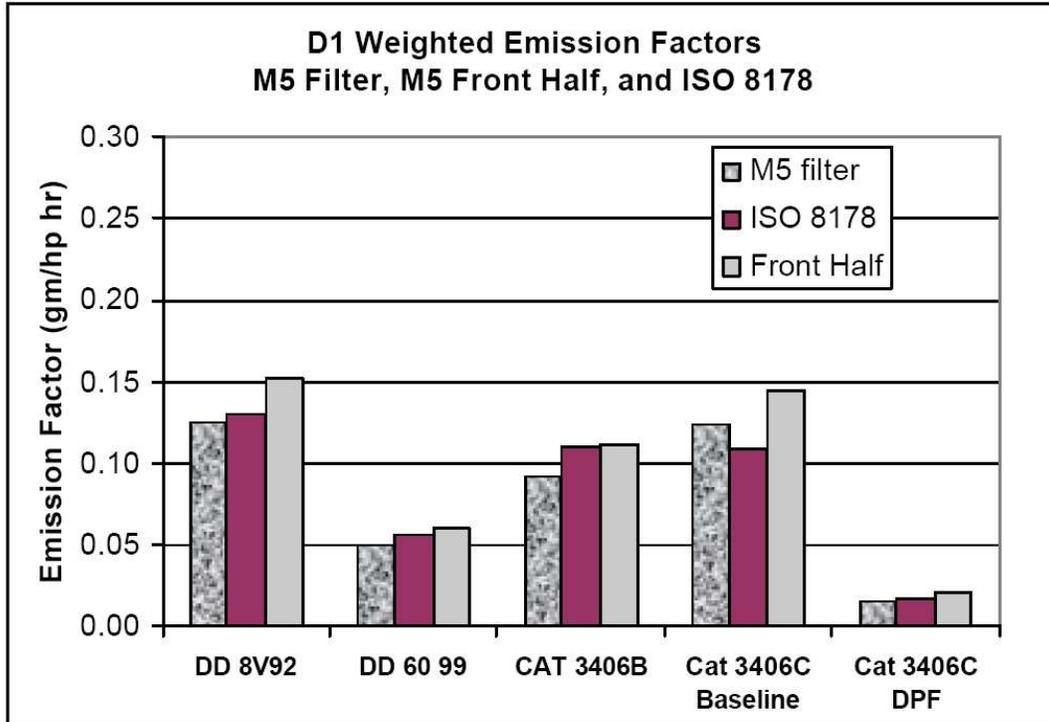
Figure 1-3 Weighted Total PM Emission Factors: ISO 8178 vs. CARB M5 Filter

1.3   Proposed Approach

The current stationary source test method, CARB Method 5, used for measuring diesel particulate matter (PM) in the field is slow, very costly to conduct and requires considerable skill and experience to obtain precise and accurate results. CARB Method 5 samples raw exhaust at eight points while traversing across the exhaust conduit on two diameters that are perpendicular to each other. The setup for testing and sampling may require special staging and several days to establish. Then samples at each engine condition take from 20 minutes to two hours for very low PM levels to measure and each sample is repeated at least three times over the three to eight modes depending on the appropriate ISO test cycle. Full characterization and measurement takes days. Once the field-testing is completed, the field samples are sent to an analytical laboratory where the requirements to separate and weigh the condensable fraction can take weeks to get results.

Based on the prior work for the ATCM, UCR had proposed simply putting a probe in the raw exhaust and accumulating measurements at a single point to measure emissions. Such an approach would require only the weighting of a filter; there is no condensable PM fraction and associated laboratory work. The sampling time will much shorter, even for engines with added or OEM-equipped PM controls, as 15 minutes was believed adequate to sample the diesel unit. The aim was to develop a quick sampling system that local districts could afford and use for enforcement. A conceptual design of the key elements in the original proposed is shown in Figure 1-4. We noted there was the

possibility to miniaturize the components into a sample portable package. The silica gel was to remove moisture and protects the pump and dry gas meter.
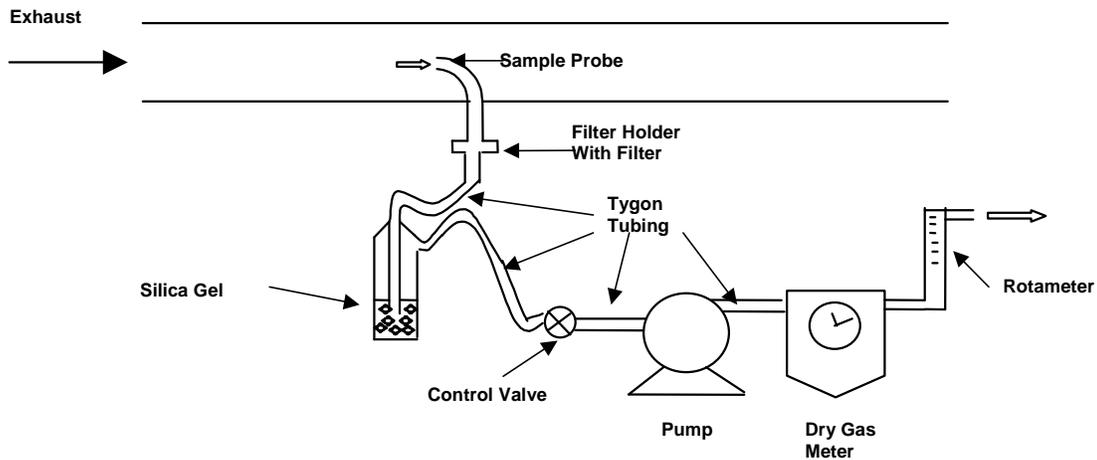
Figure 1-4 Concept for Proposed Simplified Field Test Method

1.4   Project Objectives

There were two objectives in this project that were accomplished through the number of Tasks outlined below. The first or primary object involved the development and verification of a Simplified Field Test Method and the elements that support it, including:

- A single mode test cycle,
- Use of CO_2 emissions as a surrogate to predict engine load instead of measuring load,
- Use of only the filter "catch", instead of the probe- and-impinger-catch of CARB Method 5.

As stated, the primary goal was to measure particulate matter (PM) emissions from stationary and portable compression ignition (CI) engine applications using a Simplified Field Test Method (SFTM). The method was to be accurate, precise, and compatible with the District's sampling equipment and methodologies. Developing such a test procedure for compliance testing of stationary and portable diesel engines would benefit the Districts and resolve current conflicts with the EPA values. A related objective in development of a screening method was to help the Districts identify high-emitters to test with a compliance method. A secondary goal was to test an inexpensive (~$6K) non-filter-based PM measurement method based on laser light scattering photometry (LLSP) A tertiary objective was the exploratory studies with pure compounds to develop a better understanding of why the PM mass found with CARB Method 5 was higher than other reference methods.

2   Material and Methods

2.1   General Approach

A review of the literature combined with the field testing experience during the research on emissions from diesel backup generators[3] provided the basis for the proposal of the Simplified Field Test Method (SFTM). Results from the earlier research showed that the total PM mass measured on the by CARB Method 5 was higher than the PM mass measured by reference methods of the International Standards Organization (ISO). Further the PM mass measured on the front filter of CARB Method 5 equaled the mass measured by the ISO method (see Figure 1-3). Communication with Myers of the US Environmental Protection Agency (EPA) indicated that they were working on "improving condensable PM test methods," like EPA Method 202 or CARB Method 5. Myers mentioned their aim was to specifically reduce the mass associated with the sulfate artifact[4].

With the primary goal set on developing and verifying a SFTM, the first phase involved the design of the equipment, followed by comparative testing with reference methods of two CI engine applications and demonstration on three additional CI engine applications. Secondary efforts were allocated to the tests of non-filter based methods and to developing an understanding of why the CARB Method 5 results were biased high.

2.2   Design of Equipment

A Simplified Field Test Method (SFTM) was developed to measure particulate matter (PM) emissions from compression ignition (CI) engine applications. The SFTM was intended as a screening tool to identify high-emitting engines or those with faulty emission control equipment. The objective of the SFTM is to provide a quick enforcement sampling protocol that local districts can employ at minimal cost.

The basic components of the SFTM sampling system included: 1) a small, short metal probe placed in the raw exhaust stream at a single sampling point, 2) an insulated filter holder, 3) a PTFE filter, 4) a moisture removal device, 5) a critical flow orifice (CFO), and 6) a sample pump. As compared with ARB Method 5, this approach did not require an extensive setup for shaping the exhaust flow, a staging platform to take emission measurements and weeks of waiting for post analysis of the aqueous and organic extract residue fractions in a laboratory. The SFTM is easy to set up, can be run by a single operator and requires only the weighting of a single filter after the field test measurement. A design provided below used equipment currently employed by source testing personnel at Air Districts throughout California. It is expected that an adequate PM sample can be acquired in 5-10 minutes from an engine without aftertreatment. The key elements of the prototype design used in this research are shown in Figure 2-1.
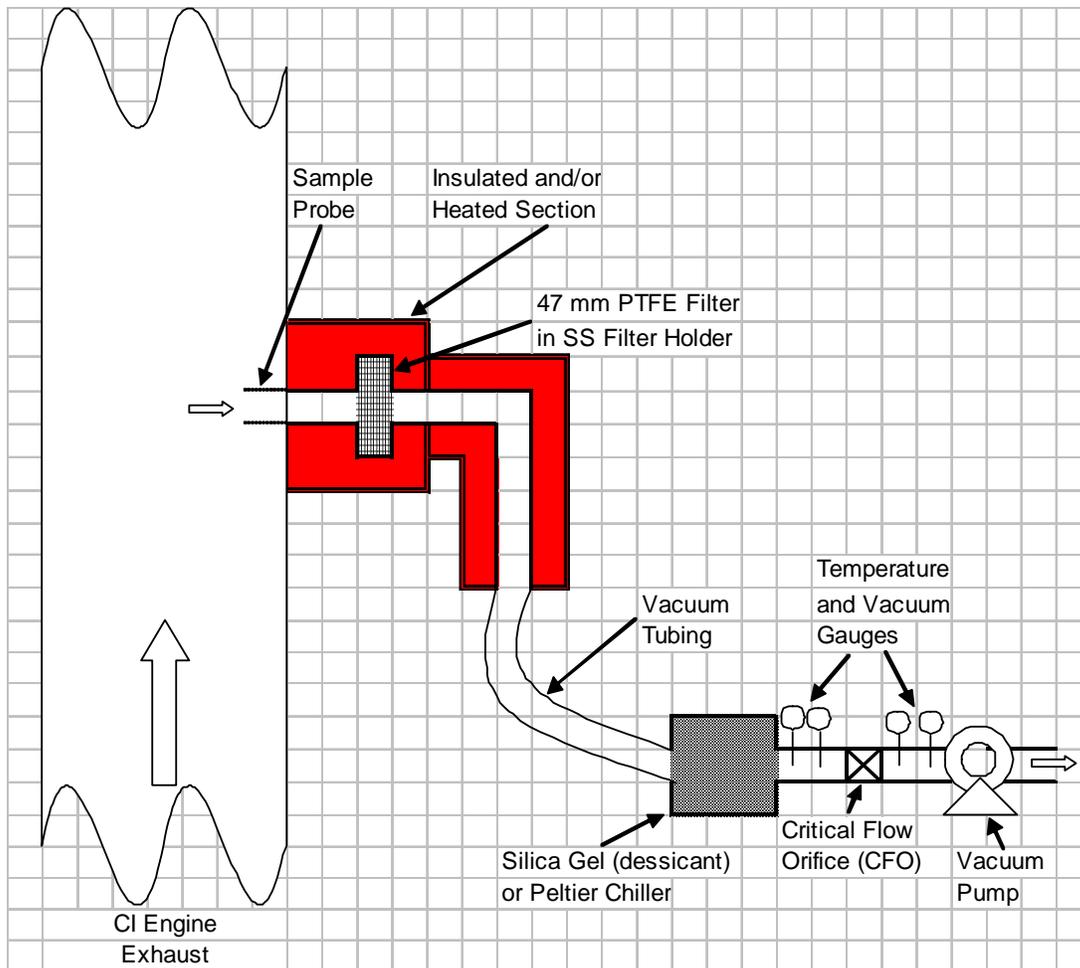
Figure 2-1 Design of the Simplified Field Test Method for Measuring PM

2.3   Details on Equipment and Materials

Sample Probe – 3/8" SS tubing, with the length dependent on exhaust duct size. The probe tip should be located at approximately 1/3 of the diameter of the duct. The probe should extend approximately 2" beyond the exterior of the duct, in order to accommodate fittings and allow for a small amount of cooling of the exhaust gases.

Quick Connects – a set of stainless steel quick connects at the outlet of the sample probe and another downstream of the filter holder to facilitate changing of filter assemblies.

Filter Holder – a stainless steel Gelman filter holder with filter backing screen sized for a 47 mm standard filter was used in this work. The inlet and outlet of the filter holder should be configured with male and female quick connect fittings, respectively.

Insulated Filter Assembly – A small insulated box housing the filter holder, as well as insulating fabric wrapped around the exposed portion of the sample probe (from the exhaust duct to the filter assembly). The design called for the filter temperature to be at or

above 250°F. Insulation alone was sufficient for maintaining the sample stream temperature above the dew point of the raw exhaust sample stream; however, for some cases (e.g. low exhaust temperatures, cold day), the small resistive heater around the box was turned on. A thermocouple provided feedback control as the temperature reached the desired 250°F. The thermocouple also monitored the temperature downstream of the filter assembly.

Filter Media – a standard 47mm PTFE (Teflon) filter. Teflon filters used to acquire PM mass are weighted following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Briefly, the filters (before and after sampling) are conditioned for 24 hours in an environmentally controlled room (RH = 40%, $T = 25$ °C) and weighed daily until two consecutive weight measurements are within 3 µg.

Vacuum Tubing – a sufficient length of ⅜" polyethylene or Teflon tubing to connect the stack-level filter assembly to the ground-level moisture removal system. The tubing should be thick enough to maintain a maximum vacuum of 10" Hg. Leak-free tubing connections are made with small lengths of Tygon® tubing fitted over the connecting points.

Moisture Removal System – A Method 5-style modified Smith-Greenberg impinger half-filled with dry indicating silica gel. Alternatively, a Peltier-style or other refrigerated chiller may be used to remove moisture from the sample stream.

Critical Flow Orifice (CFO) Assembly – A section of gauges and fittings designed to control and monitor the sample flow rate. By maintaining a minimum vacuum of 15 "Hg across the orifice, a constant volumetric (and molar) flow rate can be maintained. A nominal 5 lpm orifice was used for the verification and demonstration test runs at UCR. To complete the assembly, a set of temperature/vacuum gauges are installed both upstream and downstream of the CFO. These values are monitored and recorded during each sample run in order to correct the calibrated orifice flow rate to actual sampling conditions using the Ideal Gas Law.

Vacuum Pump – A sample pump capable of maintaining a minimum vacuum of 25" Hg at 5 lpm.

2.4   Sampling Points
The reference ARB Method 5 requires adding a special shaped exhaust conduit and sampling raw exhaust at eight points while traversing across the exhaust conduit on two diameters that are perpendicular to each other. A goal in this project was to demonstrate that since the exhaust flow was turbulent the sampling only needed to be at one point near the middle of the exhaust conduit rather than the multitude as specified in the Method 5 protocol.

2.5   Simplified Test Cycle
Usually, overall brake-specific mass emission factors from a given engine test are determined by appropriately weighting individual mass emissions and loads from

multiple steady-state mode points. For example, ARB requires a five mode test cycle for the certification of constant-speed diesel engines used in backup generators as shown in Table 2.1 UCR proposed estimating the overall emission factor from measurements at a single load point within the certification cycle.

Table 2-1 Five-Mode Test Cycle for Constant-Speed Engines

Mode number	Engine Speed[1]	Observed Torque[2]	Minimum time in mode, min.	Weighting factors
1	Rated	100	5.0	0.05
2	Rated	75	5.0	0.25
3	Rated	50	5.0	0.30
4	Rated	25	5.0	0.30
5	Rated	10	5.0	0.10

Notes: (1) Engine speed: ± 2% of point. (2) Torque: Throttle fully open for 100% point. Other points: ±2% of engine maximum.

2.6   Determining the Exhaust Flow Rate

Exhaust flow is needed in order to convert concentrations measured in the exhaust into the units of grams per unit of work. The EPA/ISO test method determines exhaust flow rate as the difference between the measured flow rate of the total diluted exhaust and the measured inlet dilution air flow rate. When using Method 5, the exhaust flow rate is determined through a multi-point measurement of exhaust velocity across two diameters of the exhaust stack. An alternative to these two approaches is the determination of exhaust flow rate from engine specifications and operating parameters. With a known engine displacement, the exhaust flow rate can be determined at any load point by measuring RPM, boost pressure, intake manifold temperature, and ambient temperature/humidity. This simple approach has been used in a number of recent programs, and has been shown to agree with reference values within 1% (UCR, 2004).

For newer engines, these parameters can be read directly from the engine control module (ECM) using diagnostic tools. For older engines, these parameters must be measured as follows:
- RPM – photo tachometer
- Boost pressure – pressure transducer
- Intake manifold temperature - thermocouple

3 Results: SFTM Protocol Development and Verification Testing

Results are presented to show that the equipment proposed for the simplified test method (Figure 2-1) is practical in the field and that the adjustments made in the protocol are effective. Further a numerical comparison is made of the PM mass measured by the simplified method (SFTM) and the ARB Method 5.

3.1 Single Sampling Point and Anisokinetic Sampling

One of the simplifications of the proposed method was to use a single sampling point and a constant (anisokinetic) sample flow rate. Ten (10) sets of tests were conducted on a diesel-powered backup generator equipped with a stock muffler, a catalyzed DPF, and a second catalyzed DPF. Duplicate tests were performed for each of two different sampling points and using two different sample flow rates.

Results show that there were no significant differences in results as a function of sample flow rate or probe position.[5] The PM mass measured over the diameter of the conduit is within the error of the measurement made with a single point near the middle of the conduit. This result was expected, as the flow was highly turbulent and PM should follow the convective fluxes in the exhaust stream and the profiles should remain relatively flat near the middle of the exhaust stream.

3.2 Filter Face Temperature

One of the design parameters was setting the temperature of the Teflon filter assembly above where moisture might condense so we used 250°F, the same temperature as that used for ARB Method 5. Thus before testing, the heater was turned on to reach the desired set point but as soon as sampling started, we noticed the heater turned off due to the thermal balance of heat coming in with the sample and low losses thermal losses due to insulation. Sometimes the filter face temperature increased 25°F. For situations where the filter face temperature is greater than the ~120°F used in the reference methods, then we would expect the PM mass measured by the SFTM to be biased low and that was the case, especially for PM sources that were enriched with organic carbon. Later results show the effect of filter face temperature.

3.3 Using CO_2 Mass Emissions as a Surrogate for Engine Load

Previous work[3] between ARB and UCR showed an excellent correlation between the CO_2 emissions and the power output. The entire UCR database of CO_2 mass emissions versus load from that study was plotted and a linear regression analysis performed. As evidenced in Figure 3-1, the coefficient of determination (R^2) of 0.98 suggest as excellent fit, thus the CO_2 mass emissions are an excellent surrogate for load. This finding is as expected since the efficiency of diesel engines is relatively constant and the curve represents the conversion of potential chemical energy into work via the combustion process.

CO$_2$ Mass Emission Rate vs. Load

$y = 0.4976x + 20.366$
$R^2 = 0.9816$

Y-axis: CO$_2$ (kg/hr) — 0.0, 50.0, 100.0, 150.0, 200.0, 250.0, 300.0, 350.0, 400.0, 450.0
X-axis: Load (Hp) — 0, 100, 200, 300, 400, 500, 600, 700, 800
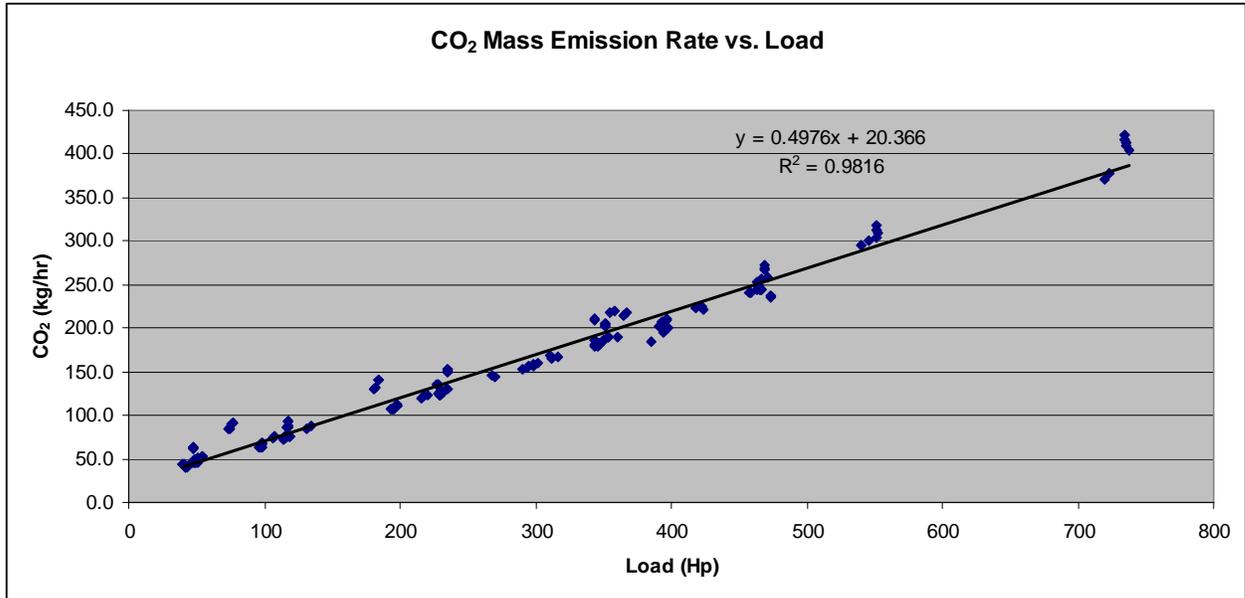
Figure 3-1 CO$_2$ Emissions as a Function of Load for 19 CI Engines

In the field, CO$_2$ concentrations can be measured directly in the exhaust stream using a portable gas analyzer employing a non-dispersive infrared (NDIR) detector. The sample stream must be filtered and dried (via a sample conditioner) prior to detection. In order to determine CO$_2$ mass emissions, the exhaust flow rate must be known. In the field, exhaust flow rate can be determined from engine parameters (rpm, boost pressure, and intake manifold temperature), or via direct measurement (Pitot tube, hot wire anemometer). Once CO$_2$ mass emissions are determined, the correlation can be used to infer the operating load.

3.4   Testing at Single Load vs. Multi-Load Points

The SFTM specified testing at a single load point rather than at the multiple loads specified in the reference test method for engine certification. To determine if a single load point was feasible, the brake-specific mass emissions at each of the load points was examined to learn whether a single load point would give the same correlation with the overall brake-specific mass emissions determined from the reference EPA method. One area of interest was the higher power levels since portable and stationary diesel units tend to operate at higher power levels and the PM brake-specific mass emissions become less sensitive with increasing load, as seen in Figure 3-2 below. However, there are potential problems when testing at high loads. First, the owner of the backup generator or similar portable/stationary unit might not have a way to absorb the output of a unit operating at full load, and second, the fuel consumption is very expensive when operating at the highest loads. These issues were considered in the design of the Simplified Field Test Method.

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Weight of PM per Weight of CO_2 as a Function of %Load
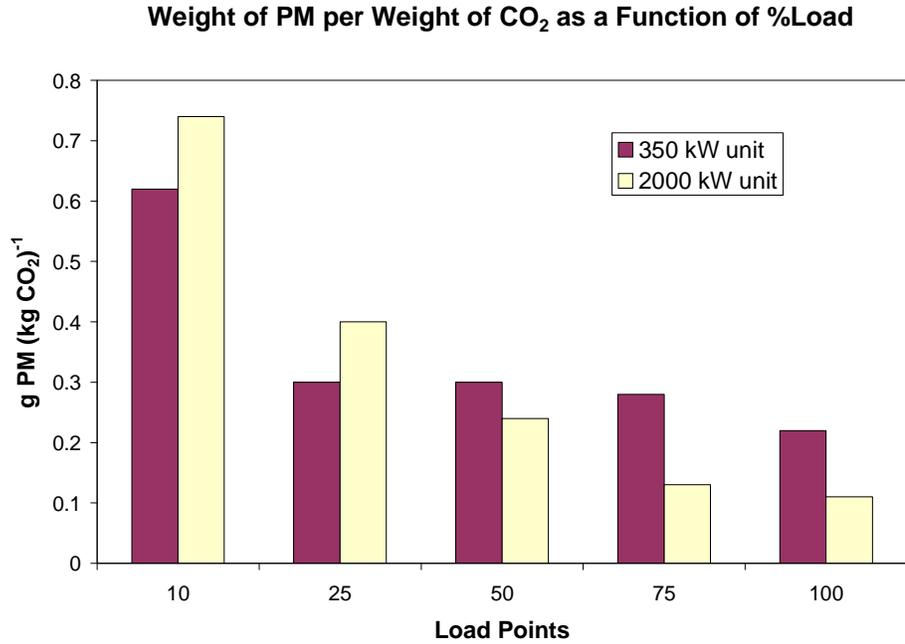
Figure 3-2 Data Showing Flatter Profile of Emission Factors as Load Increases

As for the CO_2 versus load analysis, the entire ARB/UCR dataset[3] of CI engines tested in a previous program was re-analyzed. This time PM emissions in g/Hp-hr and load were fitted to a second-order polynomial curve as shown below in Figure 3-3.

Unit 1 - CAT 3406C PM Emissions

$$y = 9E\text{-}05x^2 - 0.012x + 0.4777$$
$$R^2 = 0.9012$$
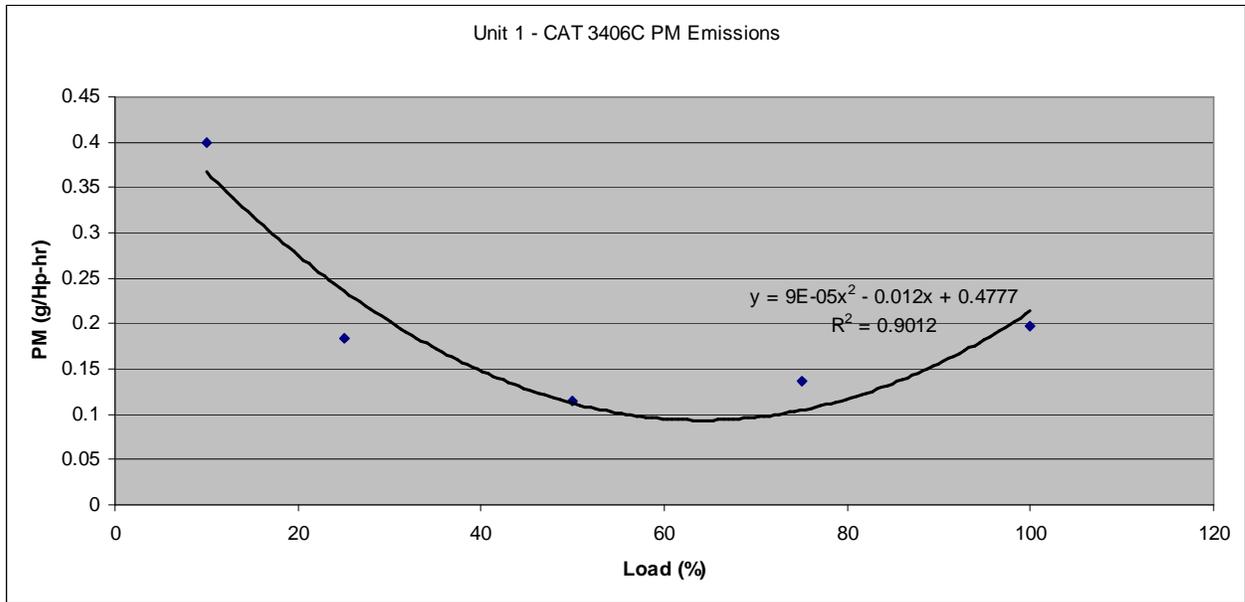
Figure 3-3 Example of Polynomial Regression Analysis

Using the equation, a trial-and-error solution was determined for a single load point that would result in the same brake-specific mass emissions as the overall weighted 5-mode result. This is shown in Table 3-1.

Table 3-1 Determination of Equivalent Single Load Point

Unit 1	CAT 3406C	Load	PM (g/Hp-hr)	
		10	0.399794	
		25	0.184361	
		50	0.115401	
		75	0.136326	
		100	0.197838	
	Overall Weighted Brake-Specific			
	Mass Emissions:		0.149862	
	Single Point			
	Load (calc):		**38.5** %	
		OR:	**95** %	
			0.14910	
			0.14995	

Results from the regression analyses allowed an average single load point to be determined. The overall average single load point was then used to calculate PM emissions for each individual unit. The calculated emissions were then compared with the overall weighted brake-specific mass emissions determined from the 5-Mode ARB Certification Test. The results showed no single load would fit all engines; instead, the best correlations came when engines were separated by both make and model.[5]

Results showed that a single mode point can be used to determine the overall 5-Mode weighted brake-specific PM mass emissions within a 15% margin of error. Based on the current dataset, the analysis suggested single mode points for the following engine makes and/or models:

Make/(Model)	Percent of Full Load
Detroit Diesel	53.5%
Cummins	47.1%
Caterpillar 3412	37.9%
Caterpillar 3406	43.5%

Further work is needed to expand the database and improve the correlations. With the exception of the Caterpillar 3406 engines, the UCR dataset is limited to only a few engines. Additional 5-Mode testing could be conducted on different makes/models of engines to improve the correlation, but such testing is costly and time-consuming. Alternatively, the modal emission factors required for engine certification testing could be used for linear regression and determination of the single-point surrogate load for each individual make/model. These surrogate load points could be published in a simple reference guide for field application.

3.5 Verification Testing of the SFTM

Tests were planned and conducted to compare the emission factors from a backup generator powered by a CAT 3406C engine with the SFTM and with reference methods. The engine load was set according to the appropriate ARB certification test cycle. Emissions were determined from the exhaust both with a high-efficiency catalyzed diesel particulate filter (DPF) and without an after treatment device. Emissions were measured at each mode with both the full-dilution protocol offered by UCR's unique mobile CFR laboratory and the SFTM described above. Following the simultaneous measurements with the SFTM and the CFR lab, ARB Method 5 samples were acquired at the 75%, 50%, and 25% load points (with and without after treatment). Due to protocol specifications, the Method 5 samples could not be acquired simultaneously with the other methods so were taken immediately following the SFTM/ISO tests.

The goals of the tests were to verify the SFTM and determine the accuracy of the results relative to the reference CFR method. Secondary goals were to compare the results determined by SFTM/ISO with Method 5, and to verify SFTM CO_2 measurement as a surrogate for load. The verification test matrix was designed to challenge each of the methods using a baseline diesel exhaust and a low-concentration (via after treatment) diesel exhaust.

Arrangements were made for conducting the verification tests on a MY 2000 CAT 3406C backup generator connected to a load bank. Testing followed the full ARB Certification cycle protocol (see Table 2-1) for the baseline engine followed by testing of the same engine equipped with a high-efficiency catalyzed diesel particulate filter (DPF). Emission tests were conducted using ARB diesel fuel with a maximum sulfur content of 15 ppmw, as this fuel was in widespread commercial use.

3.6 Verification Test Design

In addition to testing at the ARB loads points, the matrix included a test mode at 43.5% load in order to verify the single-mode surrogate relative to the weighted-average ISO results. Following SFTM/ISO testing, Method 5 samples were acquired at the 75%, 50%, and 25% load points. The sets of tests were performed on the backup generator baseline exhaust and treated exhaust of the same generator equipped with a catalyzed diesel particulate filter (DPF). The initial plan was to perform duplicate samples at each of the five modes and the 43.5% load point for the baseline and DPF test series. Extra time allowed for quadruplicate ISO/CFR sampling and triplicate SFTM sampling for the baseline test series. The baseline test matrix is shown in Table 3-2.

Table 3-2 SFTM Baseline Verification Test Matrix Design

Mode	Load (%)	ISO/CFR PM Samples	SFTM PM Samples	ISO/CFR CO_2 Samples	Method 5 PM Samples
1	100	4	3	4	
2	75	4	3	4	2
3	50	4	3	4	2
4	25	4	3	4	2
5	10	4	3	4	
3A	43.5		3		

Measuring PM in an exhaust with the catalyzed DPF was challenging and the initial 20 minute sampling times proved inadequate to capture sufficient mass on the filter. Thus the Test Plan was modified and the sampling time for the remaining samples was increased rather than carry out duplicate test runs where the mass was at the lower detection limit of the method. Samples were acquired for 60 minutes at the 100% and 75% load points. The modified test matrix (with sampling times and filter weights) is shown in Table 3-3. PM mass was determined for each of the filter samples collected. Results for the SFTM and ISO/CFR samples were then compared in terms of resultant PM emissions (g/Hp-hr).

Table 3-3 Catalyzed DPF Verification Test Matrix

	LOAD	100%			75%		50%		25%		10%	43.5%	
	run#	r1	r2	r3	r1	r2	r1	r2	r1	r2	r1	r1	r2
MEL	time, min.	20	20	60	20	60	20		20		20		120
	PTFE, mg	0.0425	BDL	0.1080	0.0265	0.1095	0.0250		0.0095		0.0065		0.2600
SFTM	time, min.	20		60	20	60	20		20		20	120	120
	PTFE, mg	0.042		0.057	0.039	0.046	0.005				0.001	0.048	0.074
M5	time, min.				120	120	120	120	120	120			
	QTZ, mg				0	0	22.5	0	0.8	0.6			

BDL - Below Detectable Limit

The Method 5 samples were separated into fractions (nozzle/probe, filter, aqueous extract, and organic extract). The PM mass for the nozzle/probe and filter fractions were determined per ARB Method 5. The aqueous extract from the impinger catch was boiled down to 100 ml in a tarred beaker. Two 5 ml aliquots of the 100 ml sample were set aside in sealed vials for further analyses. The remaining 90 ml sample was boiled to dryness, and the mass of the residue determined. The organic extract from the impinger catch was evaporated at room temperature down to 100 ml in a tarred beaker. Two 5 ml aliquots of the 100 ml sample were set aside in sealed vials for further analyses. The remaining 90 ml sample was evaporated to dryness, and the mass of the residue determined.

CO_2 mass emissions were determined at each mode with the ISO/CFR method. CO_2 mass emissions as a function of measured electrical load were determined to verify CO_2 as a load surrogate.

3.7 Results: Verification Test #1

Baseline verification tests were conducted on the CAT 3406C backup generator at UCR and modal results are shown below.
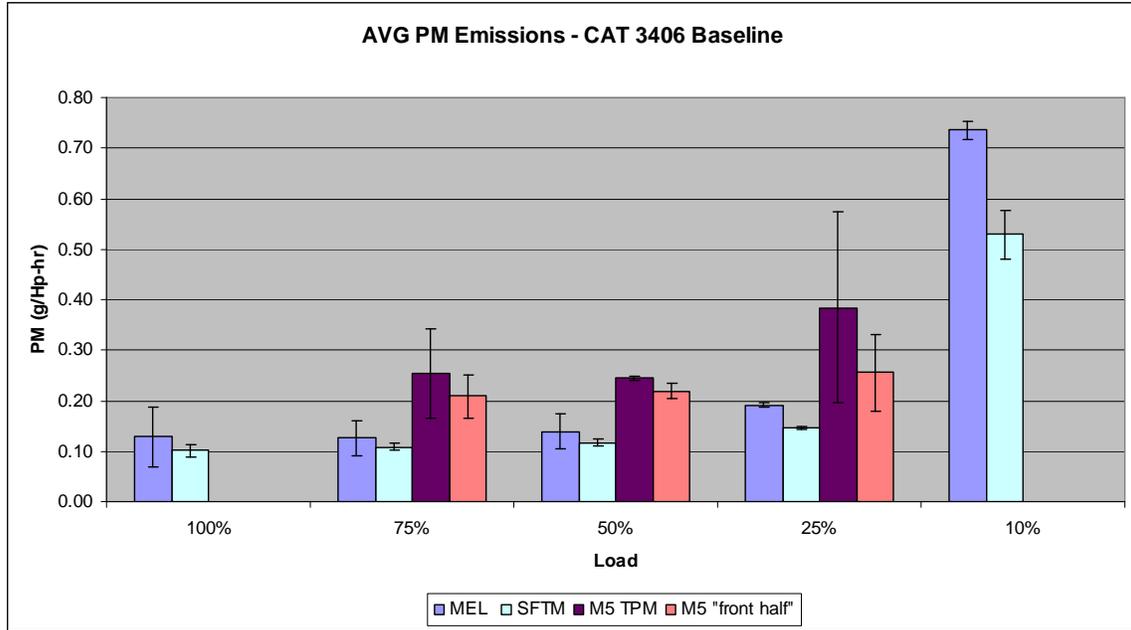
Figure 3-4 Baseline Verification Test Results

Table 3-4 Baseline Verification Test Results

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	100%	0.13	0.10		
	75%	0.13	0.11	0.25	0.21
LOAD	50%	0.14	0.12	0.24	0.22
	25%	0.19	0.15	0.38	0.26
	10%	0.74	0.53		
STDEV					
	100%	0.060	0.013		
	75%	0.035	0.006	0.088	0.042
LOAD	50%	0.034	0.006	0.005	0.016
	25%	0.003	0.003	0.190	0.076
	10%	0.018	0.047		

Results for the baseline testing show the average PM determined by the SFTM was 14% to 28% lower than the reference MEL measurements. The SFTM results, however, were statistically equivalent to the reference MEL results for loads above 50%. Additionally, a

strong linear correlation was determined between the two methods, with an R^2 value of 0.9995.
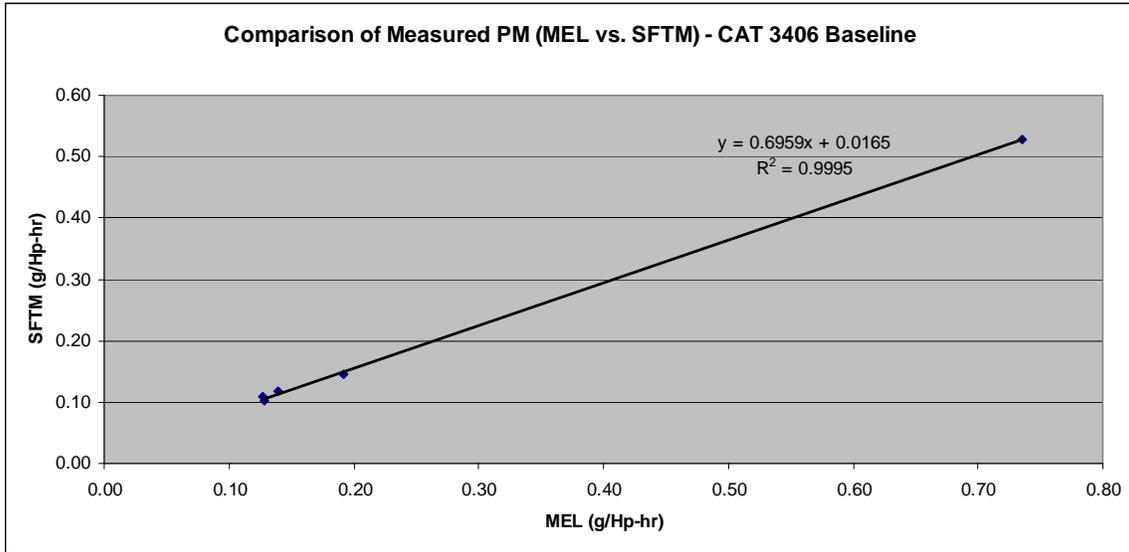
Figure 3-5 Comparison of Measured PM: MEL vs. SFTM

Method 5 total particulate matter (TPM) results averaged 76% to 100% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 33% to 65% higher than the reference measurements. A closer review of the Method 5 results revealed that a significant portion of the difference was attributed to the exhaust flow rate measurement. Table 3-5 shows the Method 5 flow rate determination compared with the reference method.

Table 3-5 Comparison of Flow Rate Determinations (Baseline Verification)

LOAD	M5 Flow (dscfm)	MEL Flow (dscfm)
75%	903	774
50%	736	602
25%	585	465

The differences in flow measurement may be due to the difficulty in performing a Method 5 velocity traverse across a small exhaust stack from a diesel engine. While a stack extension was employed that expanded the 6" diameter exhaust stack into a 10" diameter duct, the velocity profile and pulsing exhaust make measurement with a Pitot tube difficult. Because of the differences in the flow rate measurements, the results for Method 5 were recalculated using the reference MEL flow rates. The recalculated results are shown in Figure 3-4.
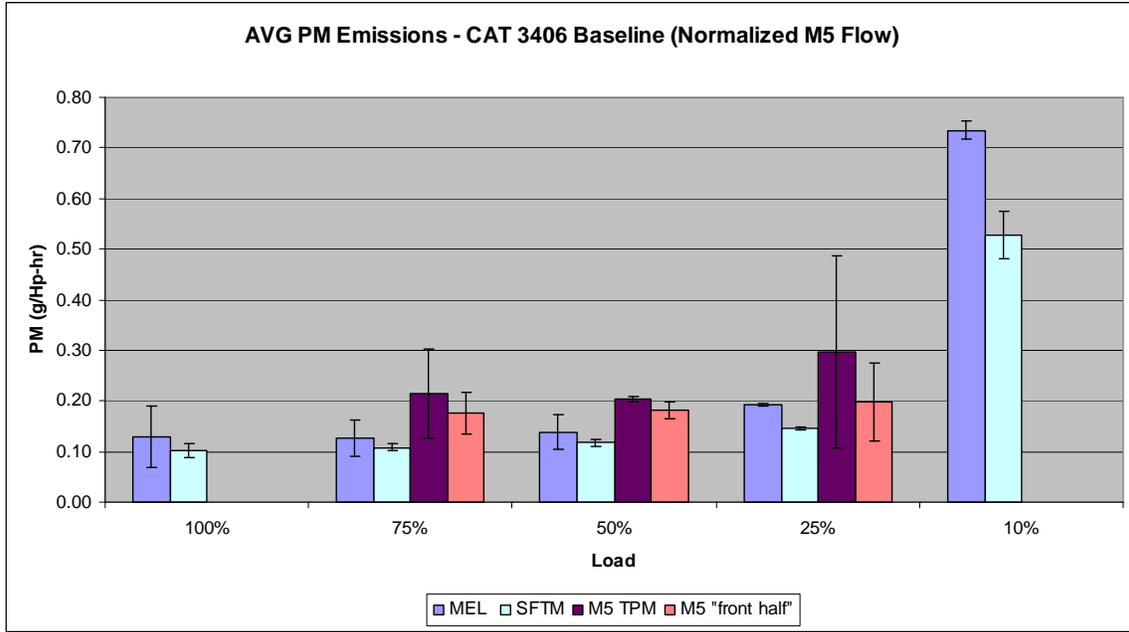
Figure 3-6 Baseline Verification Test Results

Normalized for flow, the Method 5 results compare more favorably with the reference MEL results. In particular, the up-front portion of the Method 5 results become statistically equivalent to the reference MEL measurements. The large deviations in the TPM results are due to the variable "back-half" fractions of Method 5 samples (organic and inorganic impinger catches). A regression of the limited data is shown below.
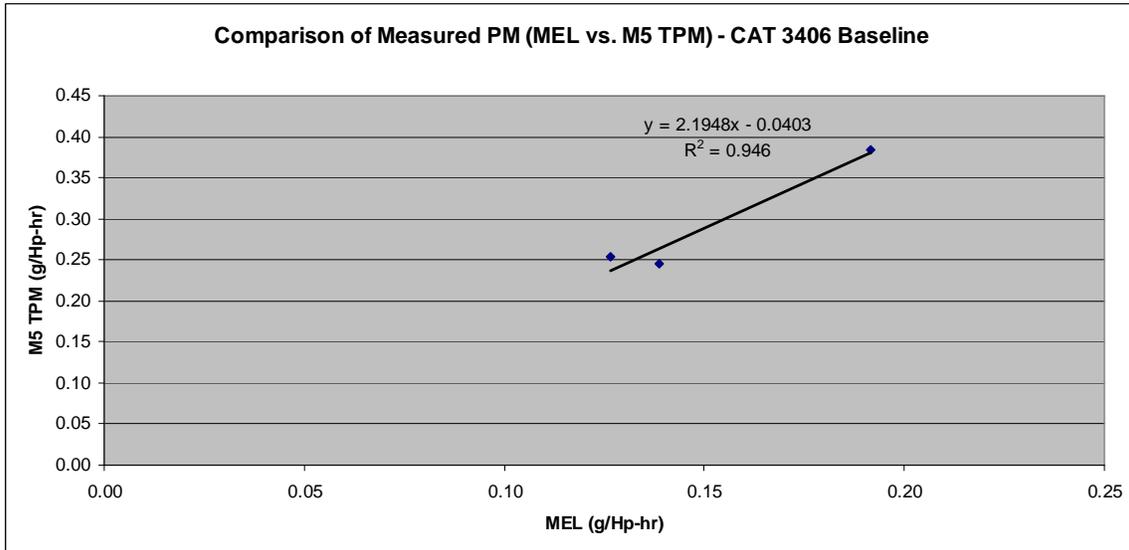
Figure 3-7 Comparison of Measured PM: SFTM vs. M5 TPM

3.8 Results: Verification Test #2

The second set of verification tests was conducted on the same CAT 3406C backup generator, equipped with a highly efficient, catalyzed diesel particulate filter (DPF). Modal results are shown below.
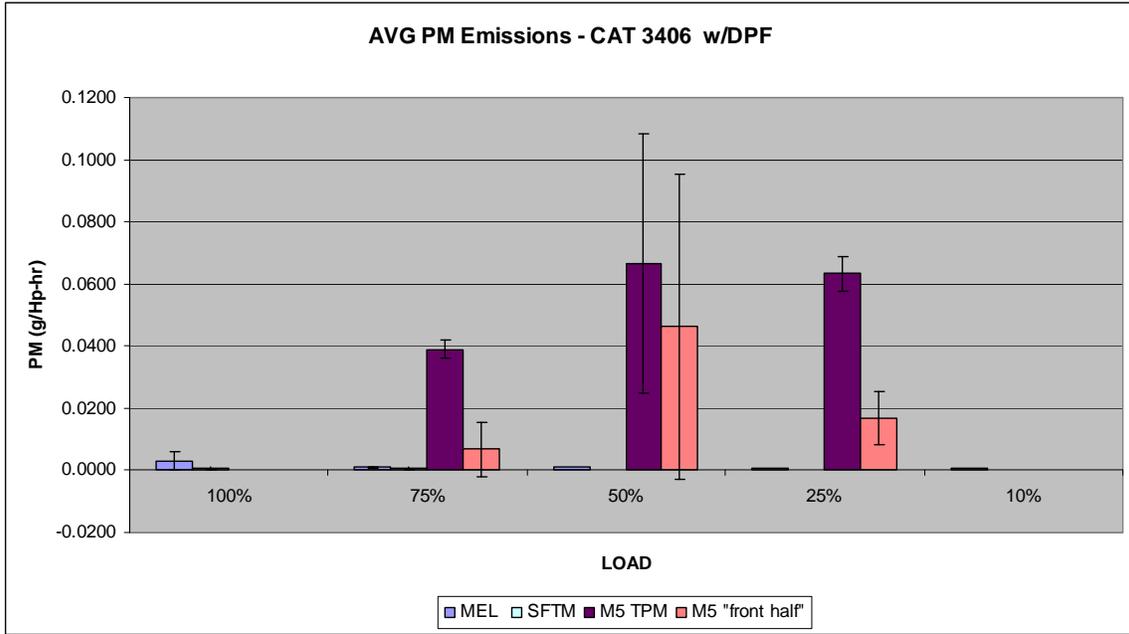
Figure 3-8 Verification Test #2: Engine with Catalyzed DPF

Table 3-6 Verification Test #2: Engine with Catalyzed DPF

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	100%	0.0030	0.0006		
	75%	0.0010	0.0006	0.0390	0.0068
LOAD	50%	0.0009	0.0001	0.0665	0.0463
	25%	0.0005		0.0633	0.0169
	10%	0.0006	0.0001		
STDEV					
	100%	0.00302	0.00033		
	75%	0.00023	0.00036	0.00283	0.00884
LOAD	50%			0.04172	0.04914
	25%			0.00544	0.00849
	10%				

Note that the Method 5 values are many up to 40 times the values measured with MEL and are excluded from further discussion. SFTM and reference MEL are plotted below.
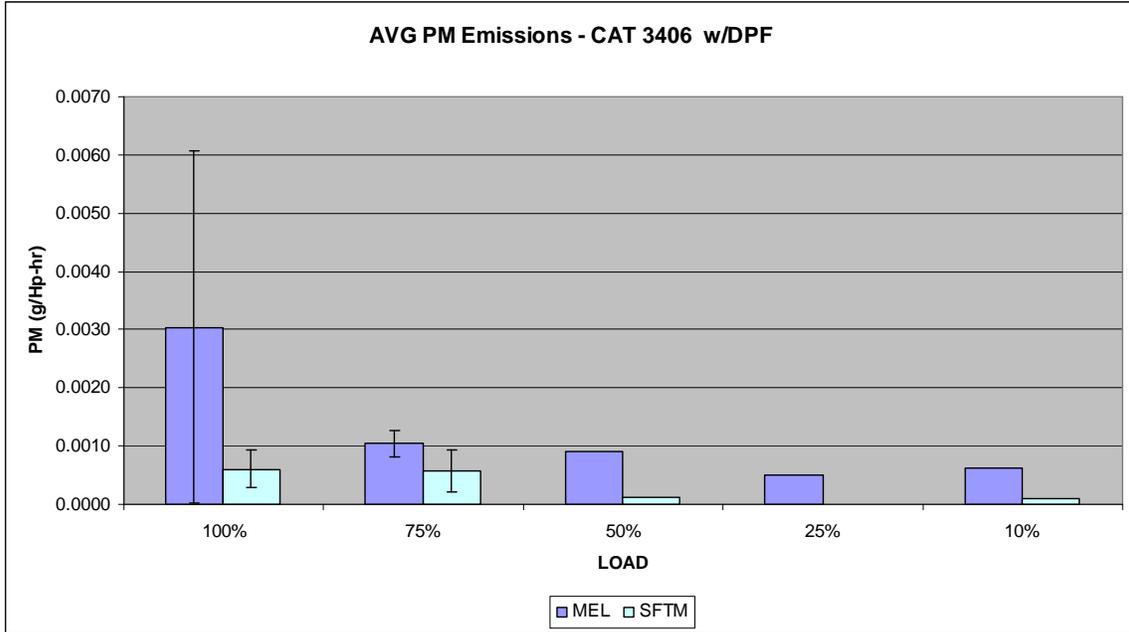
Figure 3-9 Comparison of PM from DPF: SFTM vs. MEL

As discussed earlier, measuring PM emissions with a DPF is challenging as the emissions are near the lower detection limit of all methods performed. Due to very light filter loadings observed in the initial tests, the test matrix was modified and sampling times were increased. Sample filter weights for these test runs were approximately 100 μg for MEL samples and 50 μg for SFTM samples. With single sample runs, statistical analysis is not available. Using the lower detection limit as the standard deviation; however, the PM determined by the SFTM is statistically equivalent to the reference MEL results at the 100% and 75% load points. Finally, the Method 5 samples resulted in PM emission factors that were many times higher than either the MEL of SFTM results, due mainly to the inorganic impinger catch. In conclusion, due to the small number of samples and filter weights that challenged the detection limits, no correlations were observed between methods.

4　　Results: SFTM Demonstration Testing

Five sets of demonstration tests were conducted pursuant to the objectives of the project. For all three units tested, multi-modal gravimetric PM determinations were made using the total exhaust capture dilution method (MEL), Method 5, and the SFTM. The demonstration tests were conducted at UCR and at a pump rental facility in Riverside.

4.1　　Demonstration Test Matrix #1

The first three sets of demonstration tests were conducted on backup generator applications, following the ISO 8178 D2 cycle (Table 2-1). For these demonstration test series, an additional test mode at 43.5% load (determined for the Caterpillar 3406 engine per 12/27/06 Technical Memorandum) was sampled using the SFTM only in order to verify the single-mode surrogate relative to the weighted-average ISO results. Following SFTM/ISO testing, Method 5 samples were acquired at the 75%, 50%, and 25% load points. The initial plan was to perform duplicate samples at each of the five modes and the 43.5% load point for each of the three (3) demonstration test series. Extra time allowed for triplicate ISO/CFR and SFTM sampling. The baseline test matrix is shown in Table 2.

Table 4-1 Demonstration Test Matrix #1

Mode	Load (%)	ISO/CFR PM Samples	SFTM PM Samples	ISO/CFR CO_2 Samples	Method 5 PM Samples
1	100	3	3	3	
2	75	3	3	3	2
3	50	3	3	3	2
4	25	3	3	3	2
5	10	3	3	3	
3A	43.5		3		

4.2　　Demonstration Test Matrix #2

The last two demonstration tests were conducted on agricultural pump CI engine applications. Duplicate tests were conducted with the SFTM concurrent with the total capture ISO reference system. Testing typically follows the ISO 8178 D2 cycle, as illustrated in Table 1. For pumps and compressor; however, it is not possible to duplicate the ISO cycle in field applications. Therefore, these units were tested at two operating modes: idle and working load.

Emissions were measured at each mode with both the full-dilution protocol offered by UCR's mobile CFR laboratory and the SFTM described above. Duplicate ARB Method 5 samples were acquired at both the idle and working load modes. As the Method 5 samples could not be acquired simultaneously with the total capture (full-dilution) method, this testing was conducted consecutively. The test matrix for the agricultural pump CI engine application demonstration is presented in Table 4-2.

Table 4-2 Demonstration Test Matrix #2 Ag Pump

Mode	Load (%)	ISO/CFR PM Samples	SFTM PM Samples	ISO/CFR CO_2 Samples	Method 5 PM Samples
1	Full	x	x	x	x
2	Idle	x	x	x	x

4.3　　　Analyses

PM mass was determined for each of the filter samples collected. Results for the SFTM and ISO/CFR samples were then compared in terms of resultant PM emissions (g/Hp-hr).

The Method 5 samples were separated into fractions (nozzle/probe, filter, aqueous extract, and organic extract). The PM mass for the nozzle/probe and filter fractions were determined per ARB Method 5. The aqueous extract from the impinger catch was boiled down to 100 ml in a tared beaker. Two 5 ml aliquots of the 100 ml sample were set aside in sealed vials for further analyses. The remaining 90 ml sample was boiled to dryness, and the mass of the residue determined. The organic extract from the impinger catch was evaporated at room temperature down to 100 ml in a tared beaker. Two 5 ml aliquots of the 100 ml sample were set aside in sealed vials for further analyses. The remaining 90 ml sample was evaporated to dryness, and the mass of the residue determined.

CO_2 mass emissions were determined at each mode with the ISO/CFR method. CO_2 mass emissions as a function of measured electrical load were determined to verify CO_2 as a load surrogate.

4.4　　　Test Results Demo#1　CAT 3306+DOC

The first set of demonstration tests were conducted on a CAT 3306C backup generator equipped with a diesel oxidation catalyst (DOC). Modal results are shown below.
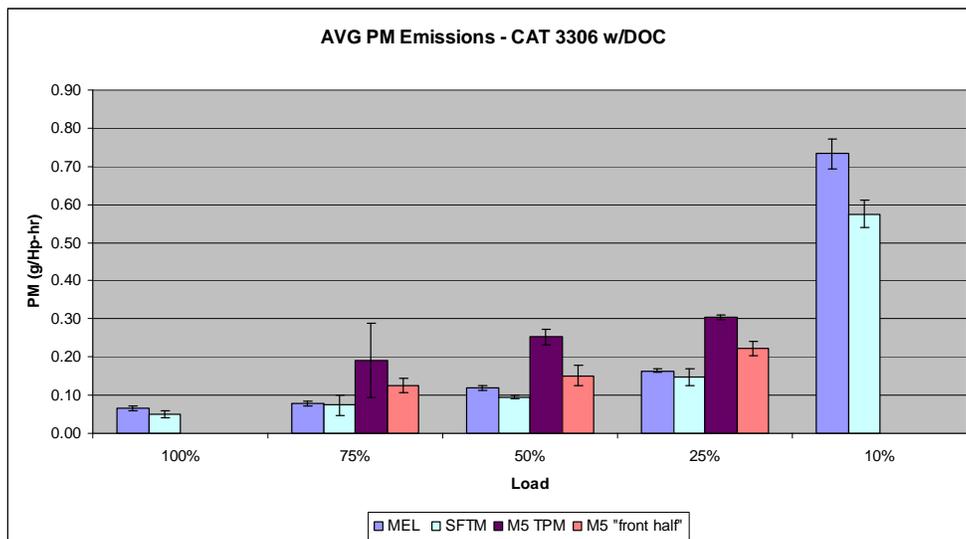
Figure 4-1 CAT 3306+DOC Test Results: MEL. SFTM & M5

Table 4-3 CAT 3306+DOC Test Results: MEL. SFTM & M5

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	100%	0.07	0.05		
	75%	0.08	0.07	0.19	0.13
LOAD	50%	0.12	0.10	0.25	0.15
	25%	0.16	0.15	0.30	0.22
	10%	0.73	0.57		
STDEV					
	100%	0.006	0.010		
	75%	0.006	0.026	0.098	0.019
LOAD	50%	0.006	0.005	0.021	0.027
	25%	0.004	0.022	0.006	0.019
	10%	0.038	0.036		

Results for the first set of demonstration tests show the average PM determined by the SFTM was 5% to 22% lower than the reference MEL measurements. The SFTM results; however, were statistically equivalent to the reference MEL results for three (3) of the five (5) modes tested. Additionally, a strong linear correlation was determined between the two methods, with an R^2 value of 0.9926 (see Appendix B)

Method 5 total particulate matter (TPM) results averaged 86% to 146% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 26% to 61% higher than the reference measurements. As with previous testing, a significant portion of the difference can be attributed to the exhaust flow rate measurement. Table 11 shows the Method 5 flow rate determination compared with the reference method.

Table 4-4 Comparison of Flow Rates: M5 vs. MEL

LOAD	M5 Flow (dscfm)	MEL Flow (dscfm)
75%	512	497
50%	424	393
25%	364	311

The results were recalculated for Method 5 using the reference MEL flow rates. The recalculated results are shown in Figure 10.
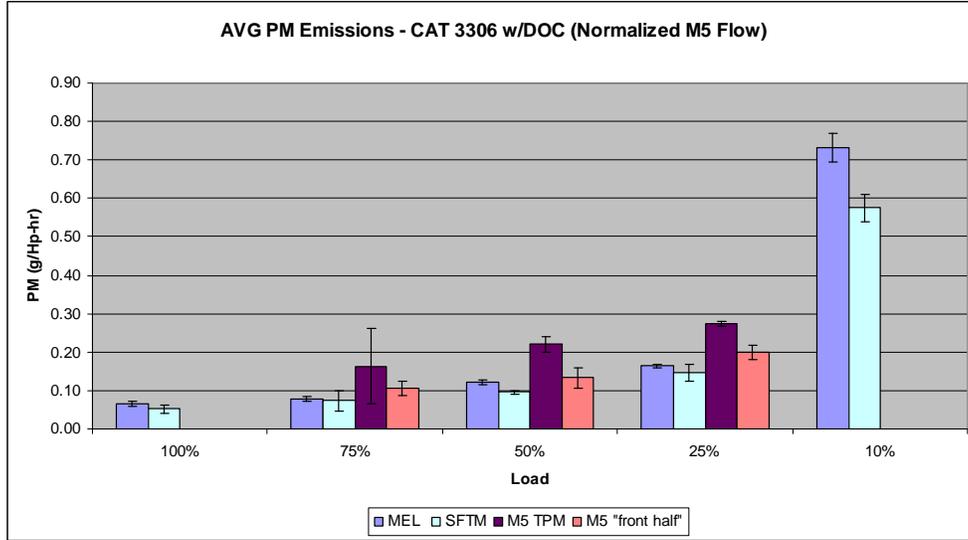
Figure 4-2 CAT 3306+DOC Test Results: MEL. SFTM & M5

Normalized for flow, the Method 5 results compare more favorably with the reference MEL results. The large deviations in the TPM results are due to the variable "back-half" fractions of Method 5 samples (organic and inorganic impinger catches).

4.5   Test Results Demo#2 CAT 3306

The second set of demonstration tests were conducted on the CAT 3306C backup generator without the DOC. Modal results are shown in Figure 11 and Table 12.
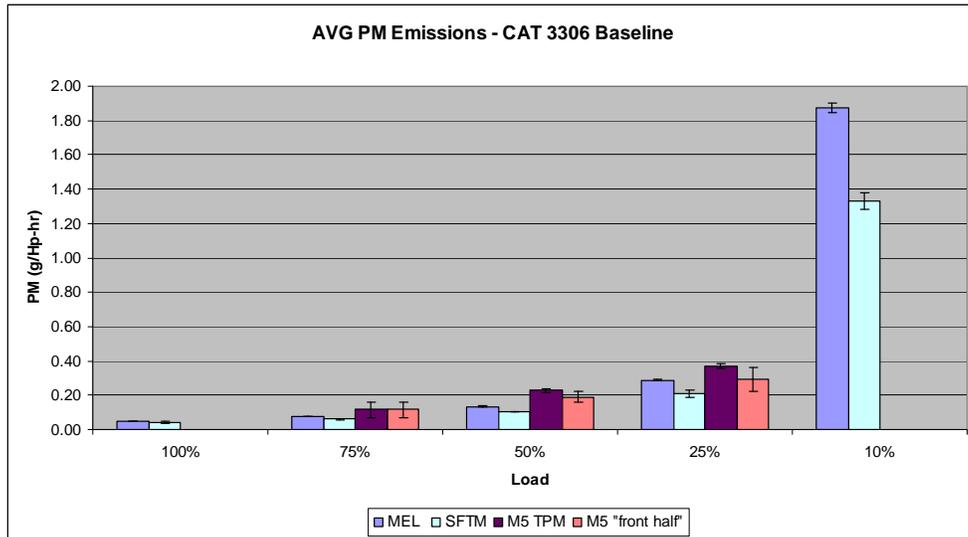
Figure 4-3 Test Results Demo #2 CAT 3306

Table 4-5 Test Results Demo#2 CAT 3306

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	100%	0.05	0.04		
	75%	0.08	0.06	0.12	0.12
LOAD	50%	0.14	0.10	0.23	0.19
	25%	0.29	0.21	0.37	0.29
	10%	1.88	1.33		
STDEV					
	100%	0.001	0.005		
	75%	0.001	0.001	0.044	0.045
LOAD	50%	0.004	0.001	0.011	0.030
	25%	0.006	0.020	0.016	0.069
	10%	0.028	0.049		

Results for the second set of demonstration tests show the average PM determined by the SFTM was 16% to 29% lower than the reference MEL measurements. The SFTM results, however, were statistically equivalent to the reference MEL results for loads above 25%. Additionally, a strong linear correlation was determined between the two methods, with an R^2 value of 0.9979 (see Appendix B)

Method 5 total particulate matter (TPM) results averaged 28% to 68% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 1% to 49% higher than the reference measurements. As with previous testing, a portion of the difference can be attributed to the exhaust flow rate measurement. Table 4-6 shows the Method 5 flow rate determination compared with the reference method.

Table 4-6 Comparison of Flow Rate: Demo #2

LOAD	M5 Flow (dscfm)	MEL Flow (dscfm)
75%	594	512
50%	407	404
25%	404	320

The results were recalculated for Method 5 using the reference MEL flow rates. The recalculated results are shown in Figure 4-4.
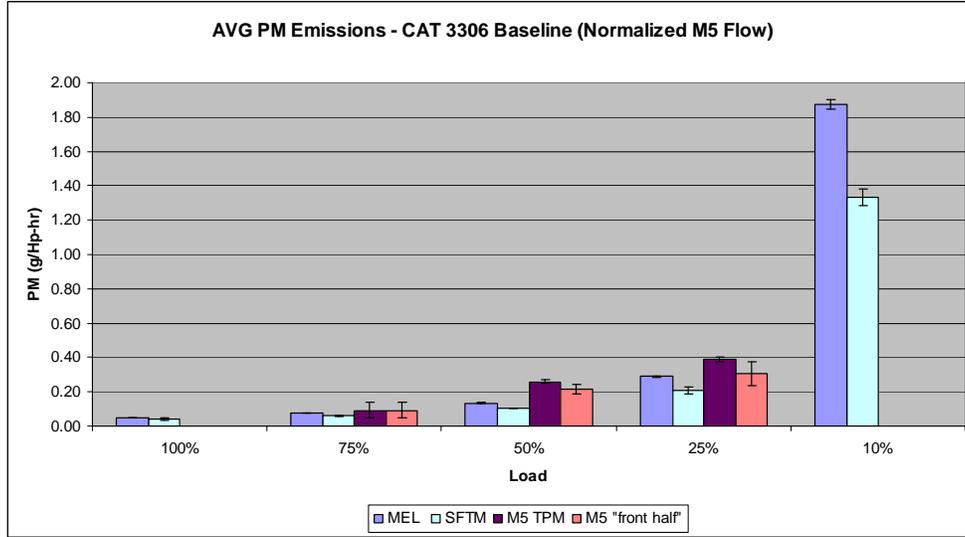
Figure 4-4 Demonstration Test Unit #2 Test Results

Normalized for flow, the Method 5 results compare slightly better with the reference MEL results.

4.6   Demo # 3 Komatzu Unit

The third set of demonstration tests were conducted on a Komatzu SA6D125 backup generator. Modal results are shown below.
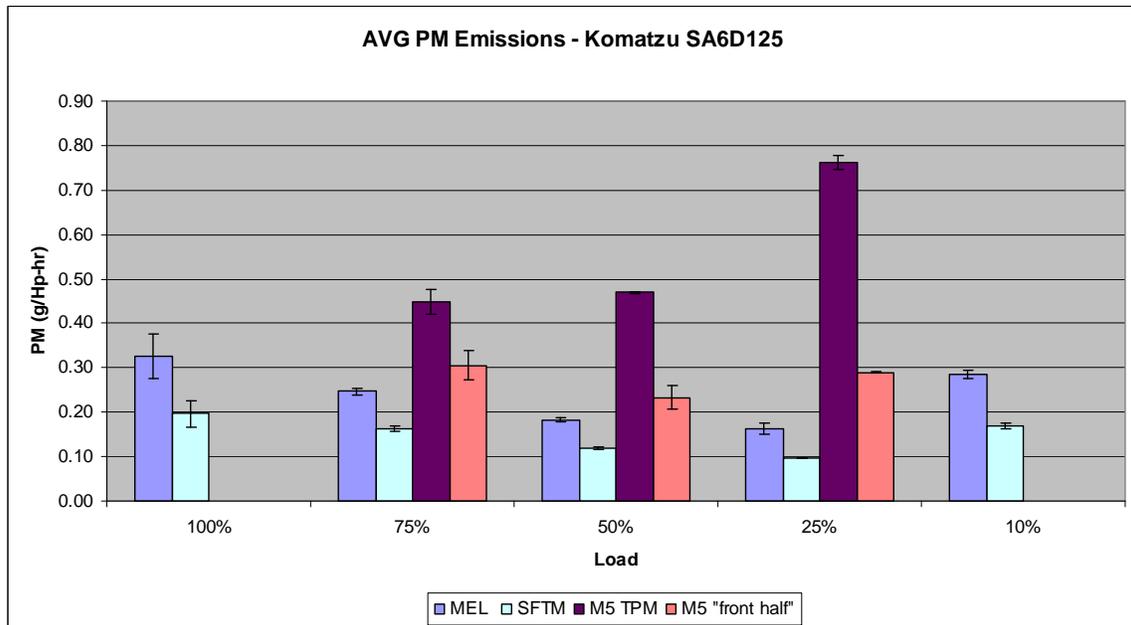
Figure 4-5 Demonstration Test Unit #3 Results

Table 4-7 Demonstration Test Unit #3 Results

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	100%	0.33	0.20		
	75%	0.25	0.16	0.45	0.31
LOAD	50%	0.18	0.12	0.47	0.23
	25%	0.16	0.10	0.76	0.29
	10%	0.28	0.17		
STDEV					
	100%	0.050	0.029		
	75%	0.009	0.006	0.028	0.033
LOAD	50%	0.004	0.004	0.002	0.027
	25%	0.012	0.001	0.015	0.001
	10%	0.009	0.006		

Results for the third set of demonstration tests show the average PM determined by the SFTM was 34% to 41% lower than the reference MEL measurements. A strong linear correlation was determined between the two methods, with an R^2 value of 0.9581 (see Appendix B)

Method 5 total particulate matter (TPM) results averaged 82% to 366% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 24% to 77% higher than the reference measurements. As with previous testing, a portion of the difference can be attributed to the exhaust flow rate measurement. Table 4-8 shows the Method 5 flow rate determination compared with the reference method.

Table 4-8 Comparative of Flow Rate (Demo Test Unit #3)

LOAD	M5 Flow (dscfm)	MEL Flow (dscfm)
75%	462	429
50%	394	362
25%	317	309

The results were recalculated for Method 5 using the reference MEL flow rates. The recalculated results are shown in Figure 4-6.
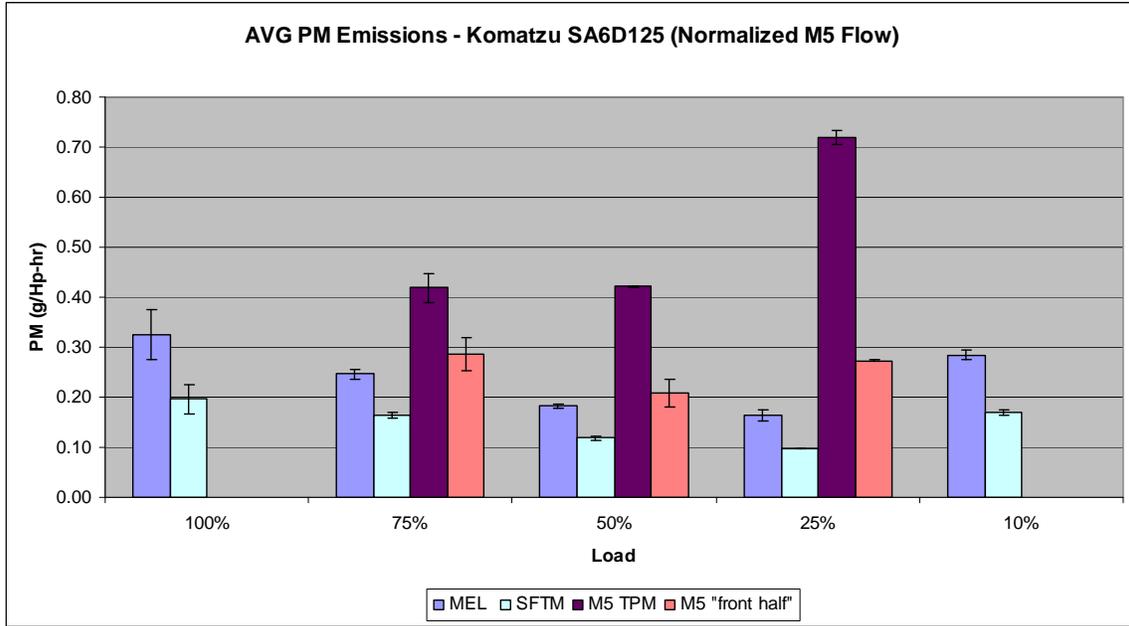
Figure 4-6 Demonstration Test Unit #3 Test Results

Normalized for flow, the Method 5 results compare slightly better with the reference MEL results.

4.7   Demo # 4 Water Pump with John Deere Engine

The fourth set of demonstration tests were conducted on a John Deere RG608 water pump. Modal results are shown below.
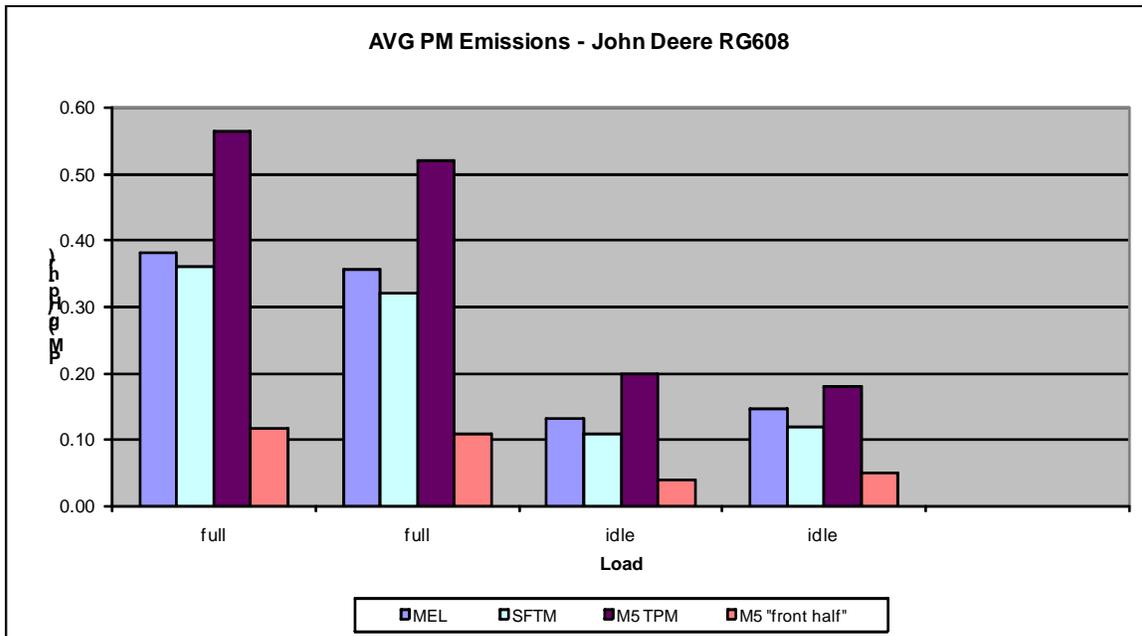
Figure 4-7 Comparative Results Demo Test Unit #4

Table 4-9 Comparative Results Demo Test Unit #4

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	Full	0.38	0.36	0.56	0.12
	Full	0.36	0.32	0.52	0.11
LOAD	Idle	0.13	0.11	0.20	0.04
	Idle	0.15	0.12	0.18	0.05

Results for the fourth set of demonstration tests show the average PM determined by the SFTM was 5% to 18% lower than the reference MEL measurements. Additionally, a strong linear correlation was determined between the two methods, with an R^2 value of 0.9926 (see Appendix B)

Method 5 total particulate matter (TPM) results averaged 23% to 52% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 66% to 70% lower than the reference measurements. This is most likely due to high organic carbon (OC) content of the PM from this engine.

Results from the EC/OC analyses of filter samples for this unit are shown in Table 4-10.

Table 4-10 Elemental and Organic Carbon Fractions of Diesel PM from Demo Unit #4

Condition	EC % wt.	OC % wt.
Load	41.6%	58.4%
Load	40.2%	59.8%
Idle	15.9%	84.1%
Idle	10.6%	89.4%

As the Method 5 samples are acquired through a probe and filter heated to 250 °F, a portion of the organic carbon remains in gaseous form, passing through the filters. Thus, the "front-half" Method 5 results are substantially lower than the reference results.

4.8   Demo # 5 Water Pump with John Deere Engine

The fifth set of demonstration tests were conducted on a John Deere R116195 water pump. Modal results are shown below.

AVG PM Emissions - John Deere R116195
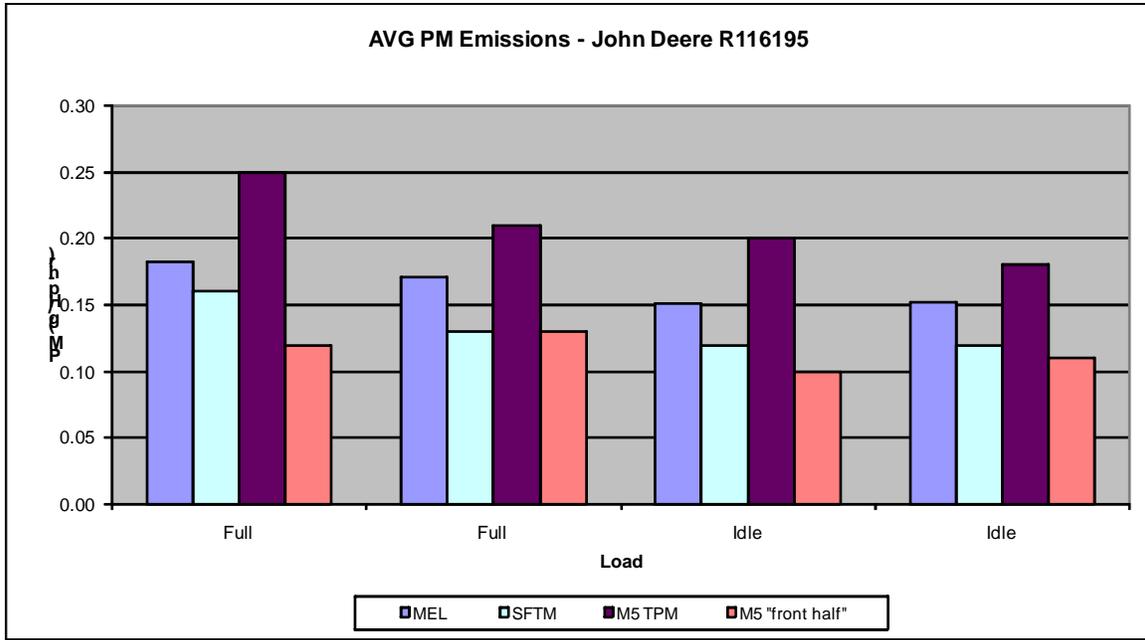
Figure 4-8 Comparative Results Demo Test Unit #5

Table 4-11 Comparative Results Demo Test Unit #5

AVG PM (g/Hp-hr)		MEL	SFTM	M5 TPM	M5 "front half"
	Full	0.18	0.16	0.25	0.12
	Full	0.17	0.13	0.21	0.13
LOAD	Idle	0.15	0.12	0.20	0.10
	Idle	0.15	0.12	0.18	0.11

Results for the fifth set of demonstration tests show the average PM determined by the SFTM was 13% to 21% lower than the reference MEL measurements. Additionally, a strong linear correlation was determined between the two methods, with an R^2 value of 0.993 (see Appendix B)

Method 5 total particulate matter (TPM) results averaged 18% to 36% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 24% to 35% lower than the reference measurements. This is most likely due to high organic carbon (OC) content of the PM from this engine.

Results from the EC/OC analyses of filter samples for this unit are shown in Table 4-12.

Table 4-12 Elemental and Organic Carbon Fractions of Diesel PM from Demo Unit #5

Condition	EC % wt.	OC % wt.
Load	11.3%	88.7%
Load	11.1%	88.9%
Idle	25.9%	74.1%
Idle	17.7%	82.3%

As the Method 5 samples are acquired through a probe and filter heated to 250 $^\circ$F, a portion of the organic carbon remains in gaseous form, passing through the filters. Thus, the "front-half" Method 5 results are substantially lower than the reference results.

4.9   Overall STFM Correlation

Results from all testing (excluding verification test #2) were compared in order to establish a correlation between the SFTM and the ISO/CFR reference method. The correlation is shown in Figure 4-9.

Comparison of Measured PM (MEL vs. SFTM) - All Data*

$y = 0.7102x + 0.0049$
$R^2 = 0.9895$
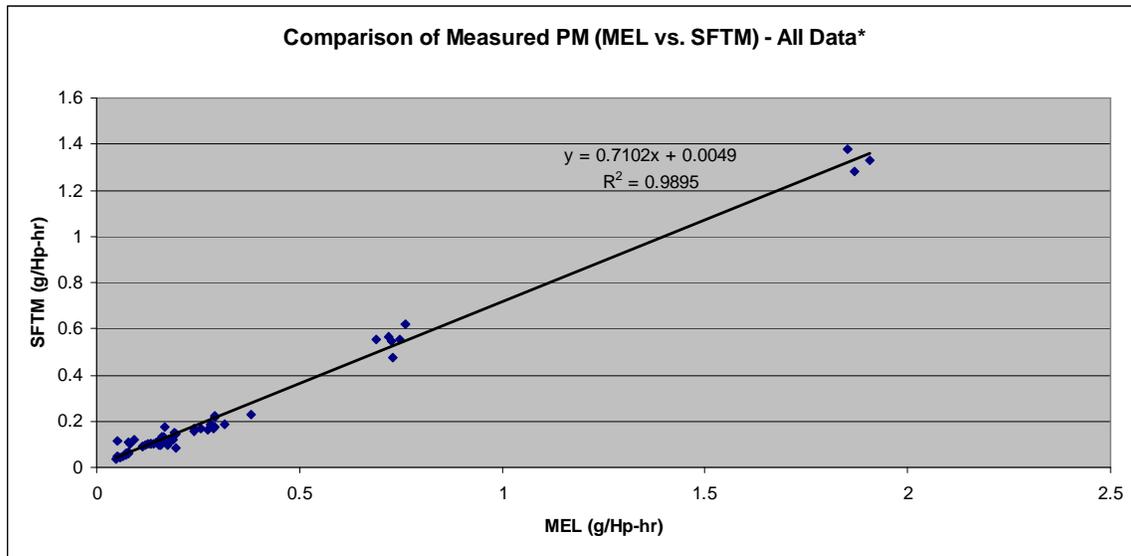
* excluding verification test #2 (results below detectable limits)

Figure 4-9 Overall SFTM/MEL Correlation

4.10   Determining PM Emission Factors with the SFTM Correlation

Using the correlation developed above, overall weighted PM emission factors were determined from the SFTM sample filter mass measurements, and compared with those determined by the reference ISO/CFR (MEL) emission factors. In addition, the single load point measurements determined by the SFTM for each of the units tested was compared with the weighted 5-mode measurements. The comparisons are shown below.

Table 4-13 Comparison of PM Emission Factors (MEL/SFTM)

				Single Load Point (43.5%)	
TEST	**Weighted AVG PM**		Difference		Difference
SERIES	(MEL, g/Hp-hr)	(SFTM, g/Hp-hr)	from MEL	(SFTM, g/Hp-hr)	from MEL
Verification #1	0.154	0.170	10.3%	0.160	3.8%
Verification #2	BDL				
Demonstration #1	0.118	0.135	14.3%	0.131	11.5%
Demonstration #2	0.164	0.165	0.3%	0.184	11.8%
Demonstration #3	0.222	0.193	-12.9%	0.169	-23.8%

BDL - Below Detectable Limits

Results show that the correlated measurements using the SFTM can determine the PM emissions from diesel engines within a +/- 15% accuracy. Furthermore, the single load point surrogate appears viable as a time saving technique for approximating the 5-mode ISO result. The PM results using the single-point SFTM ranged from -24% to +12% compared with the reference measurement. For the baseline verification test, the single load point result was within 4% of the weighted 5-mode reference result.

Referring back to the earlier section, the 43.5% load point was chosen for the verification test unit; a Caterpillar 3406 backup generator. Load point surrogates for the demonstration units were not known at the time of testing, so the 43.5% load point was used as a default value. It is expected that the PM results for the demonstration units would be more accurate (particularly for unit #3) if testing were conducted at the properly determined load point.

4.11 CO_2 as a Surrogate for Load

Using the correlation developed in previous tasks (Figure 4), UCR estimated engine loads for each test run based on CO_2 mass emissions. The predicted vs. measured engine loads are shown in Figure 4-10.

Measured vs. Predicted Loads (All Data)

$y = 0.9492x - 7.2711$
$R^2 = 0.9952$
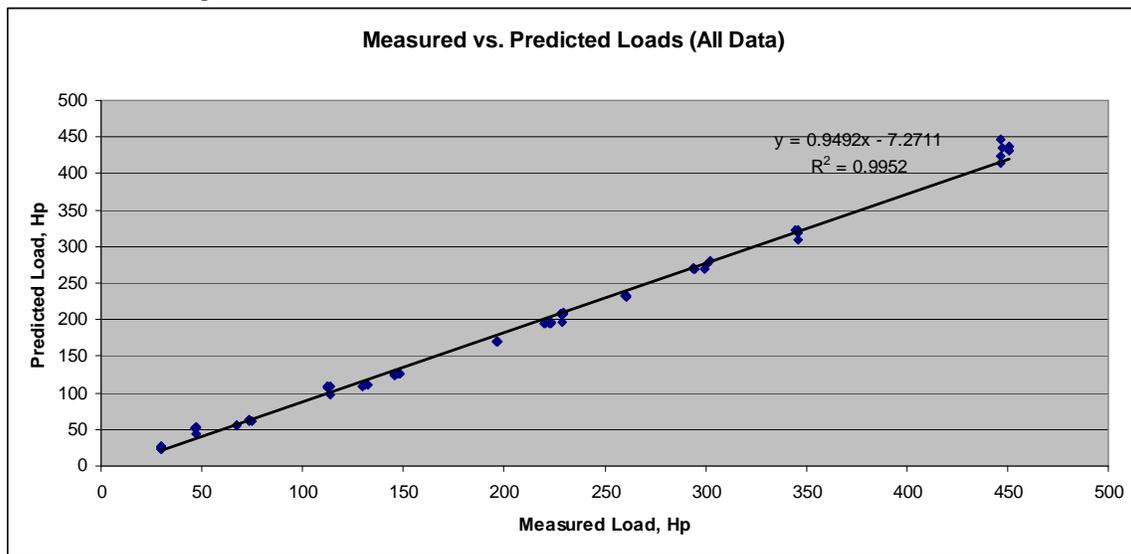
Figure 4-10 Engine Load Predicted by CO_2-Emissions

Results demonstrate that the CO_2 mass emissions can be used to accurately predict engine load, eliminating the need to directly measure the load.

As described in Section 3.2, CO_2 mass emissions can be determined fairly easily in the field. A portable gas analyzer is used to measure the CO_2 concentration in the exhaust at a given operating condition. Exhaust flow rate is determined from engine parameters (rpm, displacement, boost pressure and intake manifold temperature) or from direct measurement (e.g. Pitot tube, hot wire anemometer). With CO_2 concentration and exhaust flow rate, the mass emissions can be calculated and related back (using the correlation) to the operating load at the given condition.

5   Results: Real Time PM Screening Techniques

Two real-time PM measurement techniques were evaluated concurrently with the other methods for both the verification tests and demonstration tests. One was a Dekati Mass Monitor (DMM), and the other was a TSI DustTrak 8520. The advantages of real-time PM measurement include the elimination of filter conditioning/weighing as well as the ability to monitor and document the second-by-second PM exhaust concentrations over the course of a test run. Disadvantages include cost, and the need to dilute the sample to avoid over-ranging the instruments.

5.1   Determination of PM Emission Factors Using the DMM

The Dekati Mass Monitor (DMM; Dekati Ltd., Finland) is a real-time mass measurement instrument that was used in the test program as a screening tool. The principle of the DMM is based on particle charging, inertial/electrical size classification, and electrical detection of aerosol particles. Results from all testing (excluding verification test #2) were compared in order to establish a correlation between the DMM and the ISO/CFR reference method. The correlation is shown below.

Comparison of Measured PM (MEL vs. DMM) - All Data*

$y = 0.5267x + 0.0169$
$R^2 = 0.9505$
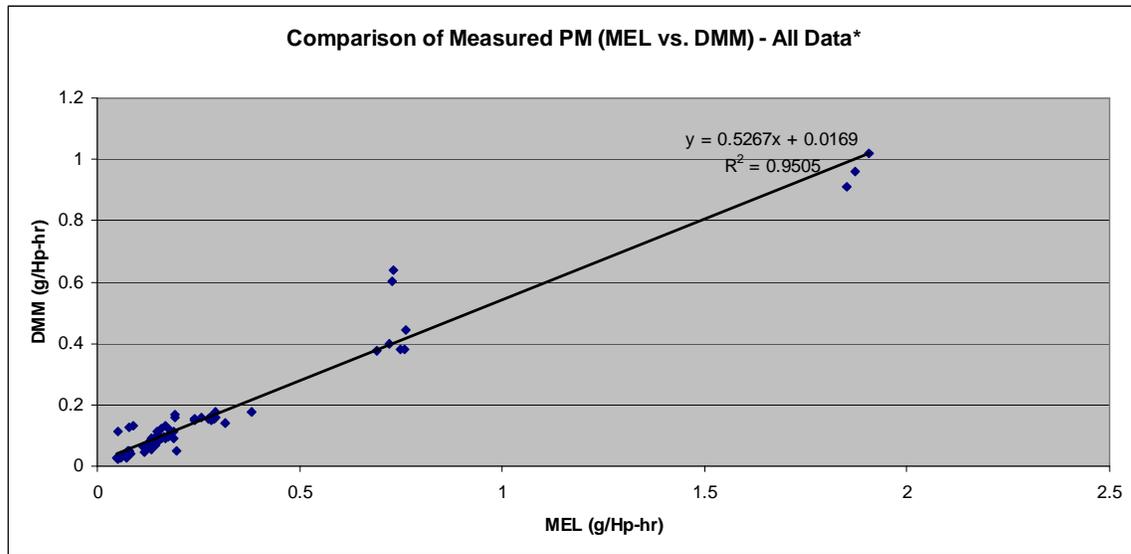
* excluding verification test #2 (results below detectable limits)

Figure 5-1 DMM/MEL Correlations

Using the correlation developed above, overall weighted PM emission factors were determined from the DMM measurements, and compared with those determined by the reference ISO/CFR (MEL) emission factors. The comparisons are shown in Table 5-1.

Table 5-1 Comparison of PM Emission Factors (MEL/DMM)

TEST SERIES	Weighted AVG PM		Difference from MEL
	(MEL, g/Hp-hr)	(DMM, g/Hp-hr)	
Verification #1	0.154	0.173	12.5%
Verification #2	BDL		
Demonstration #1	0.118	0.089	-24.5%
Demonstration #2	0.164	0.154	-6.4%
Demonstration #3	0.222	0.219	-1.5%

BDL - Below Detectable Limits

Results show that the correlated measurements using the DMM can determine the PM emissions from diesel engines within a +/- 25% accuracy.

5.2   Determination of PM Emission Factors Using the DustTrak

A second instrument was employed in the test program as a screening tool. Nephelometers measure light scattered by aerosol introduced into their sample chamber. The TSI DustTrak 8520 is a fairly simple and compact nephelometer with excellent sensitivity and time resolution. Scattering per unit mass is a strong function of particle size and refractive index, so mass measurement may be compromised across a range of diesel operating conditions with varying particle size distributions and refractive indices[6]. For this project, a TSI DustTrak 8520 nephelometer (DT) measuring 90° light scattering at 780 nm (near-infrared) was used. This instrument displays its measurement as mass density (i.e., units of mg/m^3) through a calibration with ISO 12103-1, A1 test dust. The DustTrak is a very practical, compact, and low-priced instrument.

Results from all testing (excluding verification test #2) were compared in order to establish a correlation between the DustTrak and the ISO/CFR reference method. The correlation is shown in Figure 5-2.

Comparison of Measured PM (MEL vs. DusTrak) - All Data*

$y = 1.1148x - 0.0548$
$R^2 = 0.977$
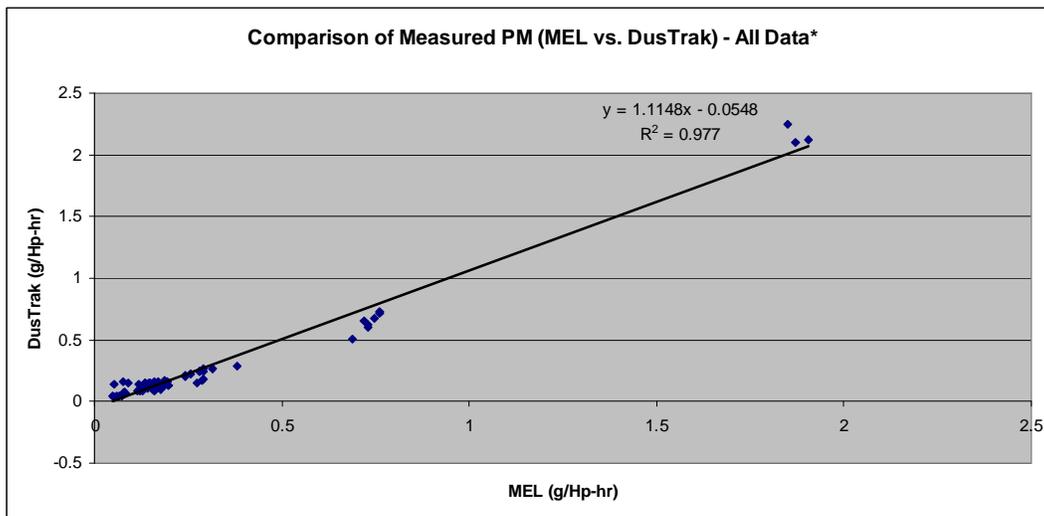
* excluding verification test #2 (results below detectable limits)

Figure 5-2 DustTrak/MEL Correlation

Using the correlation developed above, overall weighted PM emission factors were determined from the DustTrak measurements, and compared with those determined by the reference ISO/CFR (MEL) emission factors. The comparisons are shown in Table 20.

Table 5-2 Comparison of PM Emission Factors (MEL/DustTrak)

TEST SERIES	Weighted AVG PM		Difference from MEL
	(MEL, g/Hp-hr)	(DustTrak, g/Hp-hr)	
Verification #1	0.154	0.197	27.7%
Verification #2	BDL		
Demonstration #1	0.118	0.127	7.9%
Demonstration #2	0.164	0.185	12.8%
Demonstration #3	0.222	0.205	-7.7%

BDL - Below Detectable Limits

Results show that the correlated measurements using the DustTrak can determine the PM emissions from diesel engines within a +/- 28% accuracy.

6   Results: Method 5 Laboratory Tests

A number of Method 5 laboratory tests were carried out with pure compounds to gain a better understanding of the reason for the high bias for Method 5 when compared to other reference methods. Significant amounts of material were found in the "back half" of the Method 5 samples acquired from CI engines, so it was important to determine whether the material was actually PM emitted from the exhaust, PM precursors that are converted in the impinger solutions, or artifacts that would not normally form in the exhaust plume.

6.1   Background and Approach

The impinger solutions from Method 5 are separated into an aqueous and methylene-chloride extract phases before drying. Ion chromatograph allowed chemical analyses of aqueous fractions and the results showed that sulfates and nitrates made up the bulk of the final aqueous residue mass. Since these compounds would be likely captured on the up-front Method 5 filter if they existed in the engine exhaust stream, it seemed clear that they were forming in the impinger solutions. SO_2 and NO_2 gases passed through the filter and dissolved in aqueous solution where they were oxidized to sulfite/sulfate and nitrite/nitrate, respectively. The resulting equilibrium concentrations depend on the gas-phase concentrations of O_2, SO_2 and NO_2, temperature and pH of impinger solutions (both during and after sampling).

Emissions testing from CI engines suggested that the gaseous hydrocarbon emissions are equivalent to the solid/condensed hydrocarbon emissions (on a C_1 mass basis). A Method 5 train sampling 35 dscf of exhaust should have approximately 55 mg of organic gases, primarily C_1 - C_4 alkanes and alkenes, pass through the back-half impingers. Approximately 20% by volume of the organic gases are aldehydes and ketones, plus small amounts of organic acids. Assuming 100% scrubbing efficiency of the impinger solutions, the theoretical maximum amount of material recovered as organic residue would be 11 mg. Previous Method 5 samples have resulted in organic residues of 30 – 50 mg. Clearly, there is either a contamination of the organic residue with inorganic material, or reactions of organic gases in impinger solutions that lead to large residue determinations.

Studies suggest that aqueous bisulfite binds strongly to aldehydes[7], which are present in significant concentrations in CI engine exhaust. The conditions of the sample impinger solutions (cold temperature, low PH) strongly favor the formation of these complexes. As an example, 1 mg of acetaldehyde binds with 1.45 mg of SO_2. If these complexes remain after evaporation of the organic and aqueous fractions of the impinger solutions, it would help explain the significant mass of residues found in Method 5 samples from diesel exhaust. While less is known about the aqueous interactions of organic gases with NO_2, similar mechanisms are expected.

6.2   Laboratory Simulations and Results

In order to definitively address these questions, a set of tests was conducted to determine the extent and mechanism of residue formation from inorganic acid gases (SO_2 and NO_2) present in CI engine exhaust. Pure SO_2 and/or NO_2 gases of known concentration were blended with air in a manifold mixing chamber. Samples were extracted from the mixing chamber using the "back half" ARB Method 5 sampling trains (impingers containing DI water, contained in an ice bath). The inlet and outlet of the Method 5 sample streams were monitored for SO_2 and/or NO_2 gas concentrations using NDIR and chemiluminescence detectors, respectively.

Sampling continued until the inlet and outlet gas concentrations were equal (signifying equilibrium saturation of SO_2 and/or NO_2 in the impinger solutions). In some cases, the sample train was purged with nitrogen immediately (in order to remove remaining dissolved SO_2 and NO_2 and quench conversion to sulfate/nitrate). In other cases, the nitrogen purge occurred after pre-set time periods (in order to determine sulfate/nitrate formation as a function of time in the aqueous solutions. Following sampling, analyses were conducted per ARB Method 5, including methylene chloride extraction and determination of aqueous and organic residue masses. These experiments were then repeated, but with known quantities of acetaldehyde dissolved in the impinger solutions prior to gas sampling. Results from these tests are shown in Table 2-1.

Table 6-1 Method 5 Analytical Testing

Test #	NO$_2$ (~25 ppm)	SO$_2$ (~25 ppm)	Acetalde hyde (mg/ltr)	Formalde hyde (mg/ltr)	Nitrogen Purge	pH	Inorganic Mass (mg)	Organic Mass (mg)	Insoluble Mass Color
1	yes	yes	0	0	no	3.00	18.6	1.1	-
2	yes	yes	55	0	no	2.71	43.4	1.3	White
3	yes	yes	0	55	no	2.66	35.3	1.4	Translucent
4	yes	yes	0	0	yes	2.97	5.6	2.5	-
5	yes	yes	55	0	yes	3.00	7.0	1.6	White
6	yes	yes	55	0	yes	3.08	19.8	2.0	White
7	no	yes	0	0	no	2.74	22.1	0.8	Translucent with Brown Spots
8	no	yes	55	0	no	2.76	28.5	2.0	Translucent with Brown Spots
9	no	yes	0	0	yes	3.47	12.1	3.6	White
10	no	yes	55	0	yes	3.48	10.0	2.0	White with Brown Spots
11	yes	no	0	0	no	3.20	4.0	2.8	White
12	yes	no	55	0	no	3.17	17.9	3.2	Yellowish White

Results confirm that the presence of aldehydes in the impinger solutions leads to substantially higher back-half residues than impingers containing water alone. Furthermore, the nitrogen purge proves very effective in preventing the formation of the artifact.

Aliquots from each of the impinger solutions were obtained for ion chromatography analyses. Results are presented in Table 6-2.

Table 6-2 Ion Chromatography Analyses of Impinger Solutions

Test #	NO2 (ppm)	SO2 (ppm)	Acetaldehyde (mg/ltr)	Formaldehyde (mg/ltr)	Nitrogen Purge	Inorganic h2o Chloride mg	Inorganic h2o Nitrate mg	Inorganic h2o Sulfate mg	Inorganic h2o Nitrite mg
1	yes	yes	0.0	0.0	no	1.1	7.7	9.6	0.0
2	yes	yes	55.0	0.0	no	13.7	7.4	11.4	0.4
3	yes	yes	0.0	55.0	no	2.8	8.1	2.9	8.5
4	yes	yes	0.0	0.0	yes	0.5	6.4	2.4	0.0
5	yes	yes	55.0	0.0	yes	1.7	7.1	2.3	0.4
6	yes	yes	55.0	0.0	yes	6.1	6.8	2.4	0.3
7	no	yes	0.0	0.0	no	0.2	0.0	15.0	0.0
8	no	yes	55.0	0.0	no	2.0	0.0	12.5	0.4
9	no	yes	0.0	0.0	yes	2.7	0.0	4.6	0.5
10	no	yes	55.0	0.0	yes	1.6	0.0	3.1	0.6
11	yes	no	0.0	0.0	no	0.3	11.1	0.1	0.0
12	yes	no	55.0	0.0	no	4.0	11.2	0.4	0.0

In addition to confirming the effectiveness of the nitrogen purge, results show similar amounts of nitrates and sulfates independent of the presence of aldehydes. Thus, the additional masses shown in Table 6-1 for the tests with aldehydes present must be due to the aldehydes themselves, rather than from additional sulfate and nitrate formation. This is an important finding, as aldehyde residues themselves are not found in processed impinge solutions in pure water. This seems to confirm the theory that a sulfate-nitrate-aldehyde complex is responsible for the "back-half" mass in Method 5 samples of diesel exhaust, and is indeed an artifact of the sampling method, rather than a primary emission.

7   Summary and Conclusions

7.1   Simplified Field Test Method

A Simplified Field Test Method (SFTM) was developed to measure particulate matter (PM) emissions from compression ignition (CI) engine applications. The SFTM is intended as a screening tool to identify high-emitting engines or those with faulty emission control equipment. The primary elements of the SFTM include sampling equipment, a single load point surrogate, exhaust flow rate determination, and engine load estimation. The SFTM was verified and demonstrated through a series of tests concurrent with reference methods (ISO 8178/CFR and ARB Method 5).

The basic components of the SFTM sampling system include a small raw exhaust probe at a single sampling point, an insulated filter holder, a PTFE filter, a moisture removal device, a critical flow orifice (CFO), and a sample pump. The sampling system is easy to set up and use by a single operator. It can be configured using equipment currently employed by source testing personnel at Air Districts throughout California. In CI engine applications where the power output cannot be directly measured, a second small probe is employed for measurement of CO_2 in the exhaust stream using a simple portable gas analyzer.

Previous results demonstrated that a single mode point can be used to determine the overall 5-mode weighted brake-specific PM mass emissions within a 15% margin of error, provided that the modal emissions for a given engine make/(model) are known. Preliminary suggested single mode points have been determined for several engine makes and/or models. In examining results from the current verification/demonstration testing, the single load point surrogate appears viable as a time saving technique for approximating the 5-mode ISO result. The PM results using the single-point SFTM ranged from -24% to +12% compared with the reference measurement. Single load point surrogates for the demonstration units were not known at the time of testing, so the 43.5% load point (determined for the verification engine) was used as a default value. For the baseline verification test (using the proper pre-determined load point), the result was within 4% of the weighted 5-mode reference result. It is expected that the PM results for the demonstration units would be more accurate (particularly for unit #3) if testing were conducted at the properly determined load point.

With a known engine displacement, the exhaust flow rate was determined at any load point by measuring RPM, boost pressure, intake manifold temperature, and ambient temperature/humidity. This simple approach was used in a number of recent programs, and shown to agree with reference values within 1% (UCR, 2004). For newer engines, these parameters can be read directly from the engine control module (ECM) using diagnostic tools. For older engines, these parameters may be measured using a photo tachometer (rpm), pressure transducer (boost pressure), and a thermocouple (intake manifold pressure).

Previous work between ARB and UCR found an excellent correlation between the CO_2 emissions and the power output. The current verification/demonstration testing confirms that CO_2 mass emissions are a very good surrogate for load. In the field, CO_2 mass emissions can be determined from gaseous concentrations measured in the exhaust and calculation of the exhaust flow rate. CO_2 concentrations can be measured directly in the exhaust stream using a portable gas analyzer.

7.2   Verification and Demonstration Testing of the SFTM

Results from testing show the average modal PM determined by the SFTM was 5% to 41% lower than the reference MEL modal measurements. The SFTM results, however, are much closer to the reference measurements at loads above 25%, suggesting that the differences relate to the organic carbon (OC) fraction of the exhaust PM. Typically, diesel engines emit a higher fraction of OC at lower engine loads. As the SFTM uses a hot up-front filter, it is expected that a portion of the OC fraction of PM will pass through in gaseous form.

While the raw SFTM results were consistently lower than the reference MEL results, strong linear correlations were observed in every case (R^2 values of 0.9581 to 0.9995). Results from all testing (excluding verification test #2) were compared in order to establish a correlation between the SFTM and the ISO/CFR reference method.

Using the correlation developed in this research, the overall weighted PM emission factors were determined from the SFTM sample filter mass measurements, and compared with those determined by the reference ISO/CFR (MEL) emission factors. Results show that the correlated measurements using the SFTM can determine the PM emissions from diesel engines within a +/- 15% accuracy.

7.3   ARB Method 5 Findings

Method 5 total particulate matter (TPM) results averaged 28% to 366% higher than the reference results. The "front-half" only portion of the Method 5 samples (probe catch + up-front filter) averaged 1% to 77% higher than the reference measurements. Some of these differences can be attributed to the method of exhaust flow rate measurement between Method 5 and the reference method. Flow measurement is difficult in performing a Method 5 velocity traverse across a small exhaust stack from a diesel engine. While a stack extension was employed that expanded the 6" diameter exhaust stack into a 10" diameter duct, the velocity profile and pulsing exhaust make measurement with a Pitot tube quite challenging. In light of the differences observed in the flow rate measurements, the results were recalculated for Method 5 using the reference MEL flow rates. Normalized for flow, the Method 5 results compare more favorably with the reference MEL results; In particular, the up-front portion of the Method 5 results (in most cases) become statistically equivalent to the reference MEL measurements.

Another source of differences in the Method 5 TPM results are due to the variable "back-half" fractions of Method 5 samples (organic and inorganic impinger catches). Previous work showed M5 "back-half" results alone to be 1 to 2 times higher than the reference

TPM results from the ISO/CFR Method. In the current program, a new procedure (recommended by the EPA) was implemented involving a 1-hour nitrogen purge of the M5 impinger solutions immediately following sampling. Results show that the new procedure dramatically reduces the "back-half" residues, but substantial amounts remain in the organic and inorganic impinger residues. Further work is recommended to determine whether these residues are consistent with PM emitted from diesel engines, or are an artifact of the sampling technique itself.

7.4   Real Time Screening Techniques

Two real-time PM measurement techniques were evaluated as potential screening techniques during the test program along with the other methods during both the verification and demonstration tests. One was a Dekati Mass Monitor (DMM), and the other was a TSI DustTrak 8520.

Results from all testing (excluding verification test #2) were compared in order to establish a correlation between the DMM, the DustTrak, and the ISO/CFR reference methods. Using the correlations, overall weighted PM emission factors were determined from the DMM and DustTrak measurements, and compared with those determined by the reference ISO/CFR (MEL) emission factors. Results show that the correlated measurements using the DMM and DustTrak can determine the PM emissions from diesel engines within a about a 25% accuracy. While the DMM offers the potential to measure the emissions at the low levels expected from the controlled diesel engines but the cost is roughly 10-times that of the DustTrak.

8   Recommendations

Simplified Field Test Method: Further work is needed to expand the database and improve the correlations. With the exception of the Caterpillar 3406 model, the UCR data sets are limited to only a few engines. Additional 5-mode testing could be conducted on different makes/models of engines to improve the correlation, but such testing is costly and time-consuming. Alternatively, the modal emission factors required for engine certification testing could be used for linear regression and determination of the single-point surrogate load for each individual make/model. These surrogate load points could be published in a simple reference guide for field application. Even if the prescribed surrogate single load for the overall weighted average cannot be achieved, the emissions approximation can be determined at any load; provided that the 5-mode correlation is known.

ARB Method 5: More research is needed to better understand the nature and origin of the PM mass that is found in the impinger solutions. Results from this work and that of the EPA clearly indicate that the acid gases and aldehydes play a major role in the creation of the mass found in the impingers.

Real time PM Analyzers Clearly the simplest way to measure whether a diesel engine is complying with the PM regulations is to stick a monitor into the exhaust, like the Smog Check Program, and quickly learn the state of compliance. More work is needed to explore the ever evolving instruments from around the world that would provide the desired monitoring at a reasonable price. Toward that end, some progress was made in this research.

APPENDIX A

Reference Sampling Methods

A.1 ISO/CFR Total Capture (reference method)

Total capture exhaust measurement will be performed using UCR's Mobile Emissions Laboratory (MEL). The MEL is comprised of a 53-foot insulated trailer equipped with a full-scale dilution tunnel that meets the emissions measurement quality level specified in the U.S. Congress Code of Federal Regulations for Heavy Duty Diesel Engines (Code of Federal Regulations, 2004a). The laboratory is capable of total capture emissions measurements for engines up to 600 kW in size.

The entire exhaust stream from the engine is captured by the MEL via an insulated, gastight, flexible, 316-L stainless steel tube. PM samples are withdrawn from a temperature controlled Secondary Dilution System (SDS) operating at 47($\pm$ 5) ℃ (Cocker et al. 2004b). PM mass samples are collected on 47 mm PTFE Teflo® filters. Filter preparation and handling meet the requirements of the CFR (Code of Federal Regulations, 2004a). Filter weights are determined with a Cahn (Madison, WI) C-35 microbalance. A minimum of three stable filter weights are used for both tare and post-test determinations. Concurrent PM samples are collected on pre-fired quartz fiber filters for determination of Elemental Carbon/Organic Carbon (EC/OC) fractions. The MEL complies with the requirements for ISO 8178 testing.

Besides precision or repeatability, accuracy is a critical feature of any laboratory and the UCR's mobile CFR-compliant HDDE/HDDV test facility was verified against ARB's heavy-duty lab in Los Angeles. Results of the comparison are shown in the table below and the variances were within those of a round robin study and reported by Traver (2001)[8.] Thus MEL offers the opportunity to compare instruments with a mobile system that uses the "gold standard" instruments specified in the CFR.

Table A1 Differences in Measured Emissions Between UCR's and ARB's labs

Test Cycle	THC	CO	NOx	CO_2	$PM_{2.5}$
Hot UDDS	12%	18%	8%	2.7%	0.1%

Diluted Exhaust: Temperature, Absolute Pressure, Throat ∆P, Flow.

GPS: Pat, Long, Elevation, # Satellite Precision.

CVS Turbine: 1000-4000 SCFM, Variable Dilution.

Secondary Probe.

Gas Sample Probe.

Secondary Dilution System* PM (size, Mass).

Drivers Aid.

Gas Measurements: CO_2 %, O_2 %, CO ppm, NO_x ppm, THC ppm, CH_4 ppm.

Other Sensor: Dew Point, Ambient Temperature, Control room temperature, Ambient Baro, Trailer Speed (rpm), CVS Inlet Temperature.

Dilution Air: Temperature, Absolute Pressure, Throat ∆P, Baro (Ambient), Flow, Dew Point (Ambient).

Exhaust: Temperature, ∆P (Exhaust-Ambient), Flow.

Engine Broadcast: Intake Temperature, Coolant Temperature, Boost Pressure, Baro Pressure, Vehicle Speed (mph), Engine Speed (rpm), Throttle Position, Load (% of rated).

Figure A1 Schematic of UCR's Heavy-Duty Diesel Mobile Emission Laboratory (MEL)

A fuller description of the lab can be found in two recent articles in the Environmental Science and Technology. One[9] is on the sampling for regulated gases and the other[10] applies the lab to measuring in-use PM, toxic emissions and elemental and organic carbon .

A.2 ARB Method 5 (reference method)

A conventional ARB Method 5 sampling train will be used on a subset of tests to sample raw diesel exhaust from an adapted emission stack. Method 5 samples will be acquired over 60-90 minutes time period. Samples will be extracted from the adapted diesel exhaust duct through a stainless steel nozzle and heated probe (120 ^{o}C + 14 ^{o}C). Filterable PM is collected on pre-weighed, dry 0.45 micron 115 mm Gelman quartz fiber filters with subsequent capture of condensable PM in a series of impingers immersed in an ice bath. A schematic of Method 5 sampling train is seen in Figure 3.

The sample train is analyzed according to ARB Method 5 procedures. Briefly, the quartz filter is removed and desiccated until completely dry before obtaining the final filterable catch. Material deposited in the probe and nozzle is recovered with a nylon bristle brush and Optima-grade methylene chloride rinse. This rinse is allowed to evaporate at room temperature in a tared 100 ml beaker to determine the mass of material in the probe and nozzle. This, combined with the sample mass recovered on the filter, makes up the "front half" catch.

Impingers are rinsed with HPLC-grade water and Optima-grade methylene chloride. The organic (methylene chloride soluble) and inorganic (water soluble) fractions of the solution are divided in a separatory funnel. The inorganic aqueous fraction is subsequently heated to boiling to reduce the total water volume to 150 ml, transferred to a tared beaker, and placed in an oven (100 °C) until dry. The organic fraction is transferred in 50 ml aliquots and allowed to evaporate in a tared 150 ml beaker at room temperature. The sum of the residues from both fractions is reported as the "back half" catch. The total Method 5 particulate catch is then reported as the sum of the "front half" and "back half" weights.
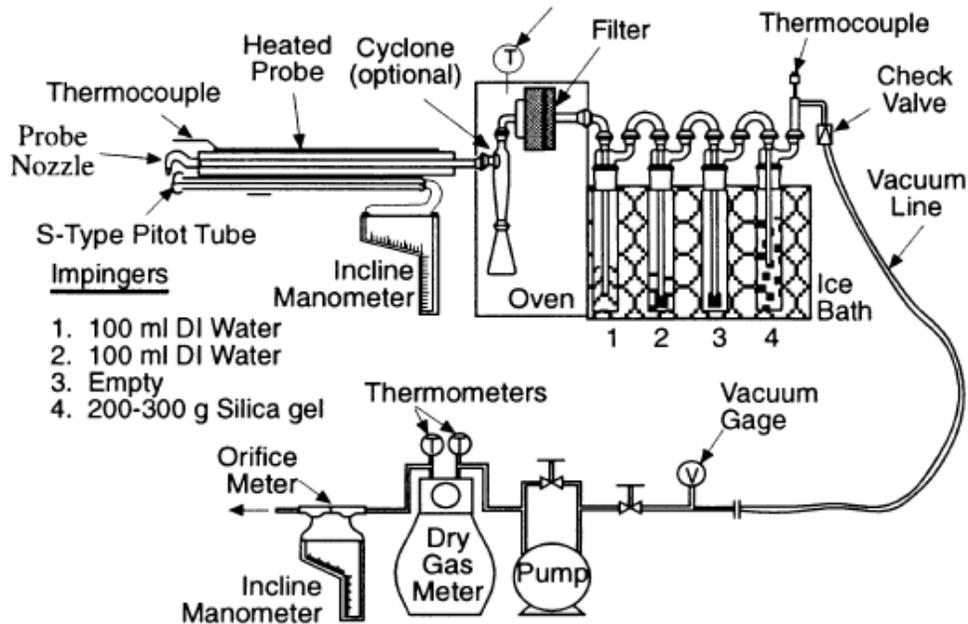
Figure A2 ARB Method 5 Sampling Train

APPENDIX B

Detailed Test Results

Verification Test #1

AVG PM Emissions - CAT 3406 Baseline
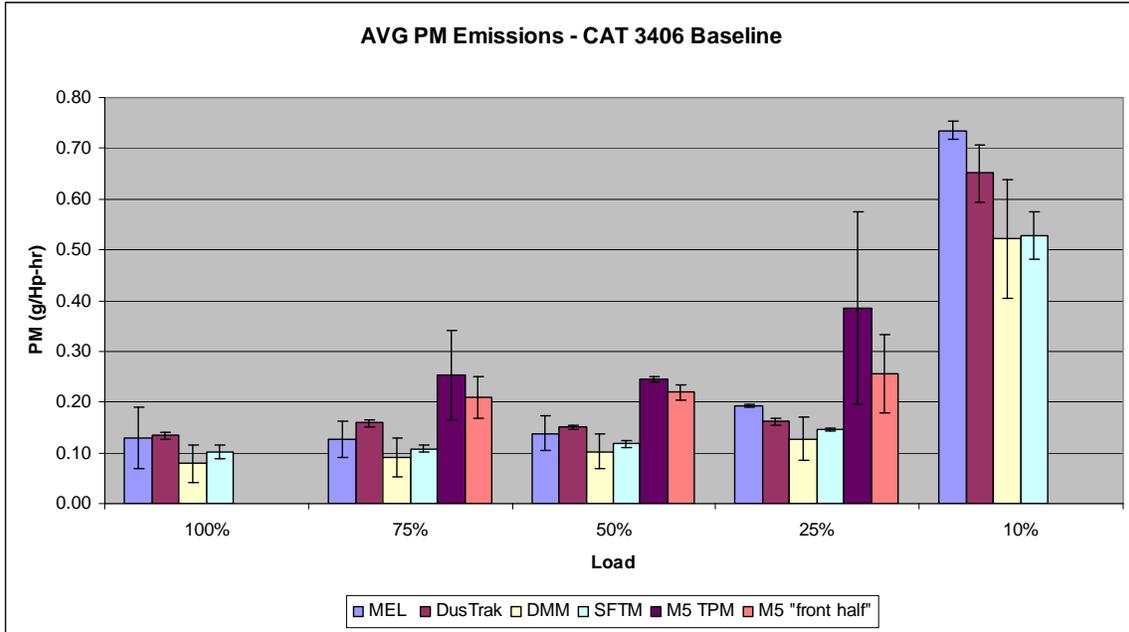
AVG PM (g/Hp-hr)		MEL	DusTrak	DMM	SFTM	M5 TPM	M5 "front half"
	100%	0.13	0.13	0.08	0.10		
	75%	0.13	0.16	0.09	0.11	0.25	0.21
LOAD	50%	0.14	0.15	0.10	0.12	0.24	0.22
	25%	0.19	0.16	0.13	0.15	0.38	0.26
	10%	0.74	0.65	0.52	0.53		
	43.5%				0.12		
STDEV							
	100%	0.060	0.006	0.038	0.013		
	75%	0.035	0.006	0.038	0.006	0.088	0.042
LOAD	50%	0.034	0.004	0.034	0.006	0.005	0.016
	25%	0.003	0.006	0.043	0.003	0.190	0.076
	10%	0.018	0.057	0.117	0.047		
	43.5%				0.009		

Comparison of Measured PM (MEL vs. SFTM) - CAT 3406 Baseline

$y = 0.6959x + 0.0165$
$R^2 = 0.9995$

SFTM (g/Hp-hr) vs MEL (g/Hp-hr)

Comparison of Measured PM (MEL vs. M5 TPM) - CAT 3406 Baseline

$y = 2.1948x - 0.0403$
$R^2 = 0.946$

M5 TPM (g/Hp-hr) vs MEL (g/Hp-hr)

Comparison of Measured PM (MEL vs. M5 "front half") - CAT 3406 Baseline

$y = 0.7208x + 0.1181$
$R^2 = 0.9988$

M5 "front half" (g/Hp-hr) vs MEL (g/Hp-hr)

Comparison of Measured PM (MEL vs. DMM) - CAT 3406 Baseline

$y = 0.7155x - 0.0049$
$R^2 = 0.9987$

DMM (g/Hp-hr)

MEL (g/Hp-hr)

Comparison of Measured PM (MEL vs. SFTM) - CAT 3406 Baseline

$y = 0.6959x + 0.0165$
$R^2 = 0.9995$

SFTM (g/Hp-hr)

MEL (g/Hp-hr)

Verification Test #2

AVG PM (g/Hp-hr)		MEL	DusTrak	DMM	SFTM	M5 TPM	M5 "front half"
	100%	0.0030	0.0002	0.0003	0.0006		
	75%	0.0010	0.0001	0.0002	0.0006	0.0390	0.0068
LOAD	50%	0.0009	0.0000	0.0001	0.0001	0.0665	0.0463
	25%	0.0005		0.0000		0.0633	0.0169
	10%	0.0006		0.0002	0.0001		
	43.5%	0.0017	0.0000	0.0000	0.0003		

STDEV							
	100%	0.00302	0.00004	0.00005	0.00033		
	75%	0.00023	0.00005	0.00003	0.00036	0.00283	0.00884
LOAD	50%					0.04172	0.04914
	25%					0.00544	0.00849
	10%						
	43.5%				0.00008		

Comparison of Measured PM (MEL vs. SFTM) - CAT 3406 w/DPF

$y = 0.2627x + 0.0001$
$R^2 = 0.0897$

Comparison of Measured PM (MEL vs. M5 TPM) - CAT 3406 w/DPF

$y = -32.981x + 0.0831$
$R^2 = 0.3859$

Comparison of Measured PM (MEL vs. M5 "front half") - CAT 3406 w/DPF

$y = 1.3434x + 0.0222$
$R^2 = 0.0003$

Comparison of Measured PM (MEL vs. DusTrak) - CAT 3406 w/DPF

$y = 0.0212x + 5E-05$
$R^2 = 0.2267$

(Scatter plot: DusTrak (g/Hp-hr) vs. MEL (g/Hp-hr))

Comparison of Measured PM (MEL vs. DMM) - CAT 3406 w/DPF

(Scatter plot: DMM (g/Hp-hr) vs. MEL (g/Hp-hr))

Demonstration Test #1

AVG PM (g/Hp-hr)		MEL	DusTrak	DMM	SFTM	M5 TPM	M5 "front half"
	100%	0.07	0.05	0.03	0.05		
	75%	0.08	0.06	0.04	0.07	0.19	0.13
LOAD	50%	0.12	0.08	0.07	0.10	0.25	0.15
	25%	0.16	0.11	0.09	0.15	0.30	0.22
	10%	0.73	0.63	0.38	0.57		
	43.5%				0.10		
STDEV							
	100%	0.006	0.002	0.005	0.010		
	75%	0.006	0.002	0.005	0.026	0.098	0.019
LOAD	50%	0.006	0.004	0.008	0.005	0.021	0.027
	25%	0.004	0.011	0.004	0.022	0.006	0.019
	10%	0.038	0.107	0.004	0.036		
	43.5%				0.003		

Comparison of Measured PM (MEL vs. SFTM) - CAT 3306 w/DOC

$y = 0.7746x + 0.0087$
$R^2 = 0.9926$

Comparison of Measured PM (MEL vs. M5 TPM) - CAT 3306 w/DOC

$y = 1.3061x + 0.0918$
$R^2 = 0.9972$

Comparison of Measured PM (MEL vs. M5 "front half") - CAT 3306 w/DOC

$y = 1.1334x + 0.0298$
$R^2 = 0.9389$

Comparison of Measured PM (MEL vs. DusTrak) - CAT 3306 w/DOC

$y = 0.8938x - 0.0205$
$R^2 = 0.984$

Comparison of Measured PM (MEL vs. DMM) - CAT 3306 w/DOC

$y = 0.5153x + 0.0025$
$R^2 = 0.9961$

Demonstration Test #2

AVG PM Emissions - CAT 3306 w/DOC
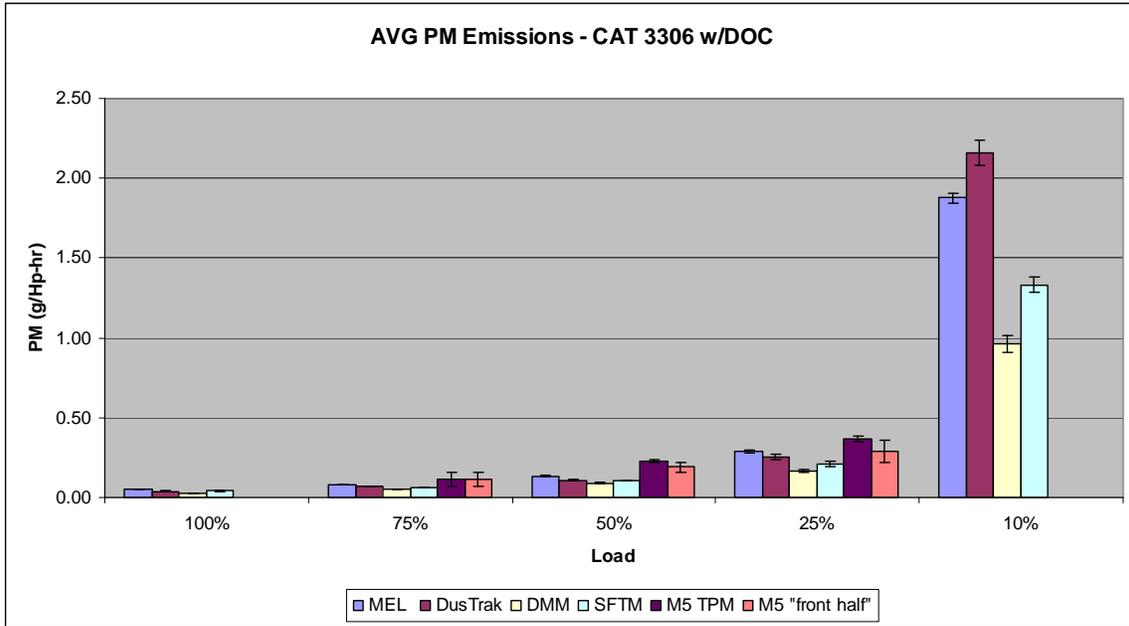
AVG PM (g/Hp-hr)		MEL	DusTrak	DMM	SFTM	M5 TPM	M5 "front half"
	100%	0.05	0.04	0.03	0.04		
	75%	0.08	0.07	0.05	0.06	0.12	0.12
LOAD	50%	0.14	0.11	0.09	0.10	0.23	0.19
	25%	0.29	0.25	0.17	0.21	0.37	0.29
	10%	1.88	2.16	0.96	1.33		
	43.5%				0.14		
STDEV							
	100%	0.001	0.002	0.001	0.005		
	75%	0.001	0.004	0.001	0.001	0.044	0.045
LOAD	50%	0.004	0.003	0.002	0.001	0.011	0.030
	25%	0.006	0.014	0.010	0.020	0.016	0.069
	10%	0.028	0.076	0.054	0.049		
	43.5%				0.008		

Comparison of Measured PM (MEL vs. SFTM) - CAT 3306 Baseline

$y = 0.7057x + 0.0063$
$R^2 = 0.9979$

Comparison of Measured PM (MEL vs. M5 TPM) - CAT 3306 Baseline

$y = 1.1471x + 0.0461$
$R^2 = 0.9654$

Comparison of Measured PM (MEL vs. M5 "front half") - CAT 3306 Baseline

$y = 0.7943x + 0.0661$
$R^2 = 0.9709$

Comparison of Measured PM (MEL vs. DusTrak) - CAT 3306 Baseline

$y = 1.1693x - 0.0419$
$R^2 = 0.9971$

Comparison of Measured PM (MEL vs. DMM) - CAT 3306 Baseline

$y = 0.5077x + 0.0127$
$R^2 = 0.9977$

Demonstration Test #3
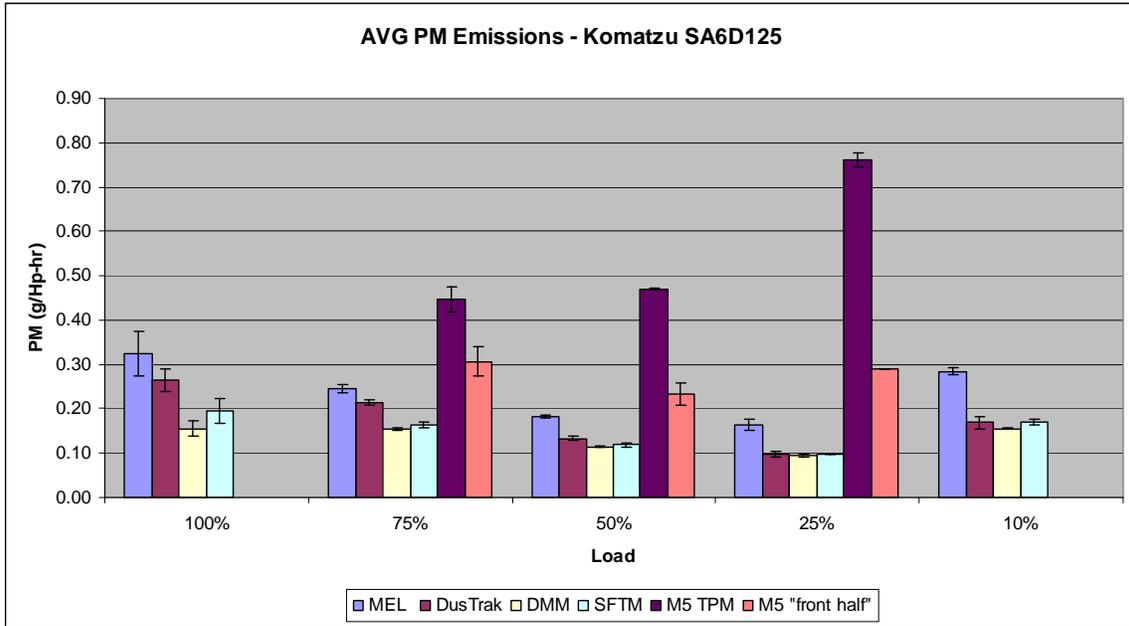
AVG PM (g/Hp-hr)		MEL	DusTrak	DMM	SFTM	M5 TPM	M5 "front half"
	100%	0.33	0.27	0.16	0.20		
	75%	0.25	0.21	0.15	0.16	0.45	0.31
LOAD	50%	0.18	0.13	0.11	0.12	0.47	0.23
	25%	0.16	0.10	0.09	0.10	0.76	0.29
	10%	0.28	0.17	0.16	0.17		
	43.5%				0.12		
STDEV							
	100%	0.050	0.024	0.017	0.029		
	75%	0.009	0.007	0.003	0.006	0.028	0.033
LOAD	50%	0.004	0.004	0.002	0.004	0.002	0.027
	25%	0.012	0.006	0.002	0.001	0.015	0.001
	10%	0.009	0.015	0.003	0.006		
	43.5%				0.000		

Comparison of Measured PM (MEL vs. SFTM) - Komatzu SA6D125

$y = 0.5761x + 0.0105$
$R^2 = 0.9581$

Comparison of Measured PM (MEL vs. M5 TPM) - Komatzu SA6D125

$y = -2.9235x + 1.1374$
$R^2 = 0.5242$

Comparison of Measured PM (MEL vs. M5 "front half") - Komatzu SA6D125

$y = 0.43x + 0.1911$
$R^2 = 0.2368$

Comparison of Measured PM (MEL vs. DusTrak) - Komatzu SA6D125

$y = 0.8348x - 0.0251$
$R^2 = 0.7795$

Comparison of Measured PM (MEL vs. DMM) - Komatzu SA6D125

$y = 0.372x + 0.0452$
$R^2 = 0.8082$

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