Final Report

Light Duty Gasoline PM:
Characterization of High Emitters and Valuation of Repairs for Emission Reduction
- Phase 3 -

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Abstract

PM emissions from light duty gasoline vehicles (LDGV) could contribute an increasingly larger portion on-road PM emissions, as aftertreatment systems for diesel engines become more commonplace. The most important fraction of the LDGV fleet for PM emissions is the worn or malfunctioning vehicles that can have PM emissions orders of magnitude higher than normal, well-maintained vehicles. While the Smog Check program in California implemented a check for visible smoke starting in January of 2008, it still does not include a direct measurement of PM.

For this project, a small fleet of high PM emitters was tested for emissions at California Air Resources Board's Haagen-Smit Laboratory (HSL). The goal of this work is to provide a better characterization of the fleet of visibly smoking and high PM emitting LDGVs, to evaluate the potential of lower cost, PM measurements for broader in-use testing, and to evaluate the potential emission reduction benefit and cost-effectiveness of professional repairs for high PM emitters. The PM instruments evaluated included an MPM4 from Maschinenbau Haldenwang (MAHA), an ETaPS from Dekati, a Dustrak and an EEPS from TSI. This project is a cooperative effort between the Air Resources Board (ARB), the University of California Riverside (UCR), the Foundation for California Community Colleges (FCCC), and the South Coast Air Quality Management District (SCAQMD) to determine the characteristics and emissions of high PM emitters, and potential emission reduction benefit and cost-effectiveness of professional repairs for high PM emitters.

The test vehicles had PM emission rates that from varied from 2.7 mg/mile to 91 mg/mile. Of the 3 vehicles repaired, one had reductions of approximately 90%, while the other two only had minor reductions. The DustTrak, the EEPS, and the MAHA were able to distinguish the three high emitting vehicles from the remaining low emitting vehicles. The DustTrak and the EEPS on average both read lower than the PM filter mass data. The MAHA required a calibration factor since the data was only available in concentration units. A linear regression between the DustTrak and EEPS and the PM mass showed a decent agreement with R^2 of 0.791 and 0.943, respectively, and negative intercepts of -1.384 and -2.797, respectively, due to the lower readings of these instruments compared to the filter mass at low levels. A linear regression between the MaHa and the PM mass showed a decent agreement with an R^2 of 0.852. It is also worth noting that only the MAHA is typically used for emissions measurements in the raw exhaust, which is an important consideration with respect to implementation into the smog check program. Four vehicles were repaired for a variety of issues that generally included both an engine related issue (distributor, valves, fuel injectors, spark plugs, etc.) coupled with the replacement of the catalyst or O_2 sensors. The repair costs were comparable to the cost of the vehicle itself, ranging from $1,297 to $2,393, and were effective for only one of the three vehicles characterized.

Executive Summary

With the implementation of new regulations requiring a 90+% reduction of PM emissions from heavy duty diesel engines in 2007, characterizing and reducing PM emissions from LDGV exhaust will become increasingly more important. The 2005 statewide California emission inventory predicts 40% of the on-road exhaust emissions from mobile sources are from LDGVs. Older gasoline vehicles and very worn or malfunctioning vehicles can emit PM ten to one hundred or more times as much as a new vehicle. There has been no requirement for PM measurement in the vehicle inspection and maintenance (I/M) program. A check for visible smoke was implemented in January of 2008. While it is a good first step to eliminate the grossest emitters, it has drawbacks: some high PM emitters do not emit visible smoke; visible smoke levels are not well correlated with PM emission levels; it could be difficult to eliminate subjectivity determining visible smoke. Therefore, it is desirable to develop instrumental methods that can identify high PM emitters directly.

The focus of the current program is to evaluate several low cost PM measurements for their potential to identify high PM emitters and to investigate the viability, cost-effectiveness, and potential benefits of professional repairs for emission reductions for the high PM emitters. This program builds on other collaborative efforts between the Air Resources Board (ARB), the Bureau of Automotive Repair (BAR), the South Coast Air Quality Management District (SCAQMD), and the Foundation for California Community Colleges (FCCC) to understand and deal with potentially high PM emitters operating in the South Coast Air Basin. The program involves laboratory testing of high PM emitting vehicles over a series of Federal Test Procedure (FTP) and Unified Cycle (UC) tests. Several PM instruments were utilized in the laboratory emissions tests, including the MPM4 from Maschinenbau Haldenwang (MAHA), ETaPS from Dekati, and DustTrak from TSI. These instruments were directly evaluated against the traditional gravimetric filter PM mass measurements. Some vehicles were tested both before and after repairs to provide a quantitative assessment of the repair effectiveness in terms of costs and associated emissions reductions. The results from this program can be used to improve emissions inventory estimates, provide some potential options to ARB to identify high PM emitters and to provide data on emission levels, repair effectiveness and repair costs for high emitters to guide development of PM control strategies. This project also supports the goals many policy-relevant programs, including SmogCheck and the Carl Moyer program.

The PM emission rates varied depend on the specific test vehicle. The PM emission rates for three vehicles were considerably higher than the emissions rates for the typical gasoline vehicle, with average FTP emission rates of 91, 66 and 37 mg/mi, respectively. These values are still below those typically found for high PM emitters in previous studies, which have averaged 100 to 600 mg/mile. The PM emissions for the other vehicles were between 2.7 and 5.5 mg/mi. This is consistent with PM levels for normal emitting LDGVs, which are generally 5 mg/mi or less, but is slightly higher than the PM emission rates for the latest technology vehicles, which can range around 1 mg/mi or less.

The regulated emissions rates varied significantly between the different test vehicles. All vehicles had NMHC FTP emissions rates higher than the Tier 1 standard, with values of

approximately 0.5 to 12.5 g/mi. The UC "average" NMHC emission levels were generally lower than those for the FTP, with the exception of the highest emitting vehicle. For CO emissions, 5 of the 8 vehicles exceeded the Tier 1 standard, with one vehicle having CO emissions 5 times the Tier 1 standard. The FTP NO_x emissions for most vehicles were higher than the Tier 1 standard (0.7 g/mi), with about half of the vehicles 2 to 3 times the standard. The UC emission levels for all of the test vehicles were higher than those for the FTP using the weighting factors applied here, except for one vehicle.

Four test vehicles were repaired for this test program. The required repairs were extensive, with costs ranging from $1,297 to $2,393, which were comparable to or exceeded the value of the vehicle. The repair generally coupled an engine related issue (distributor, valves, fuel injectors, spark plugs, etc.) with the replacement of the catalyst or O_2 sensors. The repair results show that only one of the 3 repairs characterized was successful in providing significant PM reductions. One of the other vehicles had very low PM emissions levels to begin with and the other vehicle did not show significant reductions in PM emissions following repairs.

The DustTrak, the EEPS, and the MAHA were able to distinguish the three high emitting vehicles from the remaining low emitting vehicles. The DustTrak and the EEPS on average both read lower than the PM filter mass data. The MAHA required a calibration factor since the data was only available in concentration units. A linear regression between the DustTrak and the PM mass showed a decent agreement with an R^2 of 0.791, and a negative intercept of -1.384 due to the lower DustTrak readings compared to the filter mass at low levels. A linear regression between the EEPS and the PM mass showed a decent agreement with an R^2 of 0.943, and a negative intercept of -2.797 due to the lower EEPS readings compared to the filter mass at low levels. A linear regression between the MAHA and the PM mass showed a decent agreement with an R^2 of 0.852. It is also worth noting that only the MAHA is typically used for emissions measurements in the raw exhaust, which is an important consideration with respect to implementation into the smog check program.

1.0 Introduction

Associations between ambient particulate matter (PM) and adverse health effects have been well documented in numerous studies [1, 2, 3, 4]. Diesel engines are currently estimated to be primary contributors to the PM emission inventory. The California Air Resources Board (CARB, or ARB) designated PM emitted from diesel engines as a Toxic Air Contaminant (TAC) in 1998. Diesel PM has since received special attention by air quality agencies charged with reducing the public's risk from this pollutant. The most recent EPA and ARB regulations aimed at reducing the publics' exposure to this TAC are applicable to 2007 and new engines, and require heavy duty diesel engines to be certified to a PM emission standard of 0.01 g/bhp-hr, a 90% reduction from the previous level. The 2007 regulations require phase in for new engines to be fully implemented by 2010. While the on-road diesel fleet will take many years to turn over, there should be steady progress toward the goal of a 90% reduction in diesel PM emissions.

Emissions of PM from LDGVs should also experience reductions with the introduction of the newest technologies as the fleet turns over. Under the LEV II regulations as revised November 15, 2001, both gasoline and diesel light duty vehicles must meet a PM emission standard of 0.01 g/mile. Even if all light duty vehicles emitted at the level of the LEV II standard, they could still become dominant producers of on-road PM emissions due to the enormous disparity in activity levels for light duty vehicles compared with diesel vehicles. The 2005 California emission inventory predicts 40% of the on-road mobile source emissions are from LDGVs [5]. The Department of Energy (DOE)'s Gasoline/Diesel PM Split Study in the South Coast Air Basin concluded: "Gasoline PM emissions are more important than diesel PM to ambient PM concentrations at certain times and locations. High-emitting gasoline vehicles are also very important contributors to ambient PM" [6]. Therefore characterizing and reducing PM emissions from LDGVs will become increasingly important.

In practice, most LDGVs do not emit as much as the LEV II standard. Most new LEV II and newer vehicles emit well below the standard. (Emission inventories start with a base rate of less than half the LEV II standard for LEV I and newer vehicles). However, older gasoline vehicles were not required to meet a PM standard and may emit substantially more than the new LEV II standard. Also, very worn or malfunctioning vehicles can emit tens to hundreds of times as much as a new vehicle. Data on the frequency of such high PM emitting vehicles and on the PM emissions rate distribution for such vehicles are limited.

PM emissions of smoking LDGVs have been investigated in several studies in the 1990's [7, 8, 9, 10] as well as a more recent DOE Gasoline/Diesel PM Split Study [11]. The average PM emission rates from these studies were found to be in the range of 100-600 mg/mi with the maximum higher than 2000 mg/mi. In contrast, several studies have shown that the PM emissions of normal emitting LDGVs are less than 5 mg/mi [12, 13, 14], with those of the latest technology vehicles at around 1 mg/mi or less [15]. While there is reason to suspect that a small percentage of high emitting light-duty gasoline vehicles (LDGVs) may contribute disproportionately to the PM emissions inventory, and perhaps even rival or exceed that of heavy-duty diesel vehicles the contribution from heavy–duty vehicles, it is still uncertain what the fraction of the LDGV fleet are high PM emitters and what the emitting regimes of gasoline vehicles are.

An important element of improving our understanding of the contribution of high PM emitting LDGVs to the emissions inventory is to develop cost effect methods to identify and quantity the emissions levels from a sufficiently large portion of the population. Studies that examine high PM emitters find a poor correlation between high PM emission rates and surrogates such as high HC, high CO, visible smoke, vehicle age, or vehicle mileage [16]. Therefore, it is necessary to develop methods that can identify high PM emitters directly. Remote Sensing Devices (RSD) and new Smog Check methods offer the potential to screen very large numbers of vehicles to identify high PM emitters. Remote sensing measurements of PM were made in several studies [17, 18, 19, 20]. An earlier Coordinating Research Council (CRC) study (Project No. E-56) indicated that more work was needed for the development of remote sensing measurements of PM [20]. RSD was also evaluated in the initial phase of this study. In that portion of this study, RSD PM measurements showed some correlation with laboratory PM emissions for a subset of high emitting vehicles, although there was a poorer correlation for a larger fleet of 4000 on-road vehicles. In more recent years, there has also been a greater emphasis on the development of lower cost PM instrumentation that could potentially be implemented into a Smog Check or other similar program. Examples of such instruments include the MPM4 from Maschinenbau Haldenwang (MAHA), the ETaPS from Dekati, and the Dustrak from TSI.

The focus of the current program is to evaluate several low cost PM measurements for their potential to identify high PM emitters and to investigate the viability, cost-effectiveness, and potential benefits of professional repairs for emission reductions for the high PM emitters. This program builds on other collaborative efforts between the Air Resources Board (ARB), the Bureau of Automotive Repair (BAR), the South Coast Air Quality Management District (SCAQMD), and the Foundation for California Community Colleges (FCCC) to understand and deal with potentially high PM emitters operating in the South Coast. The program involves laboratory testing of a number of high PM emitters over a series of Federal Test Procedure (FTP) and Unified Cycle (UC) tests. A number of PM instrument were utilized in the laboratory emissions tests, including the EEPS, MPM4, ETaPS, and Dusttrak. These instruments were directly evaluated against the traditional gravimetric filter PM mass measurements from the laboratory measurements. Vehicles were tested both before and after repairs to provide a quantitative assessment of the repair effectiveness in terms of costs and associated emissions reductions. The results from this program can be used to improve emissions inventory estimates, provide some potential options to ARB to identify high PM emitters and to provide data on emission levels, repair effectiveness and repair costs for high emitters to guide development of PM control strategies. This project also supports the goals many policy-relevant programs, including SmogCheck and the Carl Moyer program.

2.0 Experimental Procedures

The focus of this program is emissions testing before and after repair on a fleet of vehicles identified as high emitters. Testing consists of at least two standard FTP tests and two standard Unified Cycle (UC) tests before and after repair. The exhaust emission measurements include criteria gases, filter based PM, and real-time PM measurements using several instruments from commercial vendors. The following section describes the experimental procedures used, the test fleet, and other applicable details relating to the testing.

2.1 Test Vehicles and Test Fuel

A total of 10 vehicles were recruited for this program. The fleet included vehicles with PM emission levels ranging from baseline to heavy smoking. Prior to entering the program, all vehicles were inspected using a standard checklist to ensure that they were in reasonable mechanical and operational condition. The specific details of the vehicles used in this project are listed in Table 1.

Vehicles were recruited from two sources. The first three vehicles were recruited from the South Coast Air Quality Management District (SCAQMD) CUT-SMOG database. The CUT-SMOG database is a record or callers who voluntarily call in to identify vehicles that emit visible levels of smoke or high emissions. The remaining vehicles, with the exception of vehicle 6, were recruited based on RSD readings obtained through the SCAQMD “High Emitter Repair or Scrap Program (H.E.R.O.S.)”. The vehicles identified through the H.E.R.O.S. program were identified based on having readings at the high emitter level on at least two separate occasions. Only the top 1,000 vehicle identified as high emitters for PM by the RSD were used as the basis for the recruitment in this program. Vehicle 6 was recruited through another on-going CARB study. Note vehicles 6 and 7 were not tested as they were found to fail during a dynamometer testing cycle. The tests were conducted using Phase III summer gasoline containing ethanol meeting Title 13, California Code of Regulations, Section 2262 specifications.

Table 1. Description of Test Vehicles

#	MY	OEM	Model	Type	Disp.	Mileage
0	1990	GM	Sierra 2500 SL	MDV	5.0 L	53,694
1	1988	Mercedes Benz	300 TE S/W	PC	3.0 L	231,621
2	1987	Mercedes Benz	300 TE	PC	4.2 L	175,856
3	1998	Chrysler	Sebring JXI	PC	2.5 L	177,926
4	1999	Ford	Expedition		***x***	176,424
5	1995	Chevrolet	Astro	PC	4.3 L	174,499
6	1990	Mercedes Benz	190E	PC	2.6L	
7	1999	Hyundai	Accent GL	PC	1.5L	
8	1993	Volvo	240	PC	2.3 L	136,768
9	1991	Honda	Civic DX	PC	***x***	195,536

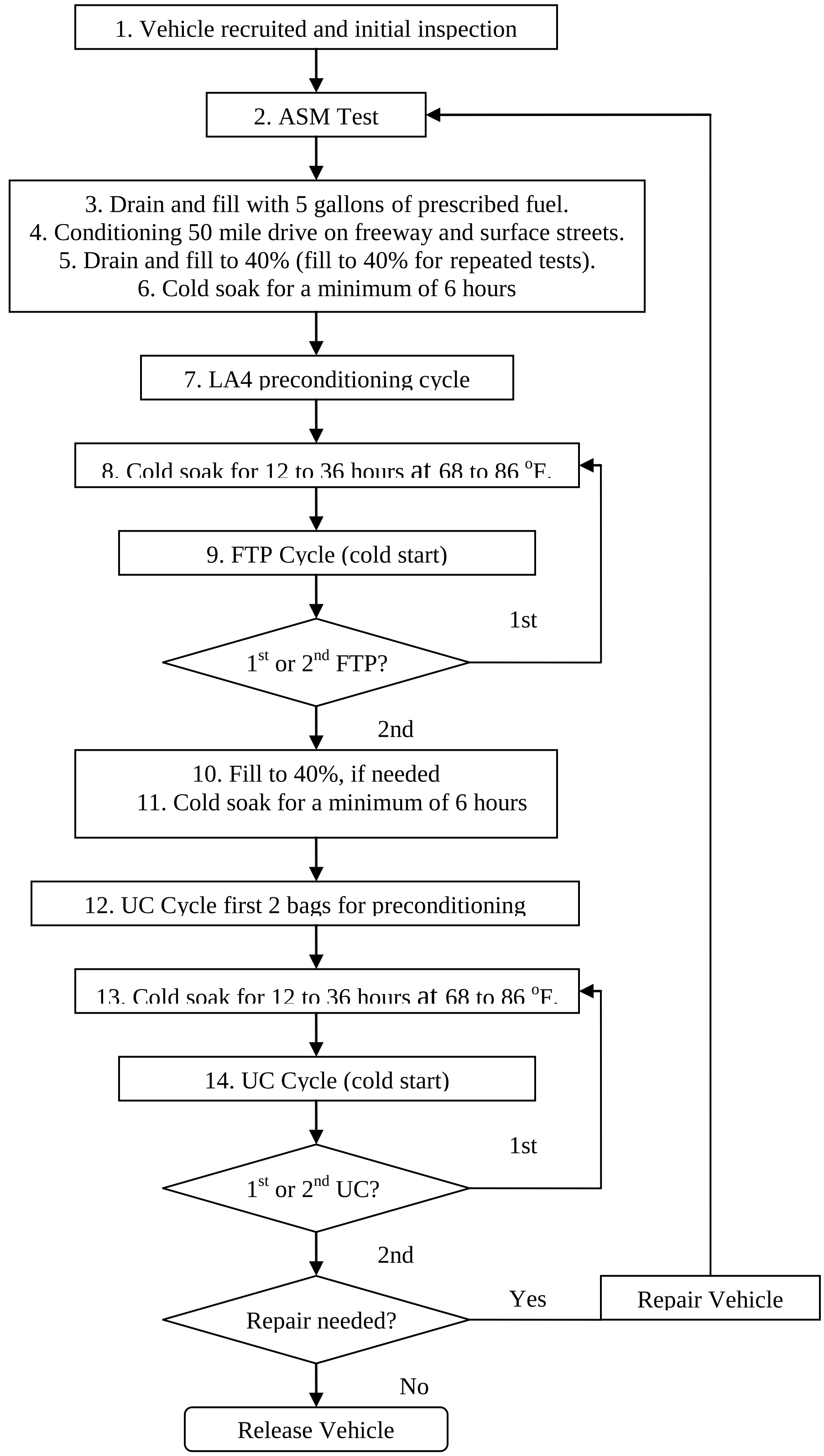
PC = Passenger Car; LDT = Light-Duty Truck; MDV = Medium-Duty Truck; NA = Not Available.

2.2 General Procedures

The procedures of this program are provided in the flowchart in Figure 1 and are briefly summarized below.

- After inspection, the vehicle was given an Acceleration Simulation Mode (ASM) test. The test fuel is then changed and the vehicle is preconditioned.
- The vehicle was then tested over a series of 2 FTPs and 2 Unified Cycles (UCs). The exhaust emission measurements include criteria gases, filter-based PM, and measurements with several real-time PM measurements.
- The vehicle is then taken for repair if eligible.
- The vehicle was then retested over 2 FTPs and 2 Unified Cycles (UCs).

Figure 1. Flow Chart of the Emissions Testing and Repair



2.3 Test Cycles and Preconditioning

The vehicles were initially tested over an ASM test at the CARB facility. The ASM test consists of two modes. One is a steady state test at 15 mph (ASM 5015) followed by a steady state test at 25 mph (ASM 2525).

The Federal Test Procedure (FTP) is the main test used for emission certification of light duty vehicles in the U.S. The FTP consists of three phases representing a cold start phase, transient phase, and a hot start phase. The third phase starts after the engine is stopped for 10 minutes. The FTP is approximately 11 miles in length, with an average speed of 21.2 miles per hour, over a duration of 1874 seconds.

UC is a more aggressive cycle and more adequately covers typical driving patterns than the Federal Test Procedure (FTP). It is similar to the FTP in that is consists of three phase representing cold start, transient, and hot start driving. It is approximately 10 miles in length, with an average speed of 24.8 miles per hour, a top speed of 67 miles per hour, 16.4 percent idle and 1.52 stops per mile. Vehicles tested over UC were found to emit significantly higher compared to vehicles tested over the FTP [21].

After inspection and acceptance and prior to the FTP/UC testing, the vehicle was preconditioned for testing. This preconditioning phase followed the standard procedure currently used at HSL. This included draining the fuel tank, filling the tank with 5 gallons of the prescribed test fuel (to be adjusted for heavier vehicles), and driven over a 50 mile route of freeway and urban driving during a consistent timeframe (i.e. 10 am to 3 pm). After completing the conditioning route the vehicle fuel tank was drained again and filled with the prescribed test fuel to 40% nominal test capacity. The vehicle then received a minimum of 6-hour soak. The vehicle was then prepared by driving an LA4 Cycle, at the horsepower and inertial weight recommended by the manufacturer. The vehicle was soaked for at least 12 hours and no more than 36 hours after this preparation before testing. For the UC cycle, the preconditioning consisted of the first two bags of the UC cycle.

2.4 Emission Measurements

2.4.1 Overview

The emissions testing was performed at CARB's Haagen-Smit Laboratory (HSL) in El Monte, CA. The testing was performed in test cell #2, which is equipped with a Burke E. Porter 48-inch single-roll electric dynamometer and Pierburg constant volume sampling (CVS)/dilution tunnel system. A CVS flow rate of 350 standard cubic feet per minute (SCFM) was used for the testing.

The exhaust emission measurements included total hydrocarbons (THC), non-methane hydrocarbons (NMHC), methane (CH_4), Carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x) and PM following the Federal Test Procedure in Title 40 CFR Part 86. For the gas measurements modal data as well as bag data was obtained for some of the tests. In addition, coupled in the raw exhaust prior to the CVS an ETaPS particulate sensor and a MAHA particle measuring system will be used to measure particulate matter emission rates. Connected to the diluted flow a DustTrak aerosol monitor will be included in the testing. The addition of the extra instruments draws a small amount of flow that is nominal in comparison with the primary tunnel flow. A schematic of the overall test set up is provided in Figure 2.

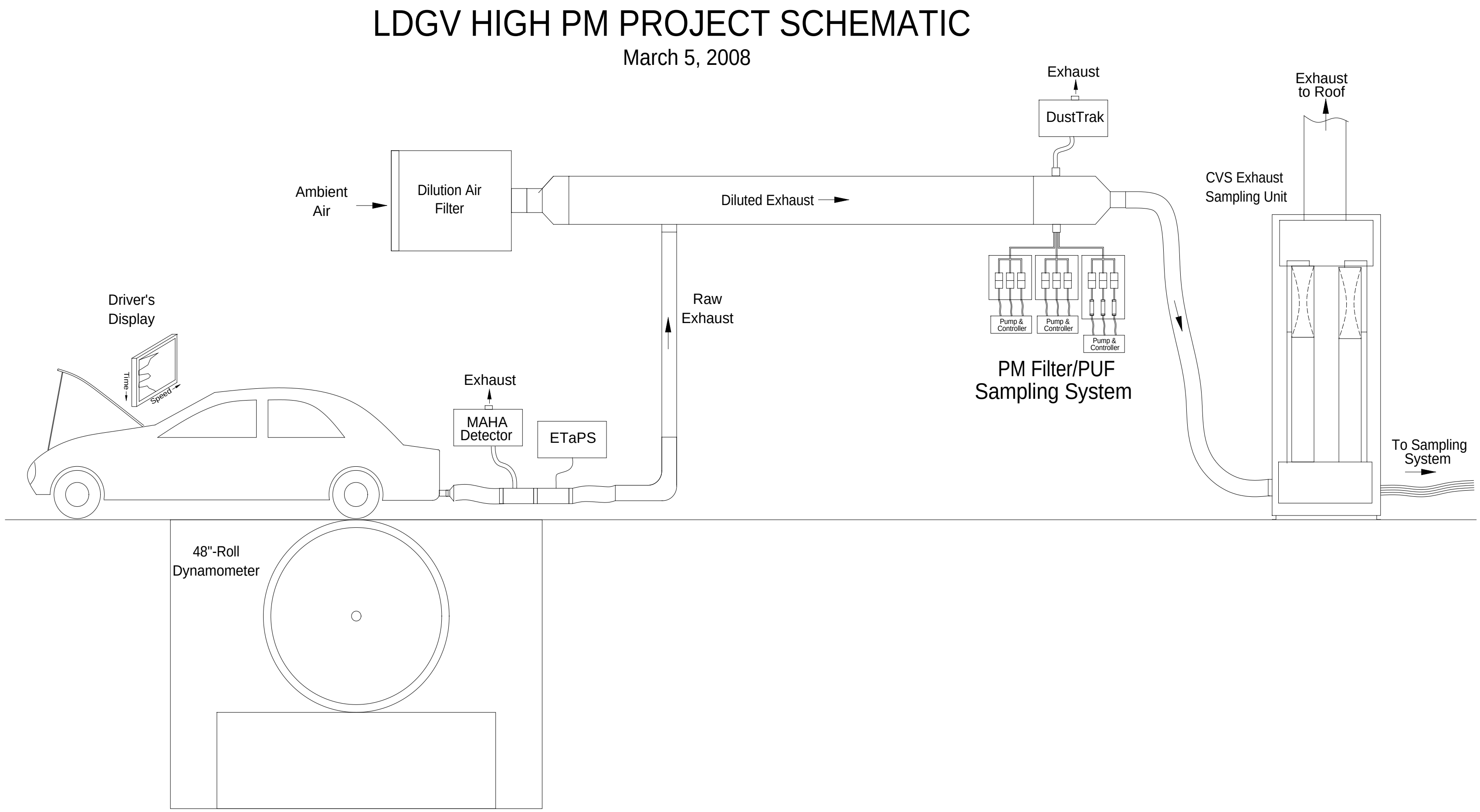


Figure 2. Schematic of Laboratory Set-Up

2.4.2 PM Measurements

2.4.2.1 Gravimetric PM Mass

Probe 1 was fitted with 47 mm, 2.0 µm pore size polytetrafluoroethylene (PTFE) membrane filters to obtain total mass particulate emission rates for each phase of the FTP. Each filter assembly was fitted with a primary and a backup filter and the mass was determined gravimetrically. The flow rates for both the PTFE and quartz filter samplings were set to 30 liter per minute (LPM) for most tests.

2.4.2.2 Elemental and Organic Carbon

Probe 2 was fitted with three 47 mm quartz fiber filters for each phase of the FTP or UC cycles, respectively. Note these filters were not analyzed for this report.

2.4.2.3 Raw Exhaust Real-Time PM Measurements

2.4.2.3.1 ETAPS

The ETAPS real-time PM instrument is based on particle charging and electrical detection of charged exhaust particles. A high voltage power supply creates a corona discharges that charges the particles. An electrometer then measures the amount of electrical charge escaping the chamber with the particles. A schematic of the ETAPS is provided below in Figure 3.

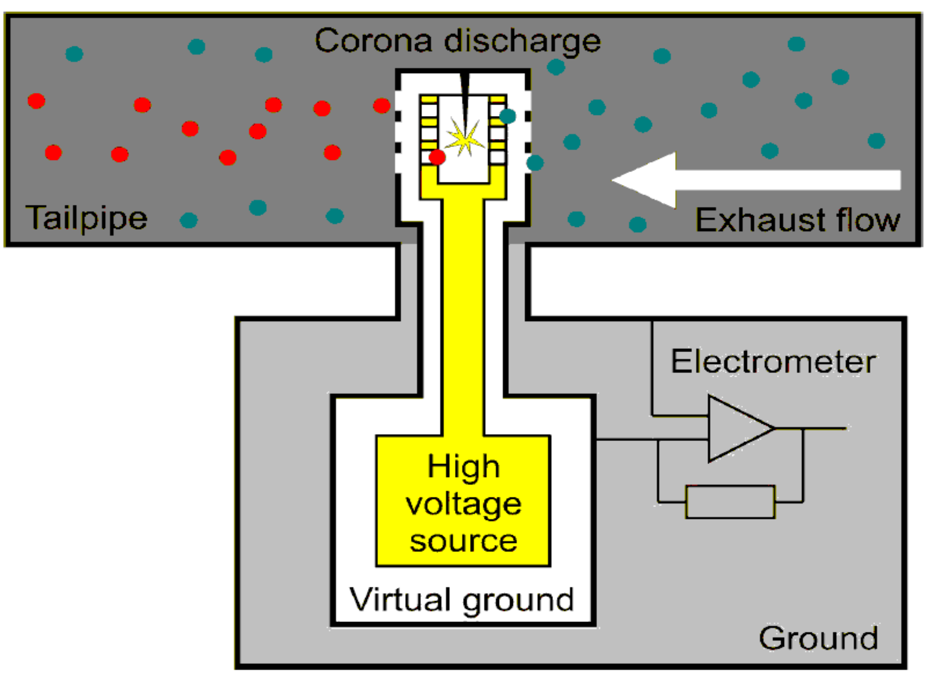


Figure 3. Schematic of ETAPS

2.4.2.3.2 MAHA - MPM 4 (raw)

The MAHA-MPM4 instrument is a real-time particulate instrument manufactured by the German company MAHA Maschinenbau Haldenwang GmbH & Co. KG. The unit is portable, with a size similar to a shoe box, and utilizes laser light scattering photometry for the particulate measurement principal. A schematic of the operation principal is provided in Figure 4.

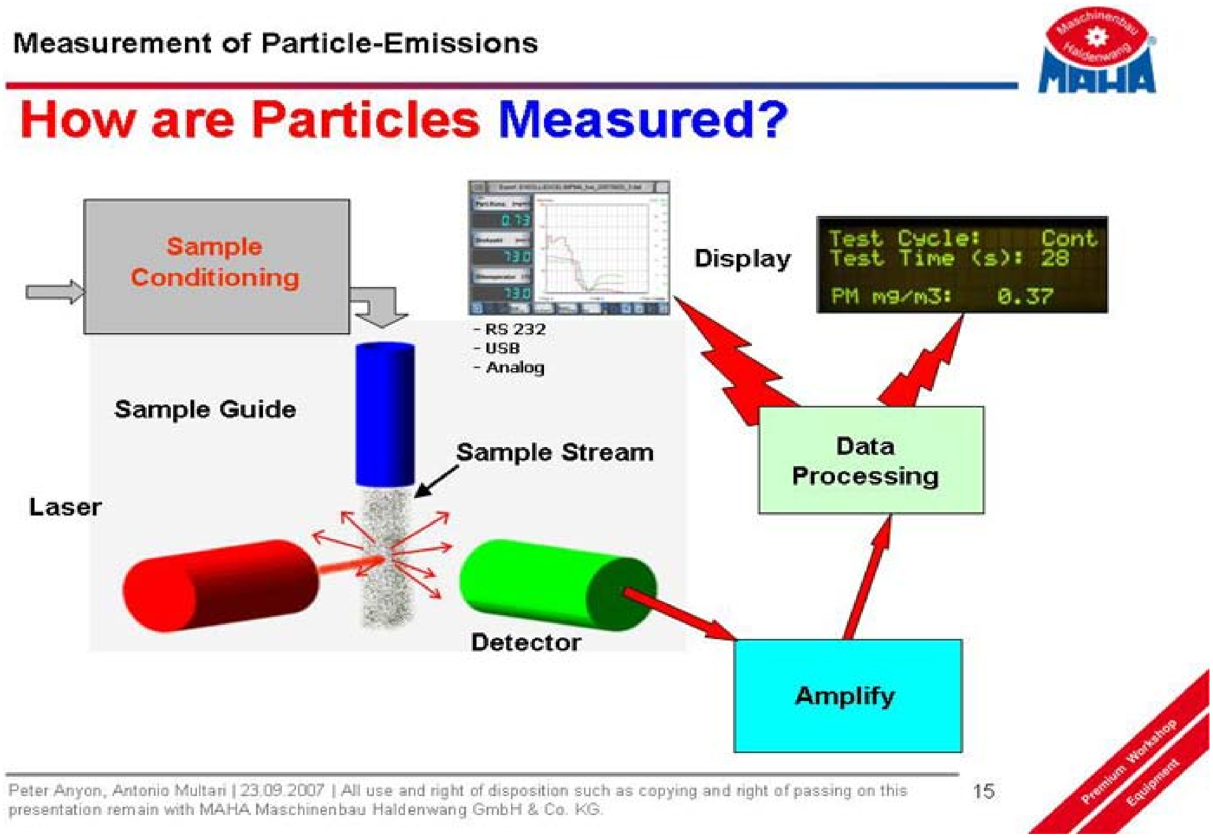


Figure 4. Schematic of MAHA

2.4.2.4 Dilute Real-Time PM Measurements

2.4.2.4.1 DustTrak™ Aerosol Monitor

A TSI DustTrak™ 8520 aerosol monitor for real-time particulate mass measurements was utilized to collect dilute PM emissions in real-time at approximately the same location in the dilution tunnel that the PM mass samples are collected. The DustTrak™ uses a laser-photometer that measures and records PM concentrations. This instrument is typically used for ambient dust measurements and is typically calibrated based on Arizona road dust. It is calibrated for National Institute of Standards and Technology (NIST) standard Arizona Road Dust. The DustTrak™ is pictured in Figure 5.

Figure 5. Picture of DustTrak™

2.4.2.4.2 TSI Model 3090 Engine Exhaust Particle Sizer (EEPS)

The EEPS utilizes differential electrical mobility to provide size distributions in real-time. The principals of the EEPS have been described in ref 22. The EEPS measures size distributions in the range from 5.6 to 560 nm. A cyclone removes large particles at inlet. A diffusion charger then creates ions which charge the particles. The particles mix with the ions and produce a predictable charge level versus particle size. Particles are surrounded by sheath flow and flow down between a central rod and outer cylinder. A high voltage on the central rod creates an electric field which repels the particles outward from a central column. Charged aerosol particles are detected on a column of electrometers. A schematic of the EEPS is provided in Figure 6.

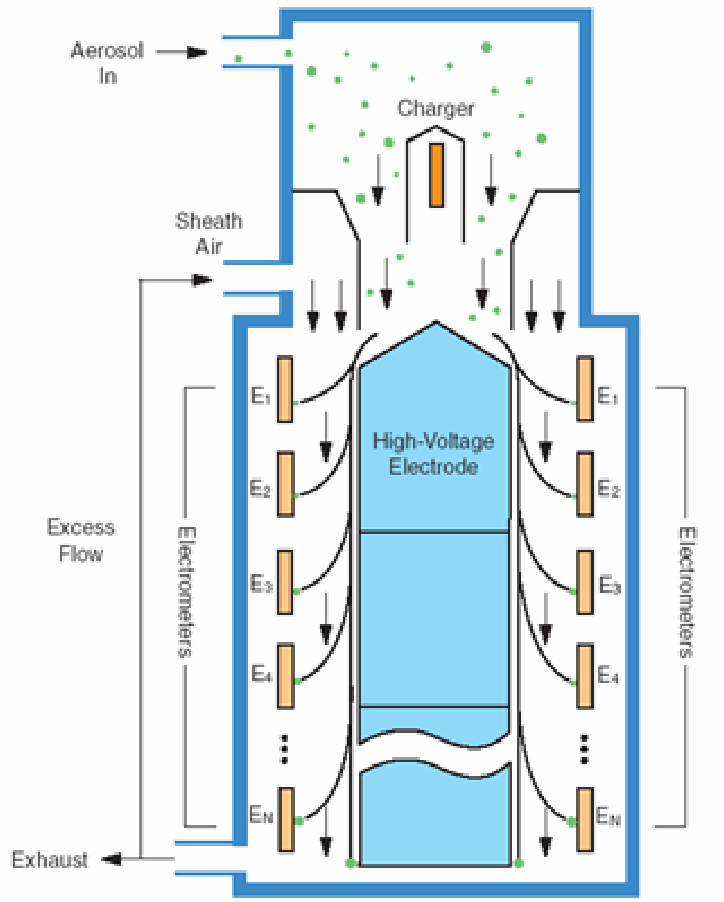


Figure 6. Schematic of EEPS

3.0 Results

Each vehicle was tested at least twice over the FTP and UC cycle before repair as indicated on the Table 2 below, with only three being tested with repair. At this time vehicle 5 is being tested with repair but the tests are not yet completed and subsequently the results are not yet ready to be included in this report. Note of the seven (7) vehicles tested and used in the analysis for this report a total of 64 tests were undertaken, 2 being invalid. Table 3 on the next page identifies each of the individual tests conducted and lists the corresponding test identification number and the actual date tested. The two highlighted tests were deemed invalid and were not used in the analysis, note tests on vehicle 5 with repair are being conducted at the time of writing this report.

Table 2. Test Summary

Veh.#	Tests	Invalid tests	Test Type	Reason (B-Baseline) W-Repair)
1	4		FTP	B
1	2		FTP	W
1	4		UC	B
1	2		UC	W
2	2		FTP	B
2	3		UC	B
3	2		FTP	B
3	6		FTP	W
3	3		UC	B
3	3		UC	W
4	4	1	FTP	B
4	3		UC	B
5	7	1	FTP	B
5	4		UC	B
5	TBD		FTP	W
5	TBD		UC	W
8	2		FTP	B
8	2		FTP	W
8	2		UC	B
8	4		UC	W
9	2		FTP	B
9	3		UC	B
Total Tests	64	2		

Table 3. Test Identification

Date	Test ID.	Veh.#	Test Type	Reason (B-Baseline, W-Repair)	Test Number
7/30/2008	1022220	1	MEC1	B	1
7/31/2008	1022232	1	MEC1	B	2
8/14/2008	1022354	1	MEC1	B	3
8/27/2008	1022453	1	MEC1	B	4
11/13/2008	1023135	1	MEC1	W	5
12/12/2008	1023363	1	MEC1	W	6
8/2/2008	1022246	1	MUC	B	1
8/9/2008	1022279	1	MUC	B	2
8/13/2008	1022314	1	MUC	B	3
8/28/2008	1022454	1	MUC	B	4
11/14/2008	1023134	1	MUC	W	5
11/26/2008	1023238	1	MUC	W	6
8/6/2008	1022270	2	MEC1	B	1
8/7/2008	1022278	2	MEC1	B	2
8/8/2008	1022280	2	MUC	B	1
8/12/2008	1022315	2	MUC	B	2
9/10/2008	1022558	2	MUC	B	3
10/30/2008	1022878	3	MEC1	B	1
11/3/2008	1022955	3	MEC1	B	2
2/17/2009	1023898	3	MEC1	W	3
2/25/2009	1023978	3	MEC1	W	4
2/26/2009	1024016	3	MEC1	W	5
4/2/2009	1024287	3	MEC1	W	6
4/21/2009	1024473	3	MEC1	W	7
4/29/2009	1024514	3	MEC1	W	8
10/31/2008	1022879	3	MUC	B	1
11/5/2008	1022956	3	MUC	B	2
11/6/2008	1023074	3	MUC	B	3
2/26/2009	1024017	3	MUC	W	4
3/25/2009	1024220	3	MUC	W	5
3/26/2009	1024239	3	MUC	W	6
2/20/2009	1023922	4	MEC1	B	1
5/12/2009	1024597	4	MEC1	B	2
5/13/2009	1024603	4	MEC1	B	3
5/14/2009	1024616	4	MEC1	B	4
5/15/2009	1024617	4	MUC	B	1
5/20/2009	1024634	4	MUC	B	2
6/2/2009	1024691	4	MUC	B	3
9/3/2009	1025191	5	MEC1	B	1
9/4/2009	1025209	5	MEC1	B	2
9/9/2009	1025222	5	MEC1	B	3
9/10/2009	1025227	5	MEC1	B	4
9/29/2009	1025291	5	MEC1	B	5
9/30/2009	1025350	5	MEC1	B	6
10/1/2009	1025353	5	MEC1	B	7
10/2/2009	1025354	5	MUC	B	1
10/20/2009	1025455	5	MUC	B	2
10/29/2009	1025597	5	MUC	B	3
10/30/2009	1025624	5	MUC	B	4
9/30/2009	1025325	8	MEC1	B	1
10/1/2009	1025364	8	MEC1	B	2
11/24/2009	1025897	8	MEC1	W	3
11/25/2009	1025928	8	MEC1	W	4
10/2/2009	1025374	8	MUC	B	1
10/8/2009	1025395	8	MUC	B	2
12/1/2009	1025938	8	MUC	W	3
12/3/2009	1025976	8	MUC	W	4
12/4/2009	1025991	8	MUC	W	5
12/8/2009	1026012	8	MUC	W	6
10/27/2009	1025556	9	MEC1	B	1
10/28/2009	1025598	9	MEC1	B	2
10/29/2009	1025602	9	MUC	B	1
11/4/2009	1025676	9	MUC	B	2
12/9/2009	1026030	9	MUC	B	3

The Figures presented in sections 3.1 and 3.2 show the FTP and UC weighted average emissions over all tests for a particular vehicle. The errors bars represent one standard deviation of the test results.

3.1 Gaseous Emissions

3.1.1 NMHC Emissions

The following two plots show, respectively, the weighted average NMHC emissions by vehicle (Figure 7) and the NMHC emissions reductions after repair (Figure 8). The NMHC emission rates varied depending on the specific test vehicle. All vehicles had FTP emissions rates higher than the Tier 1 standard, with values of approximately 0.5 to 12.5 g/mi. The FTP emission rate for vehicle #1 showed considerable variability, but was approximately 20 times the standard with an average of 6.7 g/mi. Vehicle 4 had the highest emissions of 12.5 g/mi for the FTP. These are consistent with levels that could be expected for a high emitter. The UC "average" emission levels were generally lower than those for the FTP. The UC emissions for the higher emitting vehicles 1 and 4 showed considerable variability and were comparable to the FTP results within the test variability for vehicle 1 but were a factor of 2.5 times higher for vehicle 4.

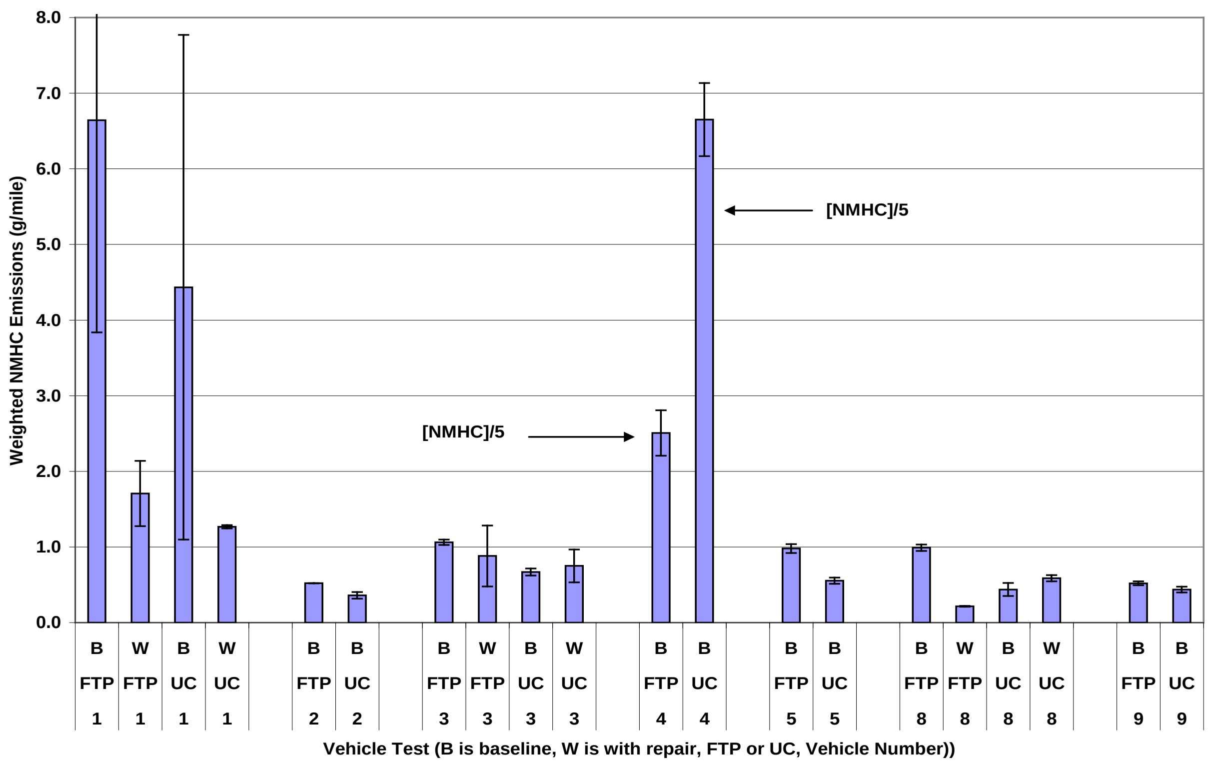


Figure 7. NMHC Emission Rates

Figure 8 shows the emissions reduction in NMHC emissions after repair. The results show a significant reduction in the FTP NMHC emissions for all 3 vehicles, with a range of 17% for vehicle 3 to 78% for vehicle 8. Conversely, only vehicle 1 shows reduction in NMHC for the UC cycle after repair. Since vehicle 1 was the highest emitter of the three vehicles repaired and vehicles 3 and 5 were less than double the Tier 1 value, this may be a result biased towards high emitters.

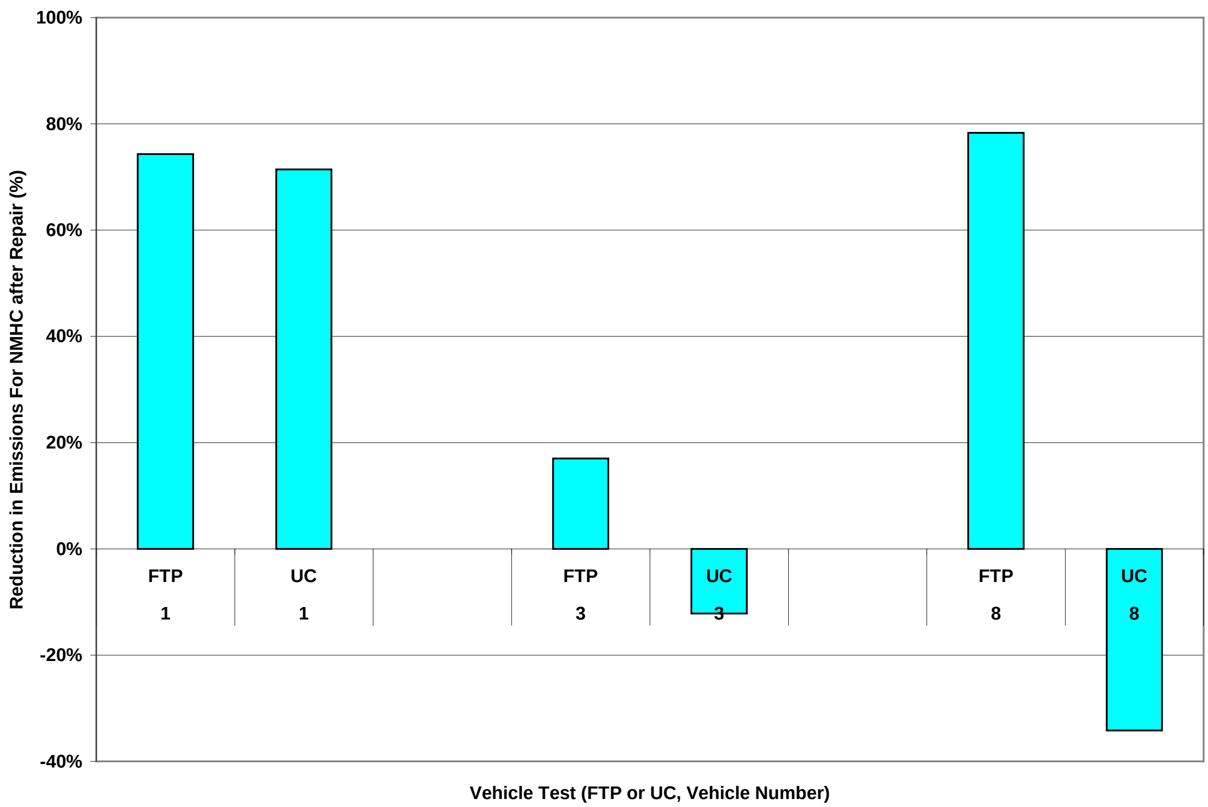


Figure 8. NMHC Emission Rates Reduction After Repair

3.1.2 CH_4 Emissions

The following two plots show, respectively, the weighted average CH_4 emissions by vehicle (Figure 9) and the CH_4 emissions reductions after repair (Figure 10). CH_4 emissions showed considerable variability over the vehicles tested with values as low as .05 g/mile for vehicle 2 and greater than 0.20 g/mile for vehicles 1 and 4. The average CH_4 emissions, for all the vehicles tested, was 0.12 g/mile. CH_4 emissions appeared to vary between all the vehicles tested but were comparable between the FTP and UC cycles for each individual vehicle.

There appeared to be only statistically significant reductions in CH_4 emissions with repair for vehicle 1 on both cycles and only on the FTP cycle for vehicle 8.

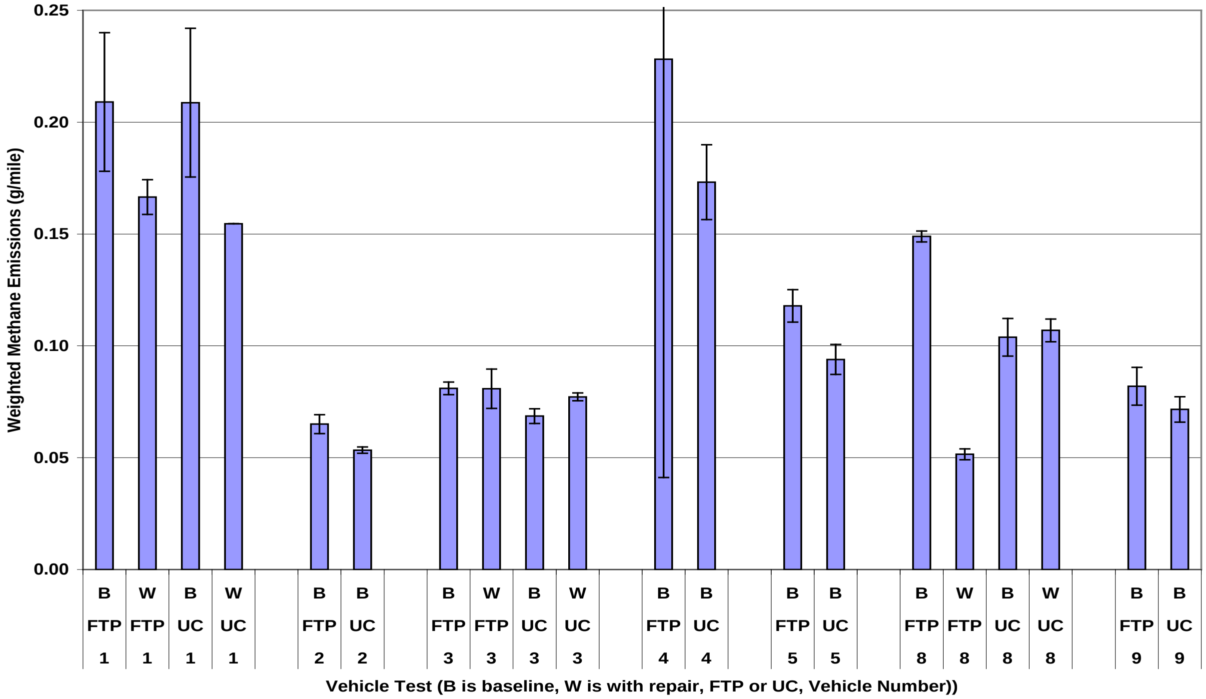


Figure 9. CH_4 Emission Rates.

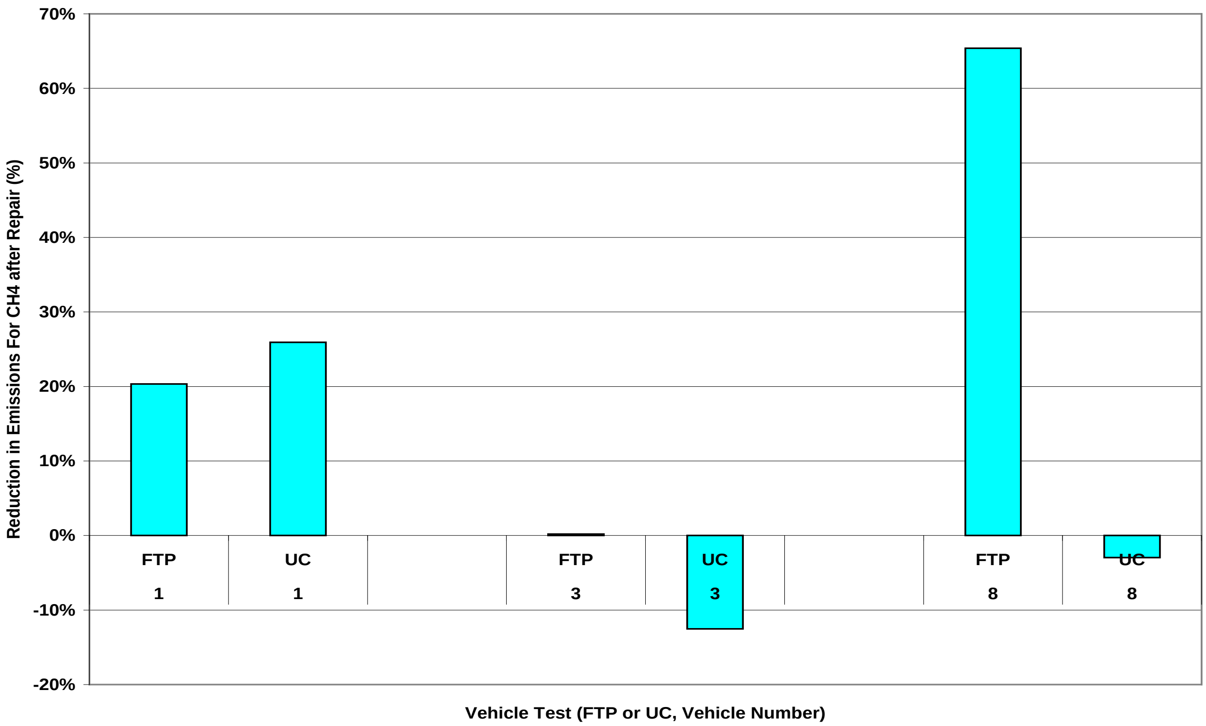


Figure 10. CH_4 Emission Rates Reduction After Repair.

3.1.3 CO Emissions

The following two plots show, respectively, the weighted average CO emissions by vehicle (Figure 11) and the CO emissions reductions after repair (Figure 12). The Tier 1 standard for CO is 7.0 g/mile. Figure 11 shows only vehicles 1, 4, 5, 8 and 9 exceeded the Tier 1 standard. Vehicles 1 and 8 were approximately twice the Tier 1 standard and vehicle 4 was over 5 times the standard. Vehicles 2 and 3 had FTP emissions rates comparable or below the Tier 1 standard, with emission rates ranging from 2.5 to 6.8 g/mi.

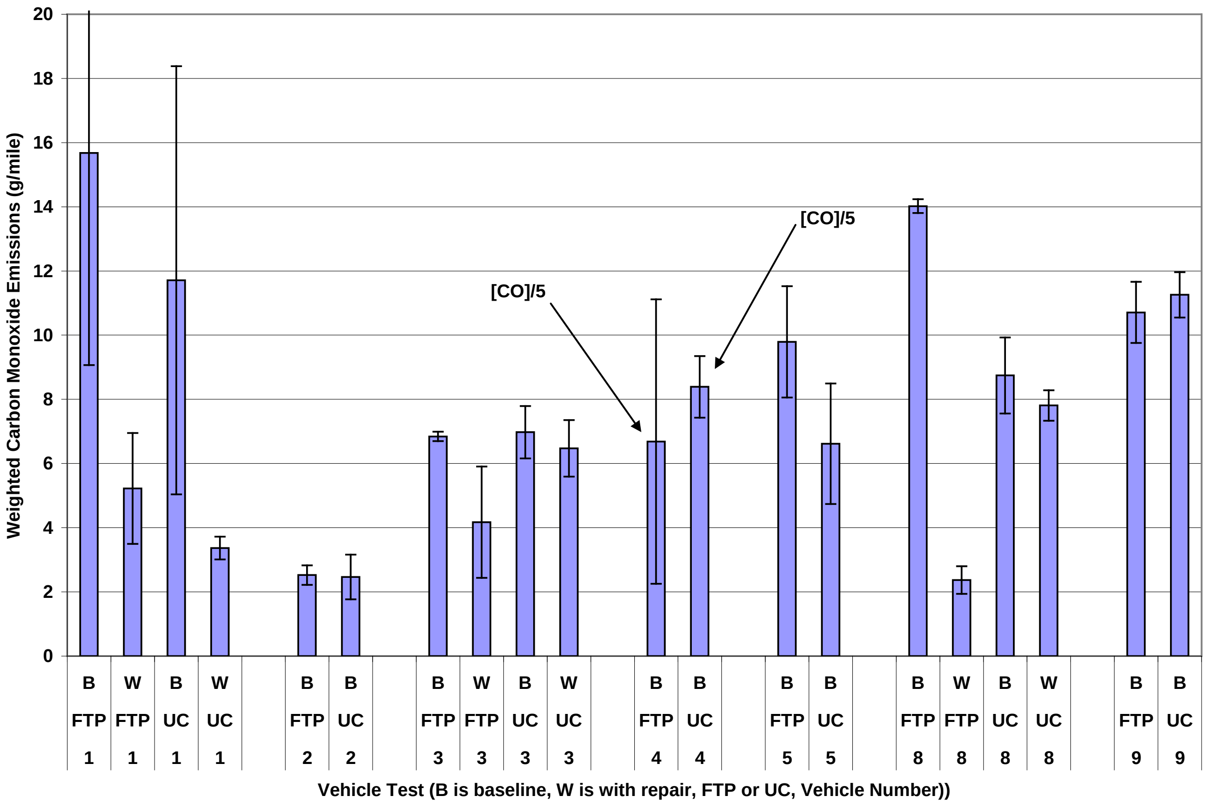


Figure 11. CO Emission Rates.

The three vehicles that were repaired, 1,3 and 8, showed considerable reductions in CO emissions for the FTP with reductions of 66%, 39% and 83%, respectively. For the UC cycle, only vehicle 1 showed statistically significant reductions with repair.

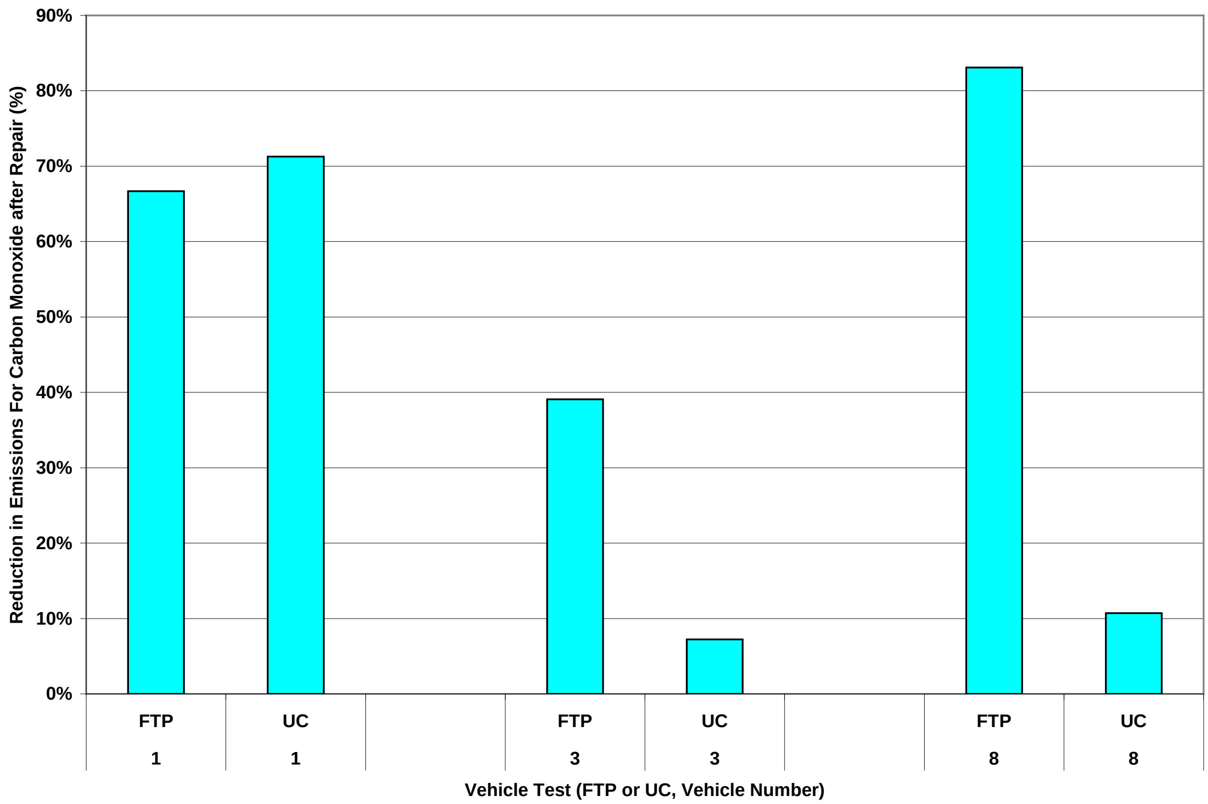


Figure 12. CO Emission Rates Reduction After Repair

3.1.4 NO_x Emissions

The following two plots show, respectively, the weighted average NO_x emissions by vehicle (Figure 13) and the NO_x emissions reductions after repair (Figure 14).

The FTP NO_x emissions for most vehicles were higher than the Tier 1 standard (0.7 g/mi). The FTP emission rates for vehicles 1, 4 and 5 were about three times the Tier 1 certification standard on average, and the FTP emission rate for vehicle #3 was about twice the Tier 1 certification. Only vehicles 2 and 9 had FTP emissions rates lower than the Tier 1 standard. The UC emission levels for all of the test vehicles were higher than those for the FTP using the weighting factors applied here, except for vehicle 4.

The range in NO_x emissions before repair for the UC cycle was a low of 0.89 g/mile for vehicle 2 to a high of 3.9 g/mile for NO_x measured on vehicle 1.

Significant reductions in the NO_x emissions were evident in all vehicles repaired, for all tests. For vehicles 1, 3 and 8, reductions ranged from a low of 38% to a high of 70% for NO_x.

Although the repairs were effective for all three vehicles, but vehicle 1 was still a factor of about two times the Tier 1 level even with repair.

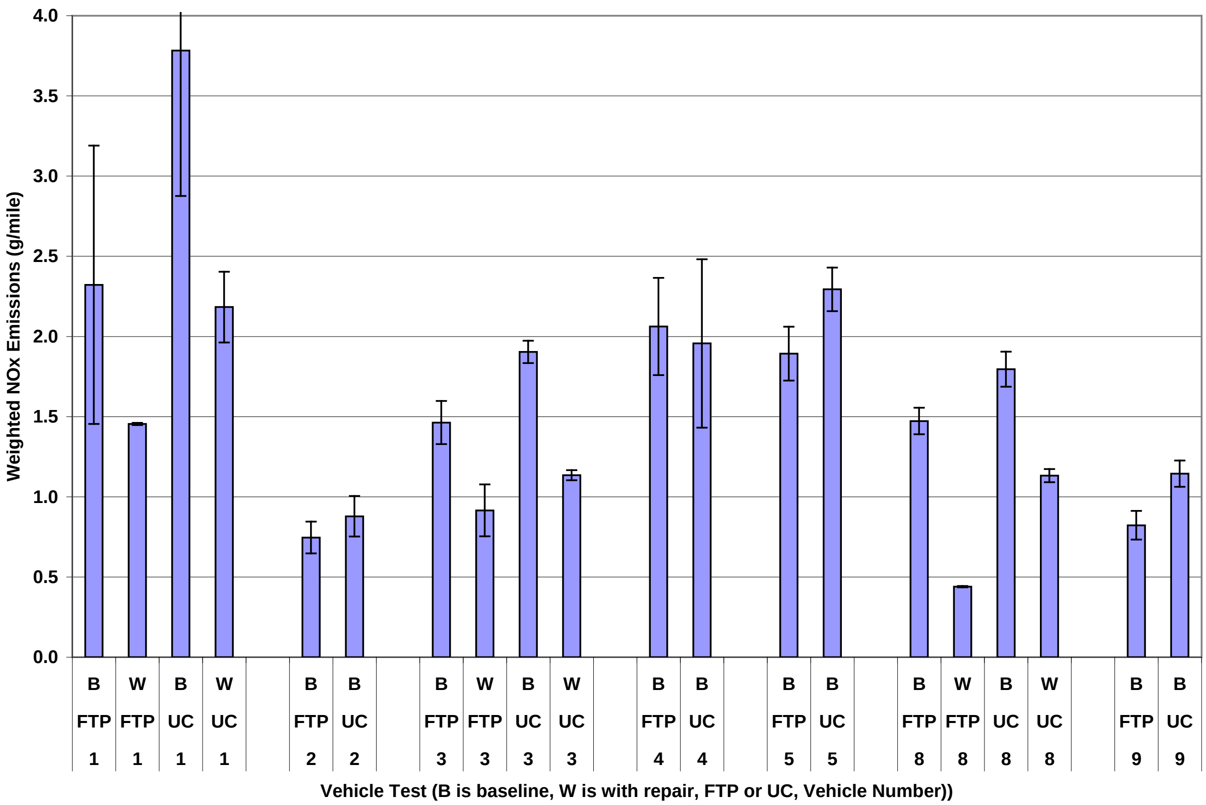


Figure 13. NO_x Emission Rates

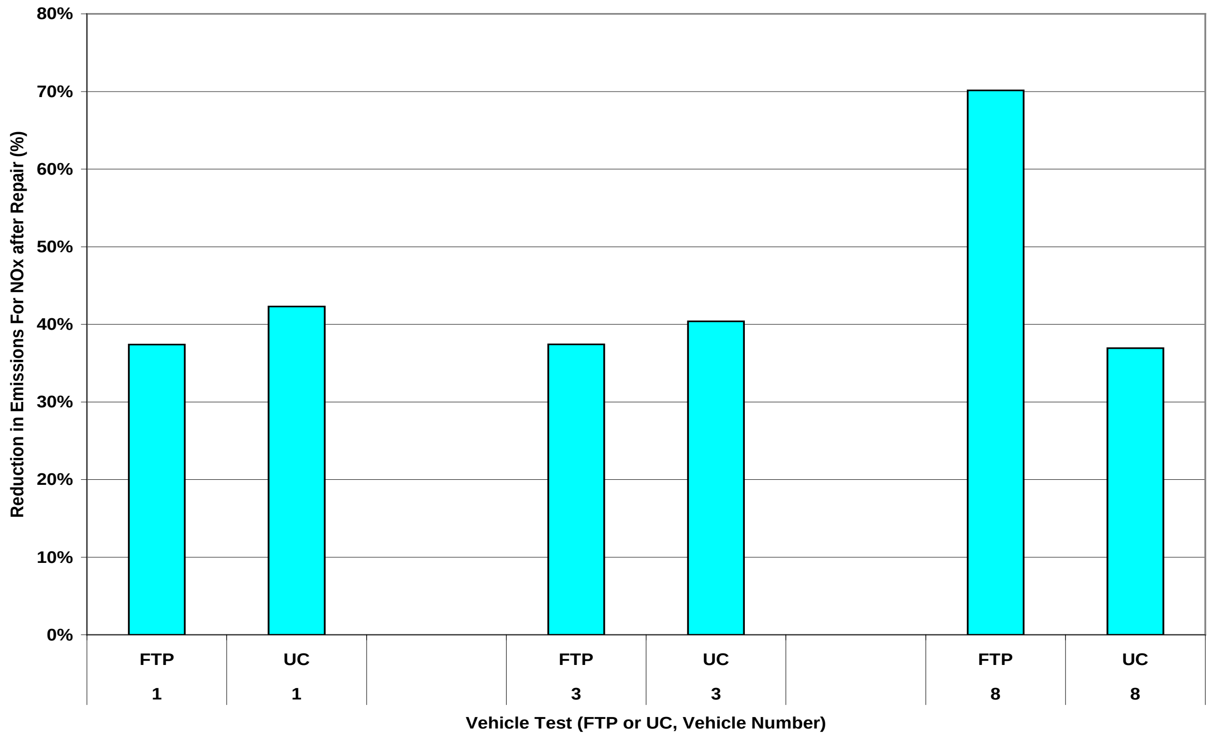


Figure 14. NO_x Emission Rates Reduction After Repair

3.1.5 CO_2 Emissions

The following two plots show, respectively, the weighted average CO_2 emissions by vehicle (Figure 15) and the CO_2 emissions reductions after repair (Figure 16). CO_2 emissions varied between vehicles, as is expected for vehicles with a range of different fuel economies. The values ranged from as low as 258 g/mile for vehicle 9 to 572 g/mile for vehicle 4. The average CO_2 emissions, for all the vehicles tested, was 427 g/mile. CO_2 emissions appeared to be consistent between the two cycles for each vehicle. There appeared to be no significant change in CO_2 emissions with repair of the vehicles.

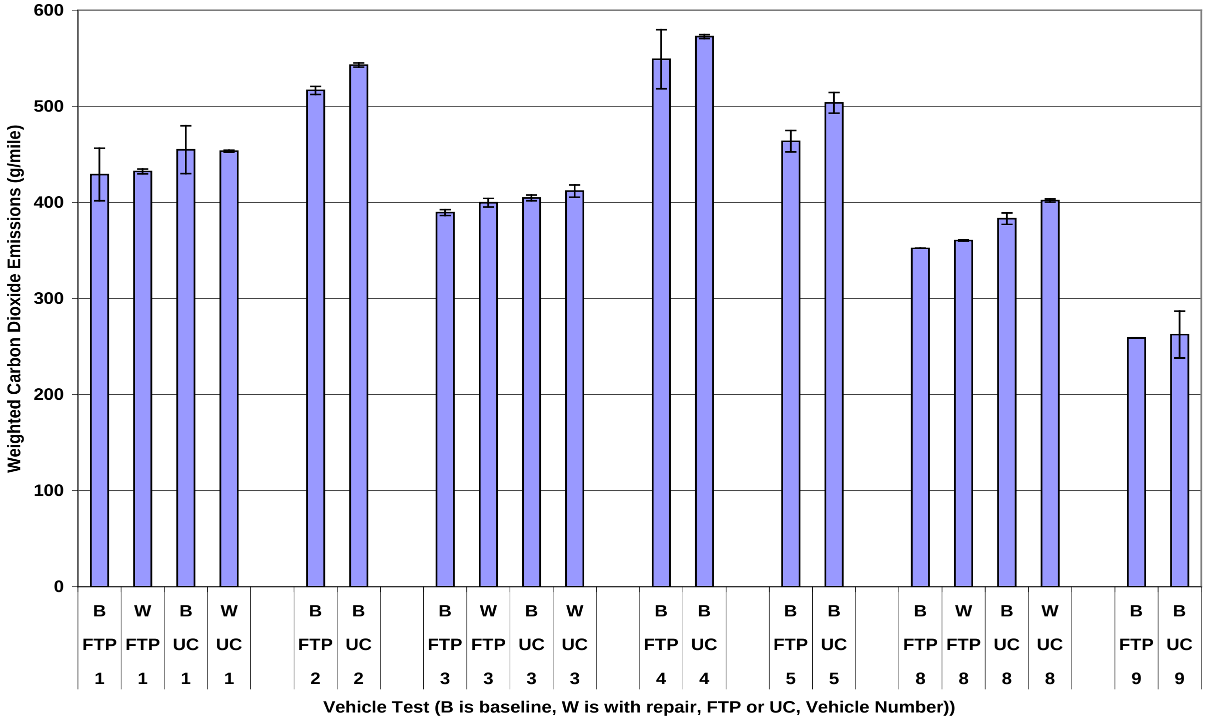


Figure 15. CO_2 Emission Rates

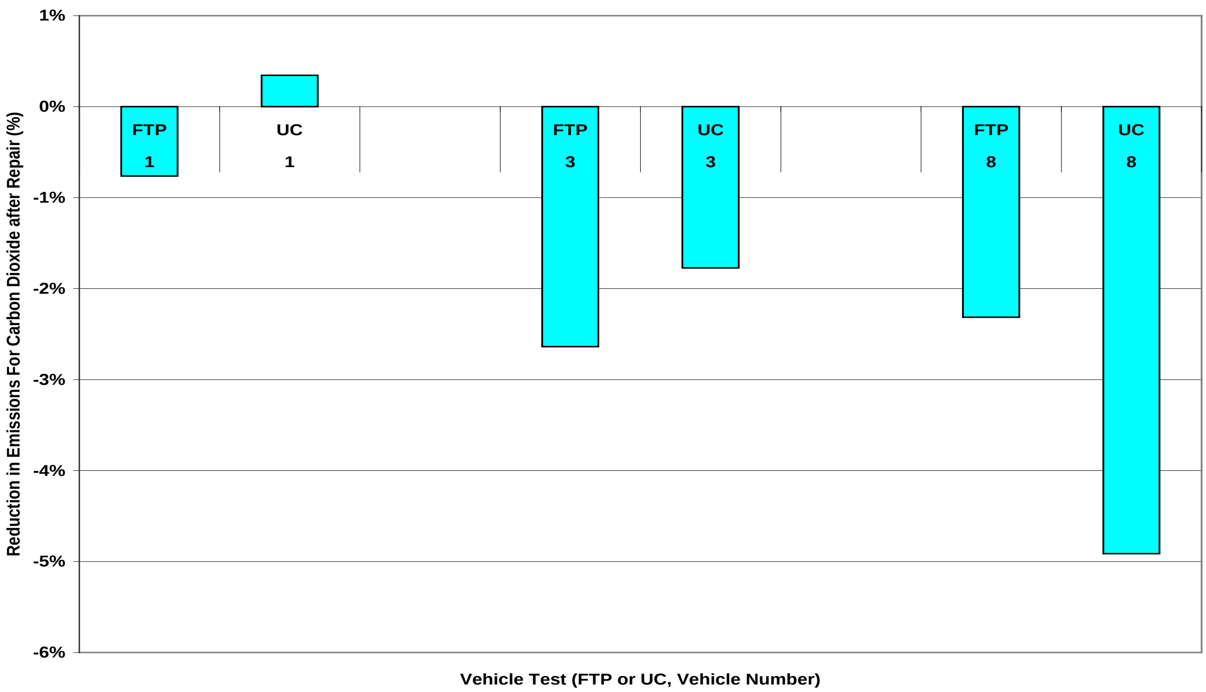


Figure 16. CO_2 Emission Rates Reduction After Repair.

3.1.6 Gravimetric PM Emissions

The following two plots show, respectively, the weighted average PM emissions by vehicle (Figure 17) and the PM emissions reductions after repair (Figure 18). The PM emission rates varied depend on the specific test vehicle. The PM emission rates for vehicle 1, 3 and 4 are considerably higher than the emissions rates for the typical gasoline vehicle, with average FTP emission rates of 91, 66 and 37 mg/mi, respectively. These values are still below those typically found for high PM emitters in previous studies, which have averaged 100 to 600 mg/mile [7, 8, 9, 10, 11]. The PM emissions for vehicles 2, 5, 8 and 9 were between 2.7 and 5.5 mg/mi. This is consistent with PM levels for normal emitting LDGVs, which are generally 5 mg/mi or less [12, 13, 14]. This is slightly higher than the PM emission rates for the latest technology vehicles, which can range around 1 mg/mi or less [15].

The UC emissions were comparable to those of the FTP and follow similar trends, the vehicles with higher FTP PM emissions (1, 3, and 4) also have higher PM emissions over the UC. In cases where the FTP emissions were below 10 mg/mile, the UC emissions were also typically 10 mg/mile or less. Looking at results for reduction after repair, only vehicle 3 shows real effective PM reductions with repair, there were observed reductions in vehicle 1, but these results are barely outside a standard deviation of the testing results.

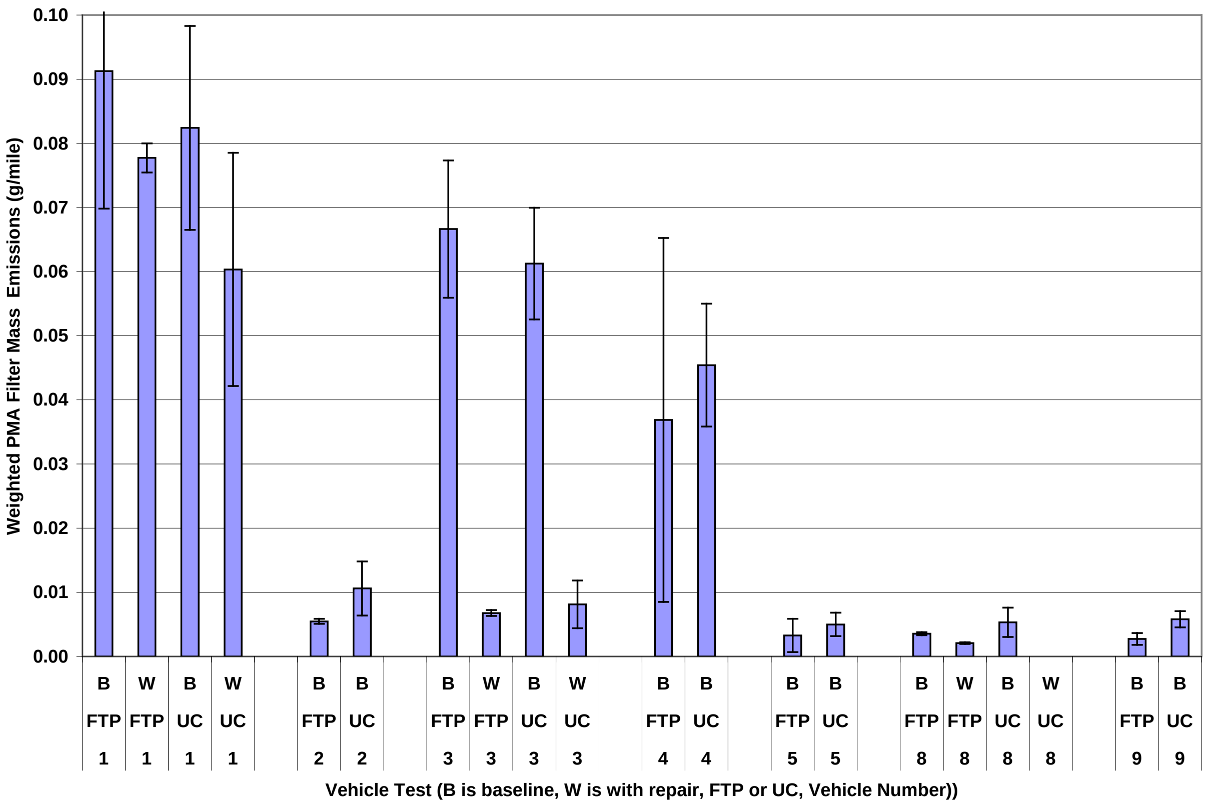


Figure 17. Gravimetric PM Emission Rates

It is interesting to note that the vehicles identified by RSD as high emitters in the H.E.R.O.S. program (vehicles 4, 5, 8, and 9) all had PM emission levels of 50 mg/mi or less, with 3 of the 4 vehicles having PM emission levels of less than 10 mg/mi or less. Although the CUT-SMOG vehicles (vehicles 1, 2, and 3) also had emission levels lower than those previously found for high emitters, only one of these vehicles had emission levels of less than 10 mg/mi, with the other two vehicles having emissions levels well above those typically seen for a properly functioning gasoline vehicles. There was a period of 20-25 months between the time when the three vehicles with PM emission levels <10 mg/mi were identified by RSD and when they were tested at the CARB facility, thus the vehicles could have undergone repairs prior to the CARB testing. Data recently available from BAR shows that, subsequent to RSD identification but prior to CARB testing, two of these three vehicles experienced Smog Check Failures followed by Smog Check Passes. This information suggests emission-related repairs took place prior to CARB testing. However, the nature of the repairs and whether or not PM was affected is unknown because PM is not quantified during smog check tests.

Figure 18 shows the emissions reductions in Gravimetric PM emissions after repair. Vehicle 3 showed the most significant reductions of approximately 90%. The reductions for vehicle 1 were relatively limited within the standard deviation of the testing, while the emission levels for vehicle 8 were at low levels both before and after repair.

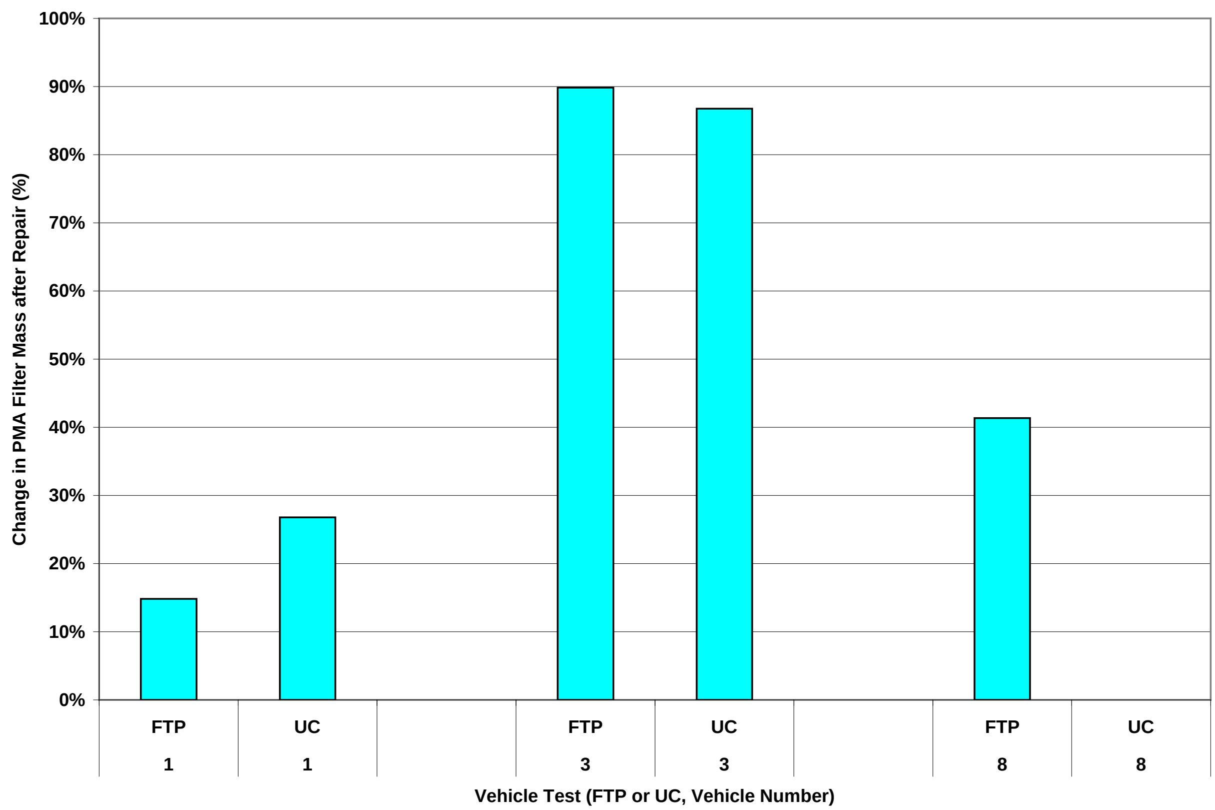


Figure 18. Gravimetric PM Emission Rates Reduction After Repair

3.2 Real-Time PM Emissions

3.2.1 Real-Time PM Emissions Tests, Data Collecting and Archival

Real-time PM emissions were collected using four different instruments, two in the raw exhaust (MAHA and ETAPS) and two in diluted exhaust (DustTrack and EEPS). A comparison of PM emissions for all the different instruments analyzed is provided in this section.

The data for the real-time PM instruments were compiled and time sequenced in second by second files. Figure 19 shows a typical data set for one test, Vehicle 1, MEC1 2B. The response was normalized for direct visual comparison. Second by second data was compiled for all tests for the vehicles tested for the MAHA, DustTrak, and EEPS. The ETAPS data were compiled for only of subset of tests, however, since many of the data files had issues, as discussed below.

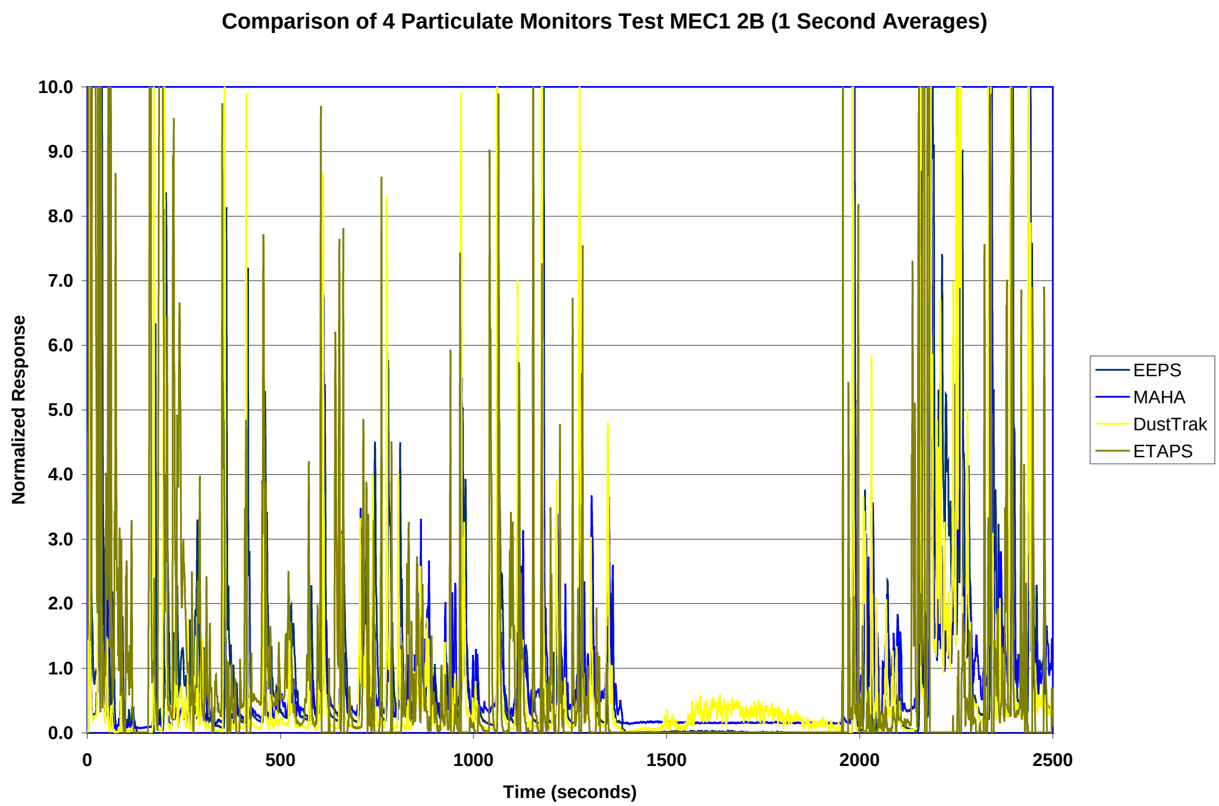


Figure 19. Normalized Second by Second response all 4 Particulate Monitors

Figures 20 and 21 show the first hundred seconds of phase 1 and phase 3, respectively, of the FTP cycle shown in Figure 19. It is clear that for this data set the EEPS, MAHA and DustTrak were time aligned to the nearest second, but the ETAPS was showing a significant response when the other instruments response were at a minimum. The ETAPS response, shown in Figure 21, may be an anomaly as the data set would overwrite time sequences and it became virtually impossible to time align the ETAPS response, or to even know which was the correct response for a given time. Efforts were made to reduce this effect for the ETAPS, but it meant discarding portions of data where more than one value occurred at a specific time. Also the ETAPS response was unitless and the manufacturer never supplied us with a way to convert it to a concentration. As a result of these problems, the ETAPS was not fully analyzed like the other three instruments. The ETAPS does respond to particles, but how to properly quantify those measurements requires further development of the instrument and its software and correction of the time sequencing problem. As the ETAPS did not provide any useful data, the results are not discussed any further in this report.

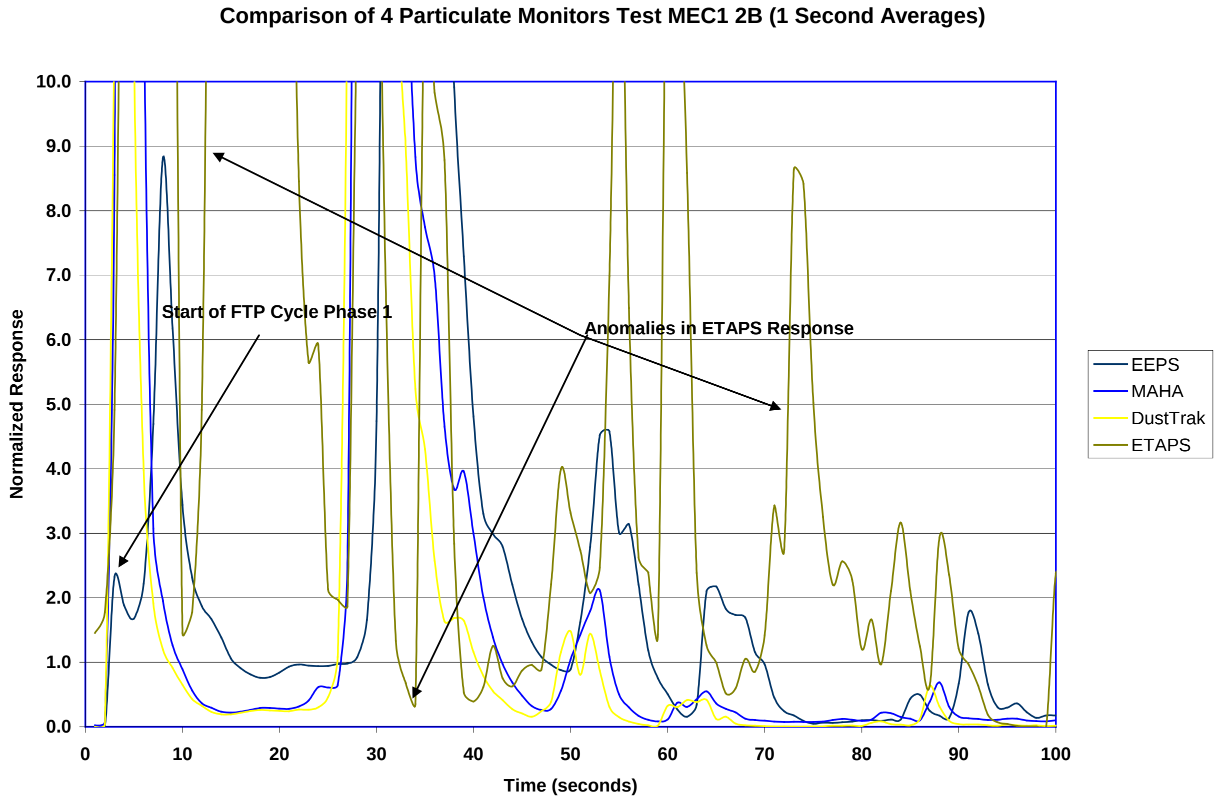


Figure 20. Normalized Second by Second response all 4 Particulate Monitors (First 100 Seconds)

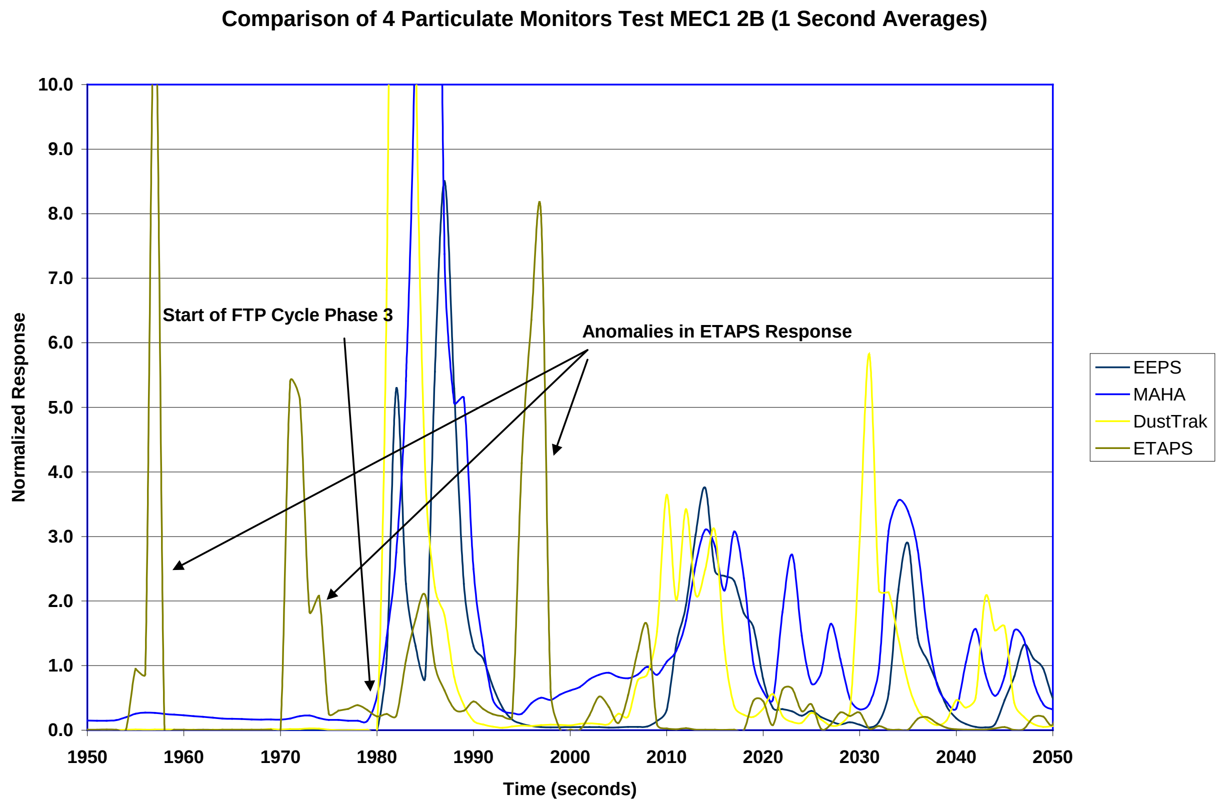


Figure 21. Normalized Second by Second response all 4 Particulate Monitors (From 1950 to 2050 Seconds)

To provide a better visualization of the comparisons between the different PM instruments over the whole FTP or UC test, the data was subsequently tabulated in a 20 second normalized average. Figure 22 shows a typical data set for one test, Vehicle 1, MEC1 1B.

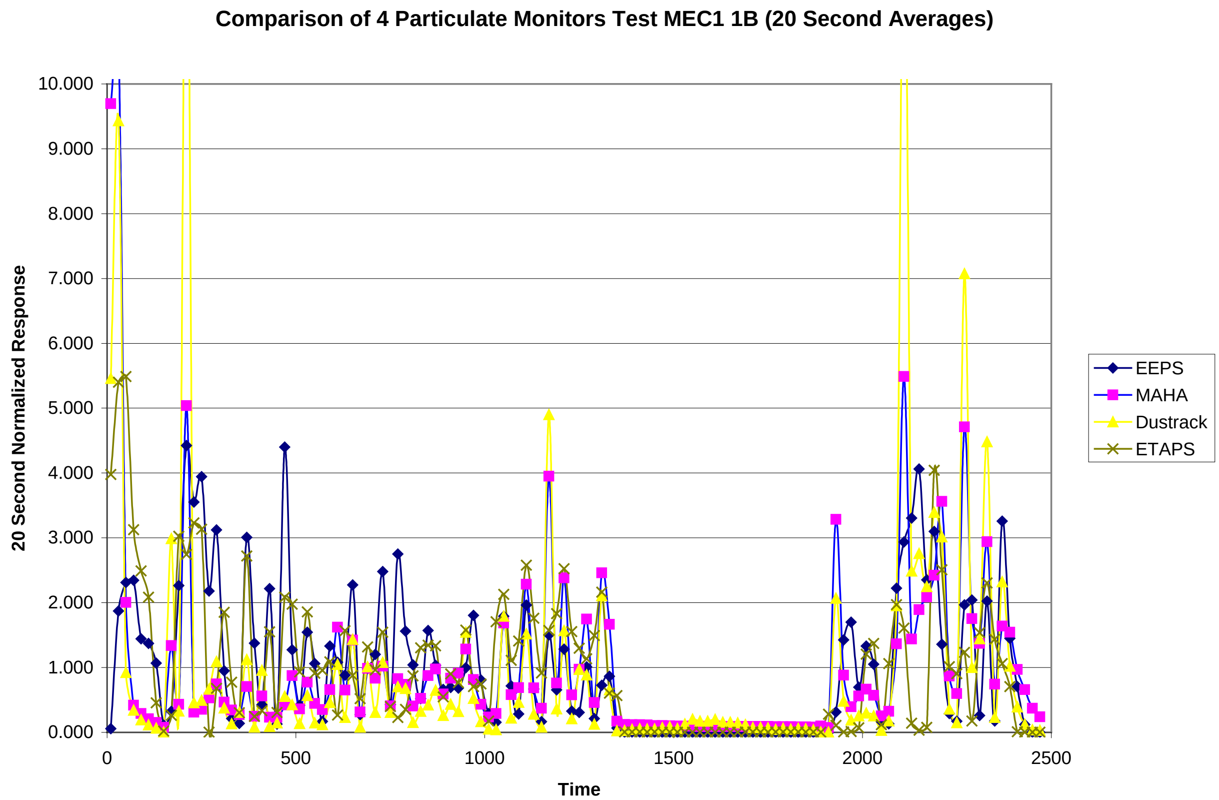


Figure 22. Normalized 20- Second response all 4 Particulate Monitors

The second by second data sets were tabulated and fully analyzed for the DustTrak, and the EEPS for all tests. For the MAHA, data was also analyzed for all vehicles, but the analysis is limited because the MAHA measurements were made in the raw exhaust and the corresponding second by second exhaust flows were not available. The MAHA data was analyzed by looking at the weighted average concentrations, and in effect cannot be a direct comparison to the filter mass data.

3.2.3 DustTrak

The DustTrak data was compiled in 1 second averages for each of the tests conducted. The time sequencing for the individual phases, FTP (505, 866 and 505 seconds) and UC (300, 1135 and 300 seconds), was done manually for each phase and the data was compiled for each phase of each test. The data was then weighted for the FTP and UC cycles based on the standard FTP weighting formula. The average for all the congruent tests for either baseline (B) or with repair (W) were tabulated against the weighted PM gravimetric Filter Mass results and are presented below in Figure 23. Note on average the DustTrak read lower than the filter mass data. The disparity seemed to be on a percentage basis higher for lower emitting vehicles. The DustTrak was able to identify high and low emitters, as can be seen for vehicles 1, 3 and 4 in comparison with the other vehicles.

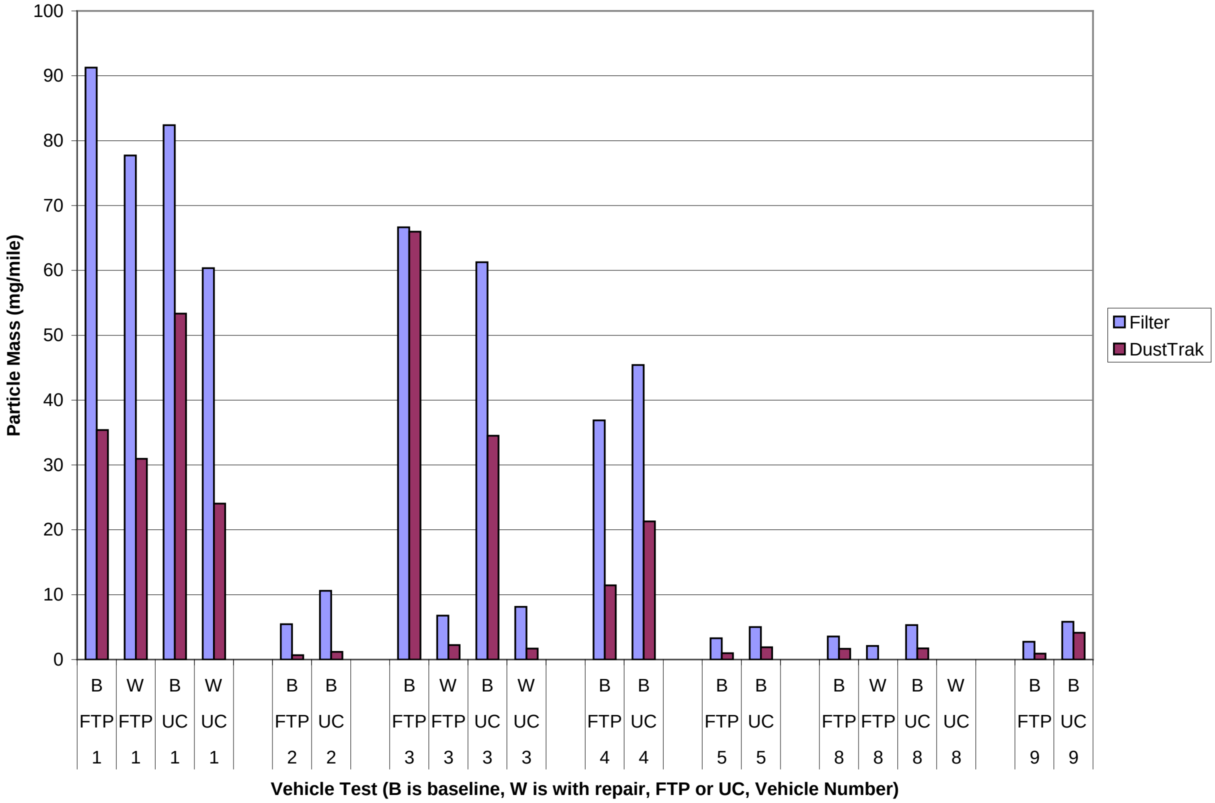


Figure 23. DustTrak Weighted Results Compared to Particle Mass (both in mg/mile)

A linear regression plot for the whole data set between the DustTrak and Particle Mass Filter data is shown on Figure 24. The two methods show decent agreement, with an R^2 of 0.791, and a negative intercept of -1.384 due to the lower DustTrak readings compared to the filter mass at low levels.

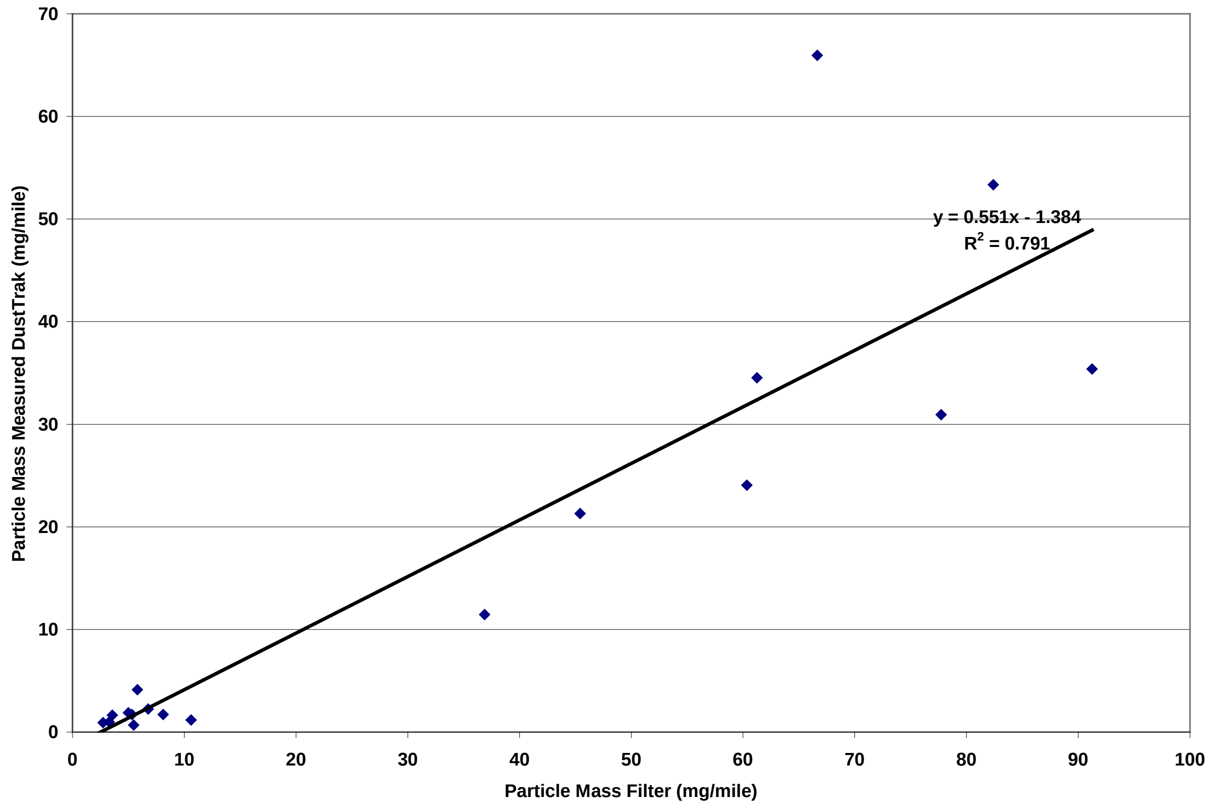


Figure 24. DustTrak Linear regression Plot Compared to Particle Mass (both in mg/mile)

3.2.4 EEPS

The EEPS data was also compiled in 1 second averages for each of the tests conducted. The time sequencing for the individual phases, FTP (505, 866 and 505 seconds) and UC (300, 1135 and 300 seconds), was done manually for each phase and the data was compiled for each phase of each test. The data was then weighted for the FTP and UC cycles based on the FTP weighting factos so that for each individual test there was one weighted number that was in units mg/mile. The average for all the congruent tests for either baseline (B) or with repair (W) were tabulated against the weighted PM gravimetric Filter Mass results and are presented below in Figure 25. On average, the EEPS read lower than the filter mass data. The EEPS performed well in identifying high emitters. For the higher emitting vehicles 1, 3, and 4, the EEPS compared favorably to the particle mass measurements.

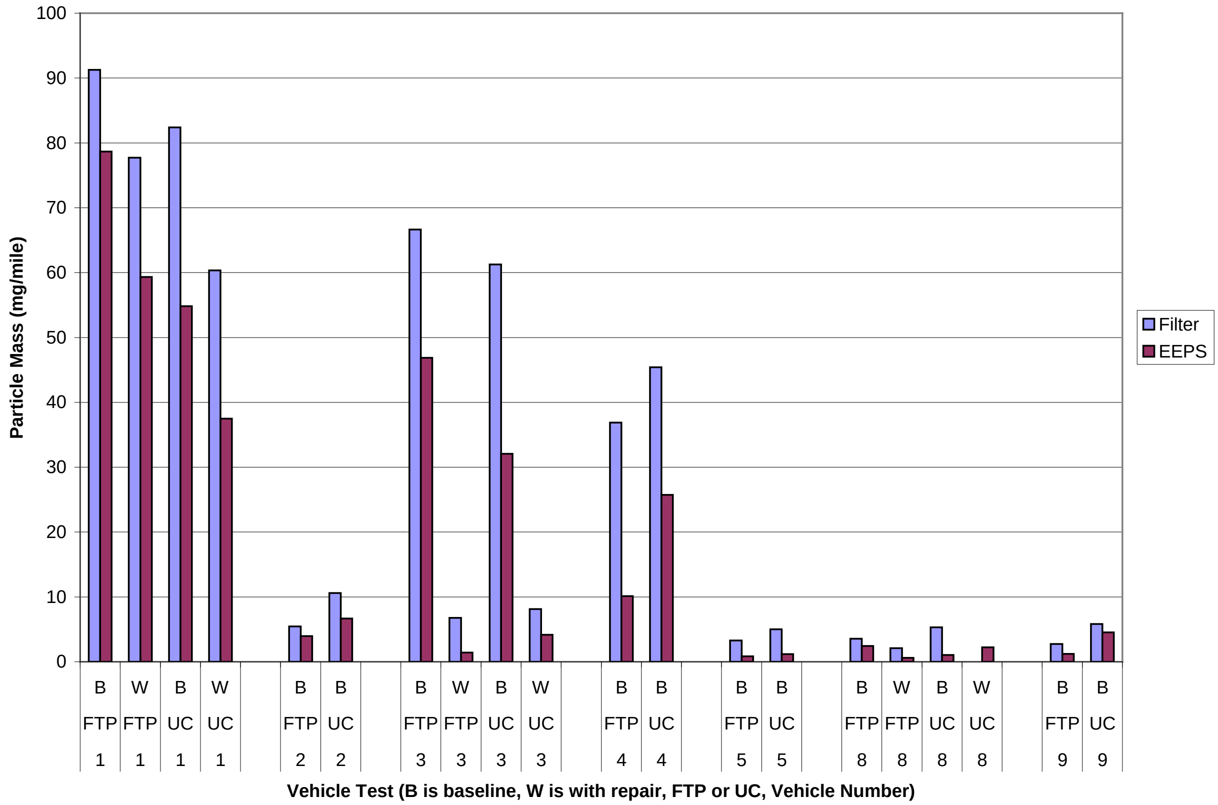


Figure 25. EEPS Weighted Results Compared to Particle Mass (both in mg/mile)

A linear regression plot for the whole data set between the EEPS and Particle Mass Filter data is shown on Figure 26. The two show excellent agreement with an R^2 of 0.943, with a negative intercept of -2.797 due to the lower EEPS readings compared to the filter mass at low levels.

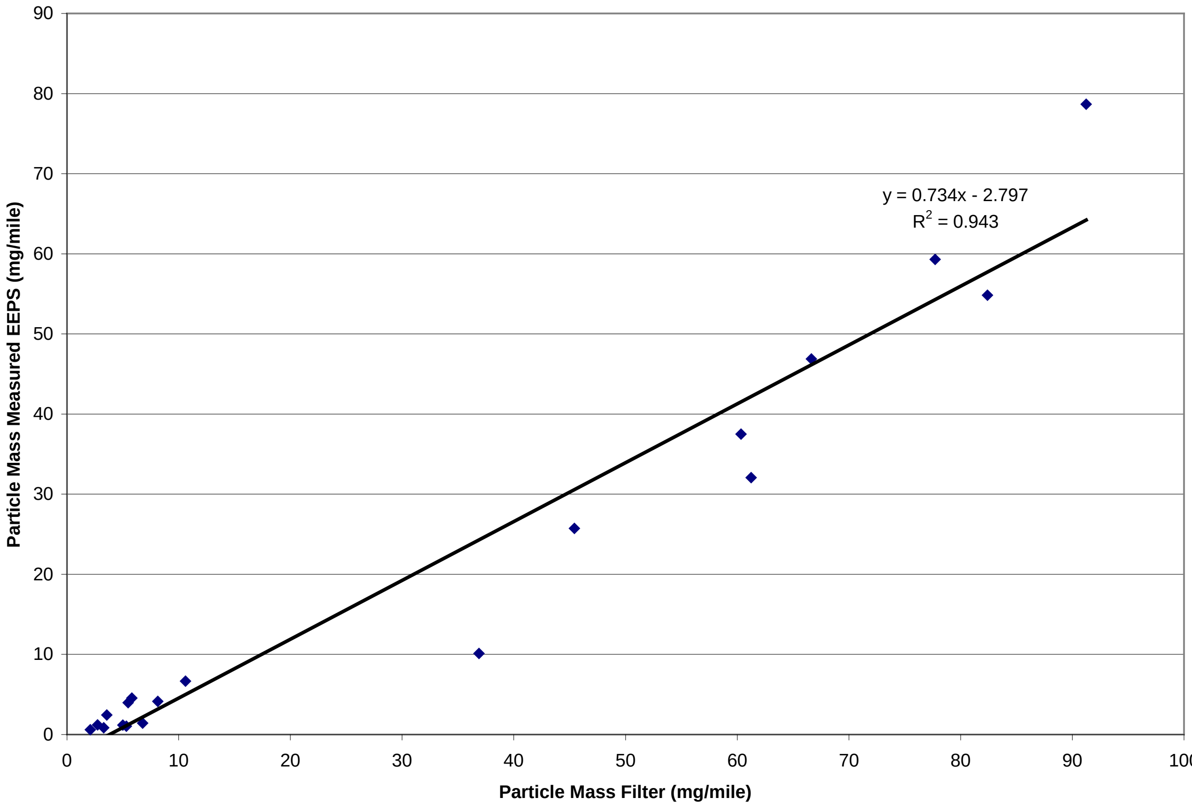


Figure 26. EEPS Linear regression Plot Compared to Particle Mass Filter (both in mg/mile)

3.2.5 MAHA

The MAHA data was also compiled in 1 second averages for each of the tests conducted. The time sequencing for the individual phases, FTP (505, 866 and 505 seconds) and UC (300, 1135 and 300 seconds), was done manually for each phase and the data was compiled for each phase of each test. Since the MAHA data is in exhaust concentration and we did not have modal second by second exhaust flow data to allow determination of the second by second mass emissions, the MAHA data was treated differently. The MAHA data was converted to an average concentration by dividing each phase of the cycle by the duration of that specific phase. So in effect the average MAHA concentration for each phase of the cycle was in units mg/m^3. The phase data was then weighted for the FTP and UC cycles based on the FTP weighting factors so that for each individual test there was one weighted number that was in units mg/mile. The data for all the congruent tests for either baseline (B) or with repair (W) were tabulated against the weighted PM gravimetric Filter Mass results and are presented in Figure 27. Note to compare the two data sets a normalization factor of 5.8 was applied to the MAHA data as determined by the regression plot. Since we cannot make a direct comparison in the values but only look at trends of the individual parameters, it appeared that MAHA performed well in identifying high emitters. For the higher emitting vehicles 1, 3, and 4, the MAHA compared favorably to the particle mass measurements.

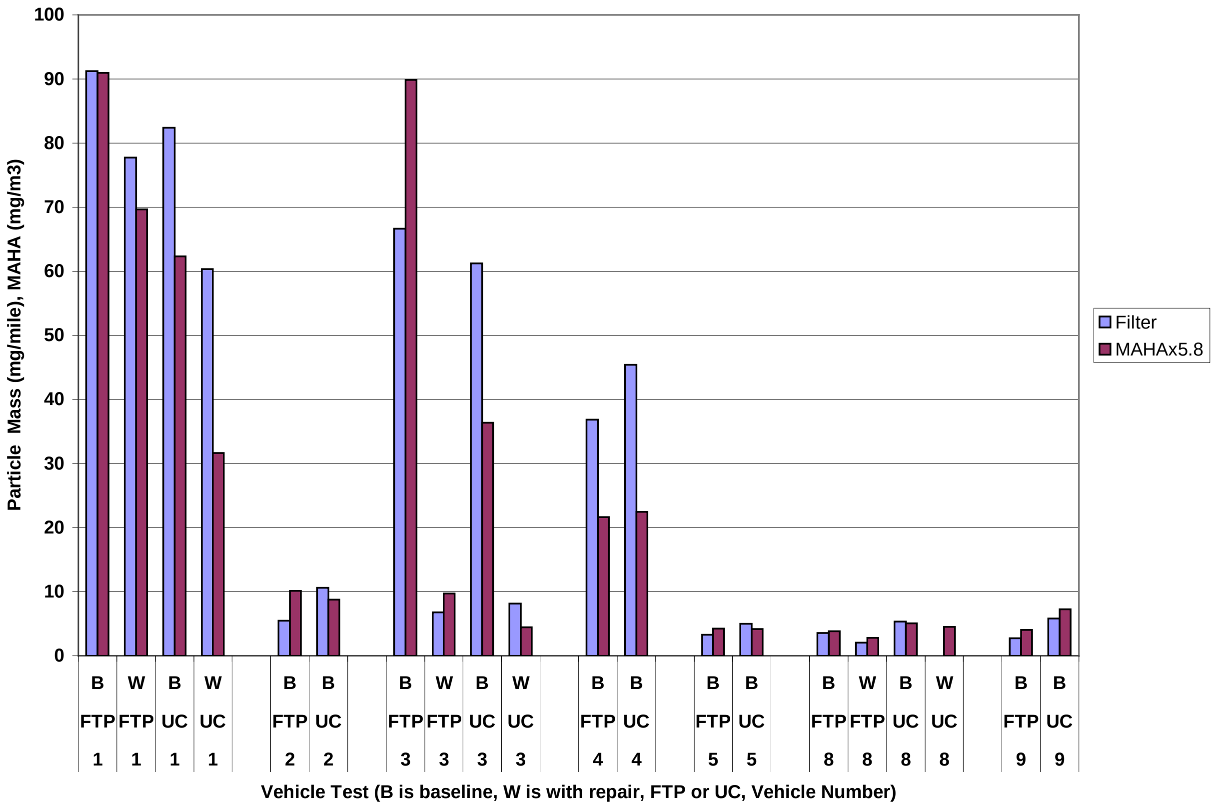


Figure 27. MAHA (mg/m3) Weighted Results Compared to Particle Mass (mg/mile)

A linear regression plot for the whole data set between the MAHA and Particle Mass Filter data is shown on Figure 28. The two show a good agreement with an R^2 of 0.852.

Note the data analysis used all the tests available for vehicles 1 to 4, but the instrument suffered a background drift problem beginning with tests on vehicle 5. The instrument was sent for repair but still periodically would suffer the same problem for subsequent tests on vehicles 8 and 9, so only the data taken when the instrument performed properly, were used in the weighted analysis for vehicles 5, 8 and 9.

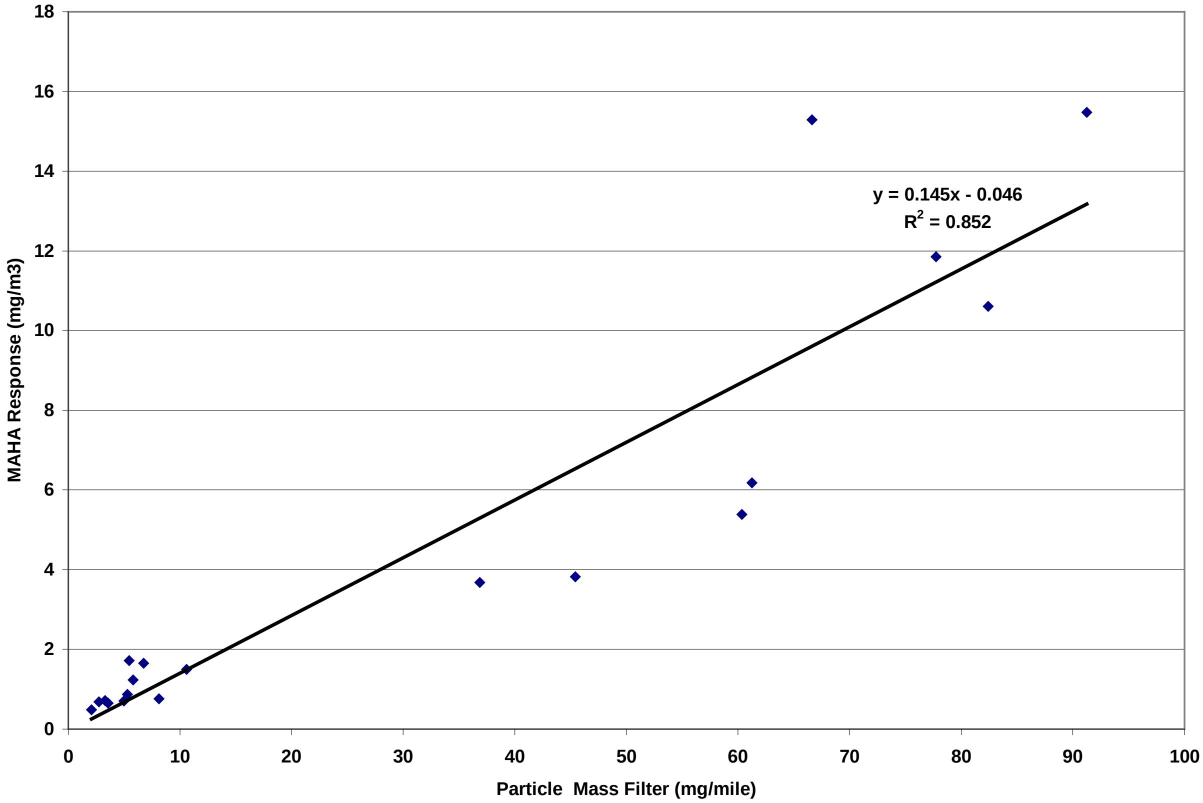


Figure 28. MAHA Response (mg/m^3) Linear regression Plot Compared to Particle Mass Filter (mg/mile)

3.2.6 Summary Real-Time PM Emissions Tests

A summary of the data for all the instruments is provided in Figure 29. Overall, the data show that all instruments showed the potential to identify and separate low emitters and high emitters.

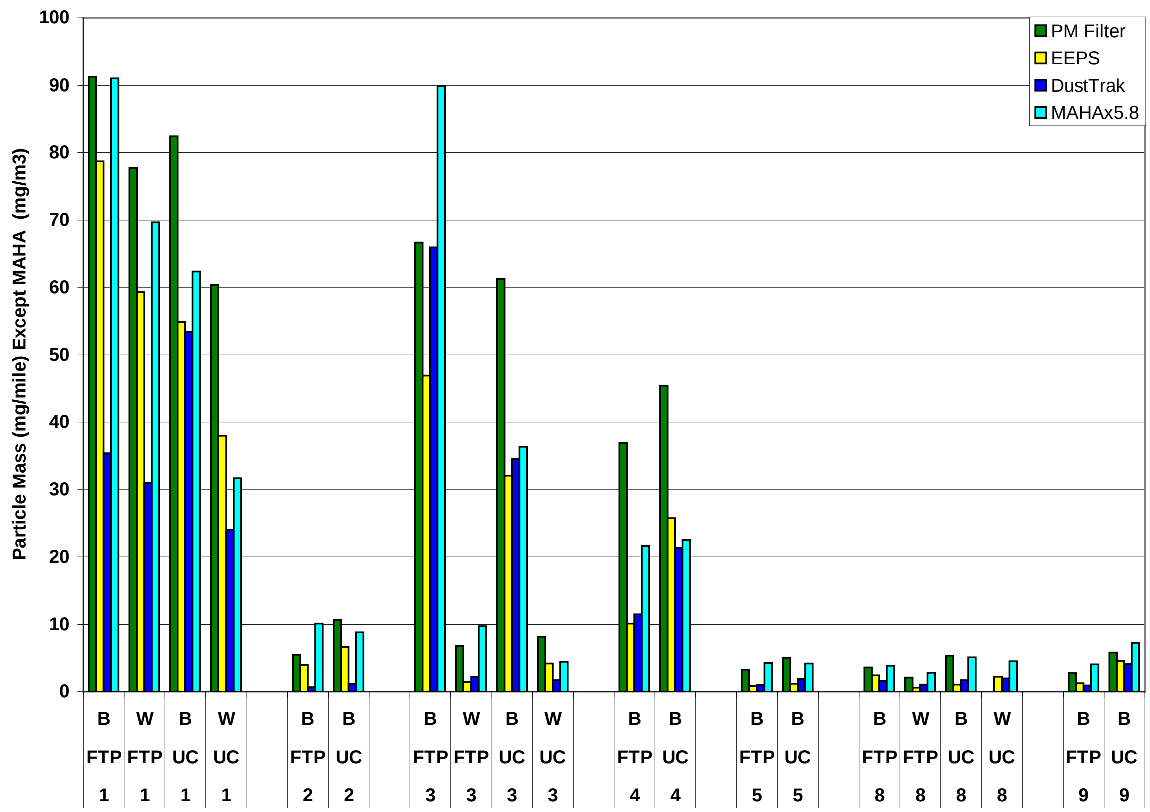


Figure 29. All Real-time Particle Measuring Instruments Weighted Results Compared to Particle Mass

3.3 ASM (Smog Check) Tests

Each vehicle was tested at the beginning of the testing sequence on an ASM Smog Check Emissions test. A subset of vehicles was also tested at the local repair station and subsequent to the repair at the CARB facility. The results are presented below in Table 4. The three highest emitting test vehicles for which formal FTPs were conducted, i.e., vehicles 1, 3, and 4, were all found to fail the Smog Check for one or more pollutants. These vehicles failed the Smog Check both at the CARB facility and at the repair station. Subsequent to the repairs, the two vehicles for which data are available both had passing Smog Check emission levels for the CARB ASM test. For vehicles 5 and 8, the pre-repair and post-repair ASM tests showed mixed trends with some of the emissions decreasing, while other emissions increased of were not changed significantly.

Table 4. Smog Check Results of the Test Vehicles

Vehicle #	Test Phase	Initial Test (CARB)			Pre-Repair Test (at station)			Post-repair test (CARB)		
		HC (ppm)	CO (%)	NO_x (ppm)	HC (ppm)	CO (%)	NO_x (ppm)	HC (ppm)	CO (%)	NO_x (ppm)
Baseline	15 mph	29	0.02	178						
	25 mph	23	0.04	150						
1	15 mph	201*	0.49	1748*	285**	0.41	1657*	39	0.10	481
	25 mph	77	0.34	875*	255**	0.49	1665*	37	0.05	176
2	15 mph	23	0.09	26						
	25 mph	25	0.13	32						
3	15 mph	169*	0.40	918*	178*	0.38	868*	16	0.05	282
	25 mph	96*	0.33	504	61*	0.24	420	13	0.03	243
4	15 mph	78	0.33	1331*	126*	0.37	730			
	25 mph	72	0.31	1269*	127*	0.37	613			
5	15 mph	25	0.01	479	13	0.23	120	84	0.19	282
	25 mph	15	0.01	101	9	0.13	166	28	0.12	103
6	15 mph	122	0.05	3060						
	25 mph	105	0.02	2935						
7	15 mph	15	0.13	427						
	25 mph	11	0.13	416						
8	15 mph	60	0.28	683				81	0.18	389
	25 mph	27	0.11	269				28	0.02	53
9	15 mph	112	0.24	818						
	25 mph	46	0.14	426						

* failed emissions test for this pollutant and speed

** failed emissions for this pollutant and speed at gross polluter level

3.4 Vehicle Diagnosis and Repair

Four of the test vehicles were sent to a local dealer for diagnosis and repair. The types of problems, the costs, and the repair effectiveness for PM are summarized in Table 5. In each case, the required repairs were extensive and often were attributed to more than a single problem. The repair costs were also usually comparable to the cost of the vehicle, making it unlikely that they would be worth it for a typical consumer. The repair also generally coupled an engine related issue (distributor, valves, fuel injectors, spark plugs, etc.) with the replacement of the catalyst or O_2 sensors. The repair results show that only one of the 3 repairs characterized was successful in providing significant PM reductions (vehicle #3). One of the other vehicles had very low PM emissions levels to begin with (vehicle #8) and the other vehicle did not show significant reductions in PM emissions following repairs (vehicle #1).

Table 5. Diagnosis and Repair Results of the Test Vehicles

Veh.	Problems / Operations	Cost	Vehicle Value	Baseline FTP (mg/mi)	Post-repair FTP (mg/mi)	Percent Reduction
1	Distributor, spark plugs, O_2 sensor, catalyst	$1,467.78	$1,675	91.3	77.7	15%
3	Valve Job, oil pan, gaskets, catalyst, O_2 sensor	$2,393.32	$1,940	66.6	6.8	84%
5	Fuel injectors, catalyst, timing, manifold gasket, radiator, fuel pump	$2,378.47	$1,475	3.3	NA	NA
8	Spark plugs, O_2 sensor, catalyst, oil leaks	$1,296.64	$1,425	3.6	2.1	42%

NA = Not Available

4.0 Summary and Conclusions

In this study, a total of 8 vehicles identified as high PM emitters were tested over a series of Federal Test Procedure (FTP) and Unified Cycle (UC) tests in CARB's Hageen-Smit laboratory. A number of PM instruments were utilized in the laboratory emissions tests, including the MPM4, ETaPS, and DustTrak. These instruments were directly evaluated against the traditional gravimetric filter PM mass measurements from the laboratory measurements. Some vehicles were tested both before and after repairs to provide a quantitative assessment of the repair effectiveness in terms of costs and associated emissions reductions. Key findings of this program are as follows:

- The regulated emissions rates varied significantly between the different test vehicles.
- All vehicles had NMHC FTP emissions rates higher than the Tier 1 standard, with values of approximately 0.5 to 12.5 g/mi. The UC "average" NMHC emission levels were generally lower than those for the FTP, with the exception of the highest emitting vehicle.
- For CO emissions, 5 of the 8 vehicles exceeded the Tier 1 standard, with one vehicle having CO emissions 5 times the Tier 1 standard.
- The FTP NO_x emissions for most vehicles were higher than the Tier 1 standard (0.7 g/mi), with about half of the vehicles 2 to 3 times the standard. The UC emission levels for all of the test vehicles were higher than those for the FTP using the weighting factors applied here, except for one vehicle. The NO_x emissions before repair for the UC cycle ranged from 0.89 g/mile to 3.9 g/mile.
- The PM emission rates varied depend on the specific test vehicle. The PM emission rates for three vehicles were considerably higher than the emissions rates for the typical gasoline vehicle, with average FTP emission rates of 91, 66 and 37 mg/mi, respectively. These values are still below those typically found for high PM emitters in previous studies, which have averaged 100 to 600 mg/mile. The PM emissions for the other vehicles were between 2.7 and 5.5 mg/mi. This is consistent with PM levels for normal emitting LDGVs, which are generally 5 mg/mi or less, but is slightly higher than the PM emission rates for the latest technology vehicles, which can range around 1 mg/mi or less. Of the 3 vehicles repaired, one had reductions of approximately 90%, while the other two only had minor reductions.
- Four test vehicles were repaired for this test program. The required repairs were extensive, with the costs comparable to or exceeding the cost of the vehicle. The repair also generally coupled an engine related issue (distributor, valves, fuel injectors, spark plugs, etc.) with the replacement of the catalyst or O_2 sensors. The repairs provided good PM reductions for one vehicle, little reduction for a second vehicle, and a vehicle had very low PM emissions to begin with.
- The DustTrak was able to distinguish the three high emitting vehicles from the remaining low emitting vehicles. The DustTrak on average read lower than the PM filter mass data. A linear regression between the DustTrak and the PM mass showed a decent agreement with an R^2 of 0.791, and a negative intercept of -1.384 due to the lower DustTrak readings compared to the filter mass at low levels.
- The EEPS was able to distinguish the three high emitting vehicles from the remaining low emitting vehicles. The EEPS on average read lower than the PM filter mass data. A linear

regression between the EEPS and the PM mass showed a decent agreement with an R^2 of 0.943, and a negative intercept of -2.797 due to the lower EEPS readings compared to the filter mass at low levels.

- The MAHA was able to distinguish the three high emitting vehicles from the remaining low emitting vehicles, as long as an appropriate calibration factor was applied. A linear regression between the MAHA and the PM mass showed a decent agreement with an R^2 of 0.852.

5.0 Discussion and Recommendations

The results of this study provide some important information to consider with respect to the identification of high emitters, the expansion of enforcement programs, and repair effectiveness on PM emissions.

Several real-time instruments showed potential for identifying medium to high PM emitters. The DustTrak, EEPS, and MAHA, with a calibration factor, were clearly able to distinguish between the low PM emission levels typical of those for properly functioning gasoline vehicles (<5-10 mg/mi) and the higher levels of the vehicles tested in this program (40-90 mg/mi). The application of these instruments for a broader program to identify high emitters would have to be verified over a wider range of vehicles, with a full range of emission values. The cost of the instruments would need to be considered for a wider spread application, with the EEPS considerably more expensive than the DustTrak. Additionally, only the MAHA is typically used for emissions measurements in the raw exhaust, which is an important consideration with respect to implementation into the smog check program.

Given the potential of these instruments to identify high emitters, one area of possible additional research would be to expand the testing to a larger subset of vehicles. In order to secure a larger population of vehicles, testing could focus more on tests at a Smog Check station rather than a more extensive testing sequence. A subset of high emitting vehicles from the H.E.R.O.S. II program and the CUT-SMOG program could also be targeted for recruitment. This proposed program could supplement the more detailed information obtained in the present study to provide a more statistically robust sample for understand the role of high emitters in the overall vehicle fleet and how effective these instruments could be in identifying them.

The potential of RSD as a screening device for high PM emissions is unclear from the results of this study. In Phase 1 of the overall study, RSD PM measurements showed some correlation with gravimetric reference-method measurements of PM emissions for a selected fleet of visibly smoking high emitting vehicles tested in a parking lot under controlled experimental conditions, but for a larger fleet of on-road vehicles, the correlation was relatively poor. In the current work, Phase 3 of the overall study, three of the four vehicles identified by RSD during routine monitoring as high PM emitters (i.e., among the top 1,000 PM readings for vehicles with 2 RSD readings) had PM emission levels <10 mg/mi. There was a period of 20-25 months between the time when the three vehicles with PM emission levels <10 mg/mi were identified by RSD and when they were tested at the CARB facility, thus the vehicles could have undergone repairs prior to the CARB testing. Data recently available from BAR shows that, subsequent to RSD identification but prior to CARB testing, two of these three vehicles experienced Smog Check Failures followed by Smog Check Passes. This information suggests emission-related repairs took place prior to CARB testing. However, the nature of the repairs and whether or not PM was affected is unknown because PM is not quantified during smog check tests. Altogether, given just a few high emitters and some possibly repaired vehicles, no definitive conclusions on RSD can be drawn from the Phase 3 portion of this study. A final report on the SCAQMD HEROS Phase I program is anticipated soon and may provide more insight on the feasibility of using remote sensing for purposes of identifying high emitting vehicles.

Although only 3 vehicles were characterized for post-repair emission reductions, some suggestions can be made regarding the repair effectiveness. The fact that the repair costs were comparable to the value of the vehicle means that the incentive for consumers to repair their vehicles would likely be low. This is consistent with results from Phase I of the study. Additionally, significant PM reductions were only found for one of the three vehicles. These finding suggest that there are some significant limitations to the PM emission reductions that could be achieved through a PM repair program.

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