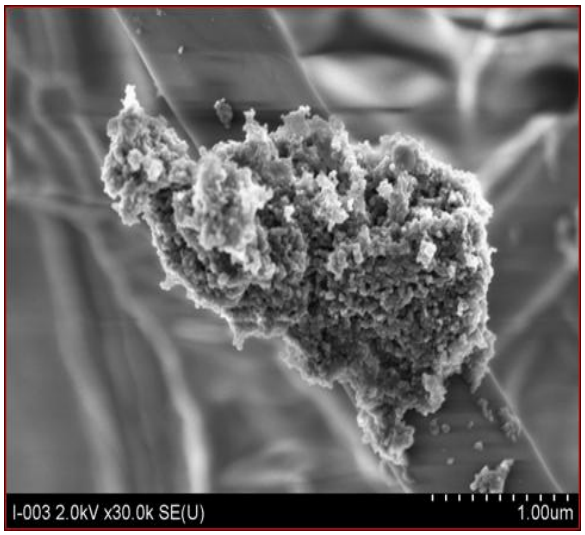
APPENDIX P

LEV III PM

TECHNICAL SUPPORT DOCUMENT

DEVELOPMENT OF PARTICULATE MATTER MASS STANDARDS FOR FUTURE LIGHT-DUTY VEHICLES



This report has been reviewed by the staff of the California Air Resources Board and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Air Resources Board, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

Date of Release: December 7, 2011
Scheduled for Consideration: January 26, 2012

Table of Contents

I. EXECUTIVE SUMMARY 1
II. REGULATING PARTICULATE MATTER EMISSIONS 5
A. Introduction 5
1. Background 5
2. Control Technology and Compliance Options 7
3. Existing PM Mass Emissions Measurement Methods 31
4. Proposed Particulate Matter Mass Standards 40
5. Feasibility 44
6. PM Benefits and Impacts 51
B. Test Method Improvement 54
1. Areas of Improvement in the PM Mass Method 54
2. Additional Industry Recommendations 57
3. Advances in PM Measurement from the U.S. EPA Test Program for Development of a PM Generator 61
4. Promising Complementary PM Methods 63
C. Conclusion 86
III. REVIEW OF FUEL EFFECTS ON PM EMISSIONS 88
A. Fuel Impact on PM Mass and Solid Particle Number Emissions 89
1. Fuel Effects on PM Mass Emissions 89
2. Fuel Effects on Solid Particle Number Emissions 90
B. Assessment of a PM Index 92
1. Methods 93
2. Results and Discussion 93
C. Conclusion 101
IV. MEASUREMENT OF BLACK CARBON EMISSIONS FROM LIGHT-DUTY GASOLINE VEHICLES 102
A. Review of Current Black Carbon Measurement Methods 103
1. Relationships between Black Carbon, Soot, and Elemental Carbon 103
2. Descriptions of BC Measurement Methods 105
B. ARB Studies on Black Carbon Measurement 110
1. Introduction 110
2. Experimental Details 110
3. Method Limits of Detection Study 112
4. Repeatability Analysis 114
5. Relationship between EC and BC in LDV Exhaust Emissions 117
6. Preliminary Selection of the Thermal/Optical Method with IMPROVE_A as the Reference Method for Measurement of BC in LDV and MDV Exhaust Emissions 119
7. Moving Forward 121
C. Relationships between Black Carbon and other PM Related Quantities in LDV Exhaust Emissions 122
1. Introduction 122
2. Relationship between EC and PM: EC to PM Fraction 123
3. Relationship between EC and SPN 124

D. Conclusion 126
V. CONCLUSION 127
VI. REFERENCES 129
VII. APPENDICES 144
VIII. LIST OF ACRONYMS AND ABBREVIATIONS 163

I. EXECUTIVE SUMMARY

Background

Motor vehicles in California are major contributors to urban air pollution and to global greenhouse gas (GHG) emissions. To simultaneously address both of these issues, the California Air Resources Board (ARB) is proposing new emission standards for GHG and criteria emissions as part of the Advanced Clean Cars regulatory development and its new Low Emission Vehicle (LEV) III program. The proposed LEV III regulation builds on ARB's longstanding efforts for low emission vehicles, a program which 50 years ago put California, the nation, and the world on a path towards successful implementation of innovative control technology and clean fuels to abate and, according to today's emission levels, nearly eliminate new automobile pollution. For the benefit of air quality, the global climate, and public health, LEV III encourages vehicle manufacturers to continue this trend. To comply, they are expected to use new and innovative solutions such as improved engine design, combustion optimization, advanced aftertreatment devices, and clean fuels all integrated into a systems engineering approach to further reduce air pollution at the tailpipe while achieving simultaneous reductions of GHG emissions and, most importantly, saving fuel.

The nexus between air pollution and climate change is well recognized and ARB is simultaneously confronting these two major environmental challenges. Particulate matter (PM) emissions, including the fraction of PM that is black carbon (BC), are at the center of this multi-pollutant challenge because, interestingly, BC links both air quality and climate change. ARB, in collaboration with industry and other stakeholders, has completed extensive study, testing, and laboratory evaluation of PM emissions and various related metrics from present-generation passenger cars, light-duty trucks, and medium-duty passenger vehicles (LDV) and medium-duty vehicles (MDV) with a Gross Vehicular Weight Rating (GVWR) of 8,501 to 14,000 pounds (lbs.) to support the proposed new PM standards. Stakeholder involvement included active participation and input from the automobile industry, the oil industry, the United States Environmental Protection Agency (U.S. EPA), and many experts from environmental advocacy organizations.

Staff Proposal for New PM Mass Limits – the 2017 and 2025 Targets

The new proposed PM mass limits under LEV III, in the near term (2017), prevent backsliding from the expected increased penetration of low-carbon technologies, which are known to put upward pressure on PM. These standards also lock in the benefit of the current over compliance with the existing limits under LEV II by the current gasoline port-fuel injected fleet, which dominates the passenger car and light truck segments. In the long term, the proposed 2025 PM standards set a clear target for low-PM technology development and set the stage for additional PM measurement research that involves the exploration of promising alternative metrics such as particle counting approaches for the benefit of arriving at a superior PM

measurement method. Setting an aggressive future PM mass emission limit is important for air quality and climate change protection. Existing knowledge gaps suggest that specific emission limits on the number of particles or on BC in the emissions from future vehicles is premature. However, advancing the understanding of the nature of those particles in terms of relevant parameters, besides particle mass, such as particle size, particle number concentration, or BC content is critical in order to arrive at the best metric for protection of health and the global climate. The specific new proposed limits are as follows.

Certification Requirements using the Federal Test Procedure (FTP)

The LEV III regulation proposes lowering the PM standard for light-duty and medium-duty vehicles from the current limit in two phases. The first phase lowers the PM standard to 3 milligrams per mile (mg/mi) starting with Model Year (MY) 2017 vehicles. The standard is phased-in incrementally with full implementation by MY 2021. The second phase lowers the PM standard to 1 mg/mi for 2025 and later MYs and is also phased-in incrementally. Full implementation of the 1 mg/mi PM standard is achieved by MY 2028. The regulation also sets intermediate standards for in-use vehicles. The intermediate in-use compliance standard for vehicles certifying to 3 mg/mi will be 6 mg/mi for MY 2017 through MY 2020. For MY 2025 through MY 2028, the intermediate in-use compliance standard for vehicles certifying to 1 mg/mi will be 2 mg/mi.

The LEV III regulation also proposes incrementally lowering the PM standard for MDVs other than medium-duty passenger vehicles (MDPV). Beginning with MY 2017, 10 percent of the MDVs with GVWR of 8,501-10,000 lbs. must comply with an 8 mg/mi PM standard. Beginning with MY 2017, 10 percent of the MDVs with vehicles weights of 10,000-14,000 lbs. must comply with a 12 mg/mi PM standard. The percentage of compliant MDVs for both categories is increased each year with full implementation by MY 2021. The intermediate in-use compliance standards for vehicles certifying to an 8 mg/mi PM standard will be 16 mg/mi for MY 2017 through MY 2021. The intermediate in-use compliance standards for vehicles certifying to a 12 mg/mi PM standard will be 24 mg/mi for MY 2017 through MY 2021.

Certification Requirements using the Supplemental Federal Test Procedure (SFTP or US06 cycle)

The LEV III regulations include a new proposed requirement for vehicle PM emission certification under the US06 drive cycle, which simulates the high vehicle loading and accelerations of an aggressive driver. The proposed standards require that LDVs and MDVs comply for the full useful life of 150,000 miles. The phase-in of US06 PM standards will be tied directly to the FTP PM certification. Phase-in of the standards will follow the FTP PM phase-in (20%/year starting in 2017 for light-duty, MDVs still TBD). In addition, ARB will be offering 5 mg/mi of in-use relief for the first 5 model years. The PM standards following the US06 drive cycle are shown in Table 3 (page 44). In the composite formula for MDVs, original equipment

manufacturers (OEMs) may use the FTP PM value in lieu of the SC03 version of the Supplemental Federal Test Procedure PM value.

All passenger cars (PC) with GVWR 8,500 lbs. or less must meet a 10 mg/mi PM standard. Light-duty trucks (LDT) with GVWR less than 6,000 lbs. would need to comply with a 10 mg/mi PM standard. LDTs with GVWR of 6,001 lbs. or more and MDPVs with a GVWR between 8,501 lbs. and 10,000 lbs., both would need to comply with a 20 mg/mi PM standard. For MDVs with loaded and adjusted loaded vehicles weights of GVWR of 8,501 to 10,000 lbs., with a horsepower (HP)/GVWR ratio > 0.24, the PM standard for compliance is 10 mg/mi. All other MDVs with GVRW of 8,501 lbs. to 14,000 lbs. must meet a PM standard of 7 mg/mi. The percentage of compliant MDVs for both categories is increased each year with full implementation by MY 2021. The PM standards are shown in Table 3 (page 44).

Additional PM Measurement Considerations

In order to achieve the GHG emissions reductions needed from the LDV and MDV fleets, manufacturers are expected to incorporate turbocharging and gasoline direct injection technology (GDI) into vehicles. Turbocharging boosts the volume of air directed into the combustion chamber and increases engine efficiency. GDI technology injects fuel directly into the combustion chamber under high pressure. The latent heat of vaporization cools the air in the cylinder and therefore increases the volumetric efficiency and allows for higher compression ratios without knock and leaner air/fuel mixtures. The net result for both technologies is more complete combustion and an engine that is more fuel efficient. The current trend toward spray-guided GDI, which produces lower PM and BC emissions, and away from wall-guided GDI will make it easy for manufacturers to meet the MY 2017 PM standard with only minor adjustments. Ample lead time before implementation of the second phase of the proposed PM standard provides manufacturers with time to make the necessary design changes to the engine during the regular course of research and development.

The PM mass test procedure specified in 40 Code of Federal Regulations (CFR) Part 1065 can be used to accurately test LDVs at the 3 mg/mi level. However, ARB anticipates that the measurement of PM emissions at the 1 mg/mi level will likely require further improvements to the measurement approach including possible alternative, supplementary approaches to the PM mass measurement. These alternatives may include an improved version of the European Particle Measurement Programme (PMP) approach based on the measurement of PM mass and the number of solid particles in the emissions or determination of PM mass emissions based on the integration of the particle size distribution in the emissions and with knowledge of particle density and morphology. A third approach currently reported in the published literature suggests determining PM emissions based on the chemical reconstruction of mass. These alternatives are not exhaustive. The proposal for a lower limit in 2025 of 1 mg/mi is intended to allow for adequate lead time (up to 13 years) for technology development and for resolution of measurement issues prior to implementation of the ultra-low emission standard of 1 mg/mi. ARB is committed to continue testing and measurement study in the

areas listed above as well as in other approaches that may emerge in response to the need for technical improvements and the 1 mg/mi stretch goal.

Fuel Effects on PM

Fuel effects on PM emissions were also investigated. Three gasoline fuels with different ethanol content were evaluated in the ARB test program: California commercial Phase 3 E6 (6 percent ethanol) summer fuel, California commercial Phase 3 E10 (10 percent ethanol) summer fuel, and California Phase 2 certification fuel (E0 – 0 percent ethanol). Test results showed that no consistent trend could be established for the narrow range of fuels used. This also held true for solid particle number (SPN) emission results. Testing showed that the SPN emissions rates remain essentially unchanged for the fuels used. ARB also investigated the PM index (PMI), a fuel composition algorithm developed by Honda Research and Development for predicting the impact on PM emissions and fuel composition. California fuels resulted in a very narrow PMI range and, for the test fuels, the predictive PMI model was not useful in estimating PM emissions for the test vehicles.

Black Carbon and Short-lived Climate Forcers

Black carbon emissions are important for air pollution and climate change. While there are still important knowledge gaps concerning the most appropriate policy construct for including BC into a CO_2 equivalent limit using a global warming potential (GWP) based on a single and common time horizon for both short-lived climate forcers like BC and long-lived GHGs like CO_2, the need to continue to enhance our understating of BC emissions and BC measurements is reflected in this report. The staff's study of BC measurement has yielded important and first-of-a-kind information concerning the best options for measurement, the trend in PM and BC correlations with engine technology, the statistical potential of a BC and SPN measurement, and the areas for further work that show the most promise for advancing the general understanding of measurements, particles, air pollution from vehicles, and the climate effects of non-Kyoto climate species like black carbon and PM.

II. REGULATING PARTICULATE MATTER EMISSIONS

A. Introduction

1. Background

Despite great progress in achieving cleaner air in California, the State still needs to further reduce air pollution. Particulate matter (PM) in ambient air, also known as particle pollution, is a complex mixture of extremely small particles and liquid droplets (U.S. EPA, 2011). Ambient PM is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.

The size of particles is directly linked to their potential for causing adverse health effects. The U.S. EPA and the California Air Resources Board (ARB) are particularly concerned with particles that are 10 micrometers in aerodynamic diameter or smaller. These particles can generally pass through the throat and nose and enter the lungs. Once inhaled, they can affect various organs. The U.S. EPA groups and describes particle pollution into three categories. The first are "'inhalable coarse particles' such as those found near roadways and dusty industries, are larger than 2.5 micrometers and smaller than 10 micrometers in aerodynamic diameter". The second group is "'fine particles,' such as those found in smoke and haze, are 2.5 micrometers in aerodynamic diameter and smaller. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air". The third group is "'ultrafine particles,' these are also present near roadways and many other sources and can appear from secondary formation from precursors found in ambient air. These very small particles are typically solid or liquid droplets within the sub-0.1 micrometer aerodynamic diameter size range. A unique characteristic is a subset of these particles, those with a diameter of approximately 0.05 micrometers or less, which can form gas-to-particle conversion".

PM emissions are a particular concern for their multiple impacts on public health, air quality, and the global climate. In general, mobile sources (mainly cars and trucks) are not major contributors to the statewide total PM mass inventory. For instance, the PM emissions from cars and small trucks add up to less than 5 percent of the total $PM_{2.5}$ inventory. However, they do contribute significantly to urban pollution and human exposure, such as the elevated concentrations of PM near heavily-travelled roadways. Historically, PM emissions from diesel engines were of most concern because of their high PM emission rates relative to internal combustion engine (ICE) sources. But as the modern diesel engine achieves increasingly lower PM emissions, the interest in and relative contribution of PM emissions from an ever increasing number of gasoline-fueled light-duty vehicles (LDV) is growing. Thus, the need for maximum mitigation of PM emissions at the source (i.e., tailpipe) in the most technically and economically feasible approach is paramount.

Fossil fuel combustion in an ICE leads to air pollution including PM emissions. Particulate matter emissions from a motor vehicle are made of volatile, semi-volatile, and solid particles of organic and inorganic composition that exist in equilibrium, which depends on a number of factors such as exhaust temperature, composition, vapor pressure, and concentration. Solid particles are generally the sooty, black material typically associated with old diesel car or truck exhaust. These particles are primarily elemental carbon (EC) formed from fuel pyrolysis due to incomplete (i.e., inefficient) combustion. Precise control of the combustion event inside a cylinder (i.e., optimized combustion and fueling design) is a key determinant for minimizing the amount of EC that is generated. The fuel and the lubricant used in an ICE contribute to the organic and inorganic fraction formed in the PM emissions. In a gasoline-fueled engine where there is little soot or EC, the lubricating oil-derived PM accounts for the largest fraction of the total PM mass emissions. Thus, the rate of lubricant consumption is a key determinant in the net amount of non-solid, organic material generated. The distinctions between the events inside an engine that lead to the various components of PM emissions (e.g., solid versus volatile PM) are important considerations of internal (to the engine) measures for low PM design.

Organic and inorganic compounds are present in vehicle exhaust in the gas and the particle phases as condensed or adsorbed aerosol or as discrete particles formed through gas-to-particle nucleation. While there are important and inherent differences in the chemical and physical characteristics of the PM emissions from various fuels (i.e., diesel versus gasoline versus natural gas), the basic definition as stated previously generally applies. For a given fuel and lubricant, PM emissions can be reduced via optimization of internal or external measures. Generally, internal measures include improved combustion design as discussed above while external measures typically involve the application of post-combustion, tailpipe aftertreatment hardware.

California did not regulate PM emissions from cars or other LDVs until relatively recently. Eventually, when a PM standard was promulgated in the Low Emission Vehicle II (LEV II) program, the limit as it applied to the gasoline-fueled vehicle was meant as a capping standard, rather than as an explicit measure to reduce what were believed to be already low emissions. The existing PM mass standard for new California cars and light-duty trucks under the LEV II program is 10 milligrams per mile (mg/mi) for all vehicle emission categories: LEV, ultra-low emission vehicles (ULEV), and super ultra-low emission vehicles (SULEV). The vehicle categories covered by the program include all passenger cars and light-duty trucks (PC/LDT) and medium-duty passenger vehicles (MDPV). This standard has generally not been a binding constraint for car manufacturers due to new and most in-use gasoline vehicles emitting PM at well below this limit. The primary impact of the 10 mg/mi PM standard has been to ensure the use of diesel particle filters (DPF) on diesel-fueled vehicles. But today, the diesel-fueled LDV is still uncommon. Various factors have led to a light-duty fleet in California that is dominated by gasoline-fueled vehicles equipped with multiport-fuel injection (PFI or MPFI), a three-way catalyst (TWC), and other technological advances.

Despite the current situation of over-compliance with the existing PM standards, ARB staff is proposing to reduce the permissible PM emission levels for new vehicles under the Advanced Clean Cars program for a number of reasons. First, California's air still exceeds the federal and state ambient air quality standards for PM. Major urban centers (e.g., the Bay Area, Los Angeles, Sacramento, and the San Joaquin Valley) are classified as nonattainment areas for these health-protective standards. As a result, it is necessary to lock in current sub-10 mg/mi LDV PM emission levels, which are achievable from present generation cars and trucks, to prevent a backslide. Second, a number of emerging low carbon engine technologies can put upward pressure on PM emissions. Federal and California standards will reduce vehicle greenhouse gas (GHG) emissions by forcing vehicles to use advanced combustion technologies with greater thermodynamic efficiency. Based on current-generation technology test results, some of the most thermodynamically efficient technologies present challenges to simultaneously limit PM emissions while still reducing carbon dioxide (CO_2) emission levels. Examples of these technologies include gasoline direct injection (GDI), turbocharging, diesel compression-ignition, stratified charge compression-ignition, and other lean-burn technologies. The stringency of the new proposed PM mass standards is meant to prevent any potential increase in PM emissions resulting from future low carbon car and light-duty truck technology while moving towards the lowest possible emission levels.

2. Control Technology and Compliance Options

GHG and PM Control Technology

The need to reduce GHG exhaust emissions and increase fuel efficiency is driving LDV manufacturers to explore options beyond the conventional PFI technology. However, the simultaneous reduction of GHG and criteria emissions [non-methane organic gases (NMOG), oxides of nitrogen (NO_X), carbon monoxide (CO), and PM] are not necessarily achievable by application of a single, silver-bullet technology solution. Rather, meeting all the proposed new limits will likely require car manufacturers to innovate and to deploy a multitude of hardware solutions integrated into a sophisticated, systems-based technology package for the advanced clean car of the future. Some of the low carbon technologies with proven track records that are most likely to be used are: advanced port fuel injection engines, GDI engines, boosted and downsized engines, clean diesel engines, hybrid, and plug-in hybrid technology among others. Each of these technologies will have a particular impact on PM emissions, which is the subject of this section. For additional discussion of these and other relevant technologies, the reader is referred to ARB staff's report on the first GHG car standards "Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Discuss Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles, August 2004".

Control Technologies that Directly Affect Vehicle PM Emissions

Port Fuel Injection

As previously mentioned, the most common type of engine powertrain in LDV applications in California is the Otto cycle (gasoline-fueled) PFI-equipped engine. As illustrated in Figure 1, PFI injects the fuel onto the intake valve in the intake manifold before the air/fuel mixture is drawn into the combustion cylinder. When combined with a TWC, this technology can be extremely effective at controlling criteria pollutants in the exhaust emissions. The gasoline engine (due primarily to relatively low compression, the fuel itself, and the TWC) can be inherently emitting low PM mass. Some current, well-maintained PFI-equipped LDVs emit PM mass levels below 1 mg/mi. For example, published research reports PM emissions rates for both PFI ULEV and SULEV vehicles of approximately 0.7 mg/mi or much less over the Federal Test Procedure (FTP or FTP-75) cycle as shown in Figure 2 (Li et al., 2006). However, PM emissions are a complex subject. There are many factors of vehicle design and vehicle use, including driver behavior that can influence them. For this reason, the lowest possible level of PM emissions achieved by the cleanest cars are not necessarily the in-use emissions for the average PFI car in the on-road fleet.

First, the cleanest SULEV vehicles represent only approximately one quarter of all LDVs and MDPVs on the road today (ARB, 2010) and most are in the PC/LDT1 (LDTs with GVWR of less than 6,000 lbs.) category. Second, aggressive driving and deterioration with vehicle age including higher oil consumption are all factors that can increase PM emissions from a PFI vehicle well upwards of the current standard. Recent test data collected by the U.S. EPA from a fleet of ten high mileage (>100,000 miles odometer) PFI vehicles shows that aggressive driving, which can be simulated by the US06 cycle of the Supplemental Federal Test Procedure (SFTP), can increase PM emissions by a factor of 17. Deterioration and subsequent oil burning can add an additional factor of five for a total increase of 22 times the PM level over the typical FTP cycle (test cycles are described later in this document).

Furthermore, the variability in new versus in-use vehicle emissions is illustrated in Figure 3, which is taken from the U.S. EPA's Kansas City Study (U.S. EPA, 2008). The Kansas City Study was a comprehensive testing study conducted by the U.S. EPA in partnership with the Coordinating Research Council (CRC). The study was undertaken primarily to support the Motor Vehicle Emissions Simulator (MOVES) model, the new modeling tool for mobile source emissions. This study resulted in one of the most complete reports on PM emissions from in-use gasoline LDVs to date. Important differences between cold-start and hot-stabilized running emissions and ambient temperature effects (vehicle use in summer versus winter) were noted. Heavier vehicles (i.e., trucks) were found to have higher PM emissions than lighter vehicles (i.e., cars). It is generally recognized that PM emissions increase with vehicle age; a fact that points to the need for PM control over the entire useful life of a vehicle. In particular, electronic fuel injection led to lower PM emissions than the

older vehicle technology using a carburetor for fuel delivery. Finally, this study showed clearly declining $PM_{2.5}$ emissions with advancing vehicle MY.

ARB considered the U.S. EPA's Kansas City data and more recent test data generated by both agencies to arrive at a more realistic representation of the current state of vehicle emissions from the fleet. The conclusion is that average PM emissions from a fleet of 2004 MY and newer PFI LDVs are a reasonable baseline and they are on the order of 4 mg/mi. The reader is referred to Appendix U - Technical Support Document – Mobile Source Emissions Inventory for a complete discussion of the use of this data and the derivation of this baseline emission level.

The magnitude of the PM emissions shown in Figure 2 is a good illustration of the level of over-compliance with the current PM standards that can be achieved by the cleanest gasoline cars on the road today. In addition, the typical chemical composition of PFI PM emissions is also shown in Figure 2. Particulate matter from gasoline-fueled PFI vehicles is composed of mostly organic carbon (OC). This is in sharp contrast to the composition of GDI PM emissions. The OC is likely high molecular weight hydrocarbons from the fuel and lubricating oil. Poor fueling control that leads to a rich mixture can result in the formation of EC from a gasoline engine. Other inorganic compounds such as metals and sulfates can contribute to PM emissions, but they are generally a small fraction (smaller than EC) of the total. Also, the use of a TWC can lead to the emission of substrate material that increases the overall PM emissions. For a given PFI vehicle, the same design characteristics that can yield low PM mass emissions also lead to lower thermodynamic efficiency and generally higher GHG emissions relative to other options discussed here.

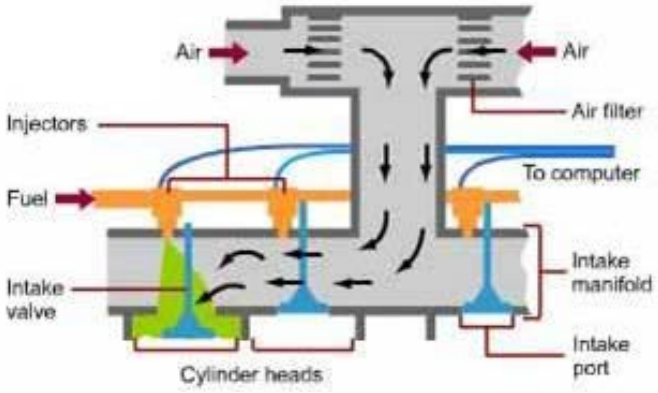


Figure 1. Port fuel injection diagram
Source: http://www.indiacar.com/infobank/mpfi.htm

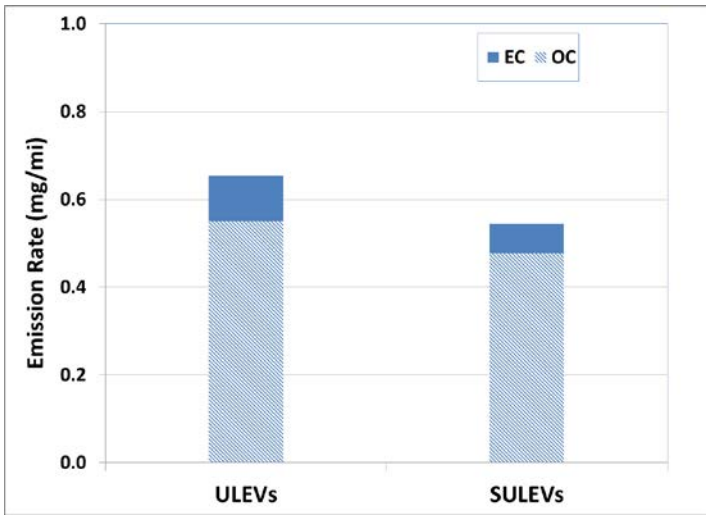


Figure 2. Average emission rates of PM (shown as the sum of organic carbon (OC) and elemental carbon) for both ULEVs and SULEVs, not corrected for background. Source: Li et al., 2006.

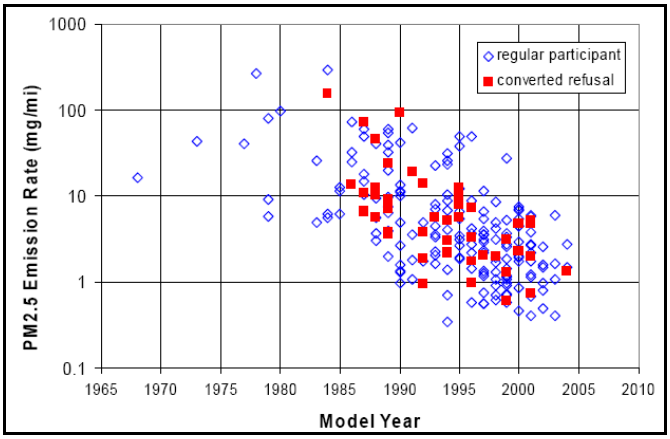


Figure 3. PM emissions as a function of vehicle model year from the LDV test fleet taken from the U.S. EPA Kansas City study. Source: U.S. EPA, 2008.

Gasoline Direct Injection

Car makers who choose to pursue gasoline-fueled, CO_2 friendlier GDI internal combustion engines for their future vehicles will have two principal technical solutions for further reduction of PM mass emissions. One solution can utilize next generation state-of-the-art engines (e.g., start-stop system where the ICE automatically shuts down and starts up at idle) with optimized fuel injection strategies (e.g., spray-guided central injector) at nearly no net cost increase. The second solution employs post-combustion control in the form of the gasoline particle filter (GPF) at an additional cost. In general, for reducing PM emissions, industry is focusing on the areas of fuel system component improvement (e.g., mixture

formation) and on control strategies (e.g., injection timing and injection splitting). Additional discussion on cost is provided later in this document in the PM Benefits and Impacts section.

A GDI engine achieves higher efficiency by mimicking a diesel engine. A GDI engine injects gasoline directly into the combustion chamber during the intake stroke of the cycle. A GDI engine can operate in two modes. The first mode is lean-burn stratified charge mode which has excess air in the combustion chamber; a combustible air/fuel ratio only exists in the immediate vicinity of the spark plug. The second mode is stoichiometric homogeneous charge; this mode is the same as a PFI vehicle where the combustion chamber contains a stoichiometric air/fuel ratio and is totally mixed. A spark plug still provides the fuel ignition source. In some cases higher and diesel-like PM emissions can result. The illustration shown in Figure 4 shows the basic chemical makeup of lean-burn GDI PM emissions (Andersson et al., 2009). A GDI engine can generate carbonaceous "soot" or EC, which closely resembles the chemical makeup of the PM emissions from a conventional (i.e., non-DPF equipped) diesel engine. The GDI engine demands precise air/fuel ratio control to prevent over-fueling during cold starts, hard acceleration, and transient operation. A GDI engine incorporates many of the advantages usually associated with a diesel engine. In the homogeneous charge mode, a GDI engine achieves higher efficiency from higher compression ratios, better volumetric efficiency, and lower octane requirements due to charge cooling fuel injection. The fuel mixture used can be at stoichiometric conditions, like a conventional PFI engine, and therefore, not require Selective Reduction Catalyst (SCR) or other forms of NO_X control. The engine can also run in a stratified charge mode and lean-burn condition, which offers some thermodynamic advantages such as no pumping or throttling losses and lower heat loss. However, this mode of operation requires NO_X control. In summary, the technology results in an increase in fuel efficiency and reduction of CO_2 emissions by up to 25 percent.

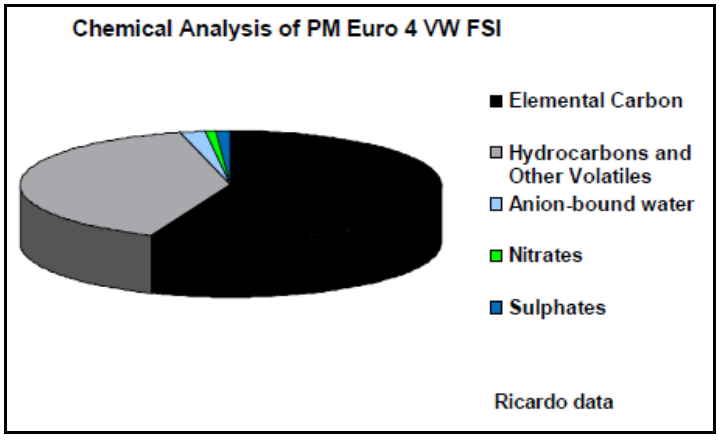


Figure 4. Chemical makeup of PM from a lean-burn spark-ignited GDI engine. Source: Andersson et al., 2009.

The use of GDI technology in production vehicles is not a new approach. In the late 1990s, Mitsubishi, Nissan, and Toyota began limited introduction of vehicles equipped with GDI engines as costs for key system components declined. More recently, these and other manufacturers have started to offer larger numbers of GDI engines, which have lower fuel consumption rates and GHG emissions rates, in response to the increasing public interest in fuel efficient vehicles. This trend is only expected to continue and to accelerate as illustrated in Figures 5a and 5b based on ARB projections and vehicle emission certification database information. The bases for the projections shown in Figure 5a are discussed in detail in the staff's Initial Statement of Reasons (ISOR). The figure is included here for illustrative purposes to convey the point that there is an expectation for an increasing trend in GDI penetration. The certification data shown in Figure 5b supports that trend.

In general, the data available on PM emissions from production vehicles using current generation PFI and GDI technology from a recent study by Delphi Powertrain Systems suggests that, directionally, per-vehicle PFI PM mass emissions are lower than stoichiometric GDI and these, in turn, are lower than lean stratified GDI as shown in Figure 6 (Piock et al., 2011). However, similar to the PFI emissions shown in Figure 2, these per-vehicle data may not reflect the true future fleet-wide average GDI PM mass emissions. For instance, the precise fueling control of the GDI engine may allow for improved PM performance during aggressive driving, reversing the impact seen in the PFI vehicle. Limited data obtained by the U.S. EPA for two current-generation GDI, high-mileage (100,000+) vehicles moderates the results illustrated in Figures 36 and 37 as it shows only a minor increase in PM emission of approximately 20 percent for the US06 cycle relative to FTP results rather than the 17-fold increase found for the PFI vehicles as discussed previously. ARB's test results are discussed in the Feasibility section of this document (section II.A.5).

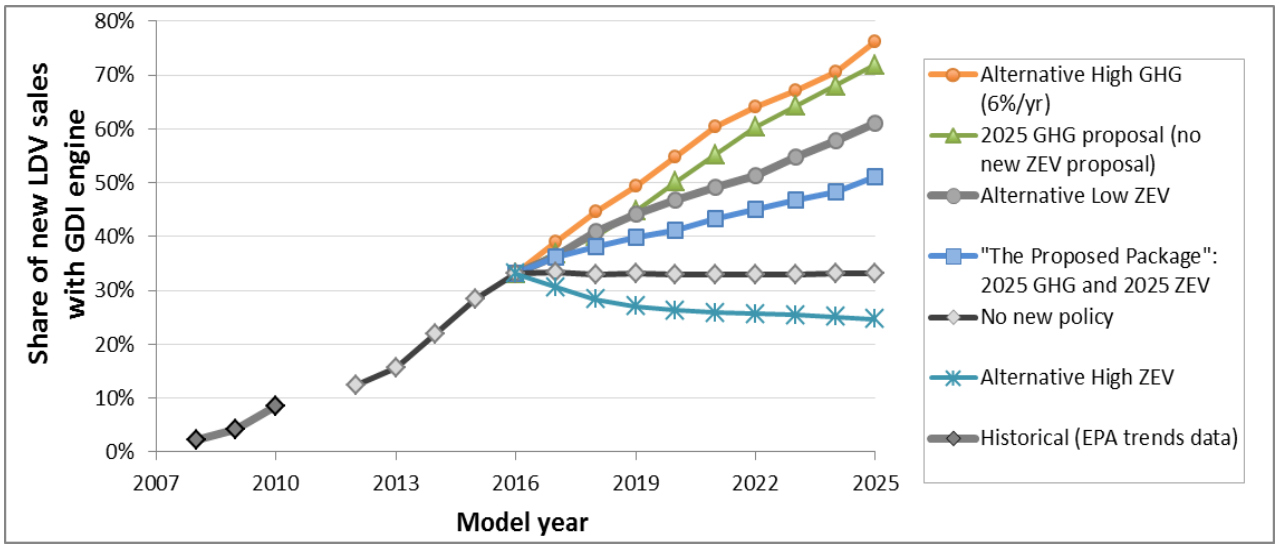


Figure 5a. Trend in GDI penetration in California for various policy scenarios.

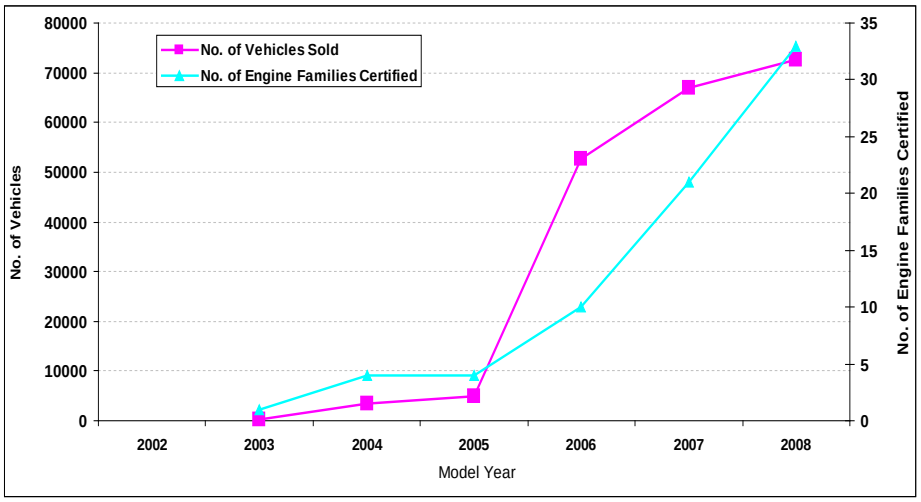


Figure 5b. Number of GDI engine sold in California and the number of GDI engine families certified for California. Information from ARB's certification database. Source: Zhang et al., 2010.

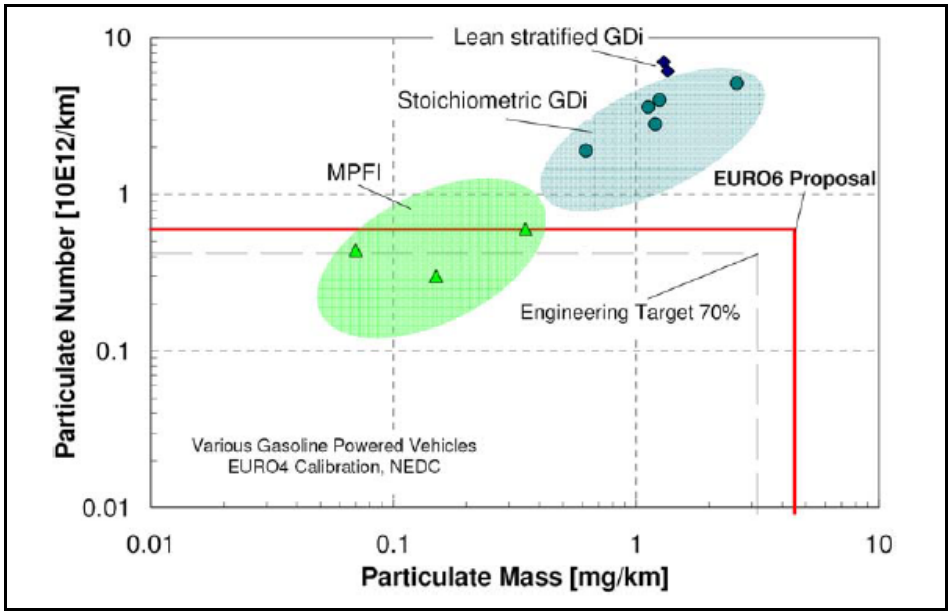


Figure 6. Vehicle emission measured on EURO 4 production vehicles. Source: Piock et al., 2011.

GDI Design

Charge mixture formation is critical in engine design for low PM emissions and non-homogeneity of the mixture charge is a principal concern. PM mass formation in a GDI engine can result from poor, non-homogeneous mixture formation, wall wetting, and a stratified charge. Figures 7 and 8 illustrate the two primary fuel injection schemes for GDI technology. The first, wall-guided GDI, uses the top of the piston and the cylinder wall to define the shape of the fuel spray. Therefore, wall-guided

GDI is simpler to design and cheaper to implement. But it can also result in wall-wetting and, hence, higher PM emissions. When fuel hits the cold cylinder walls of the combustion chamber, it can add to the non-homogeneity of the charge and lead to fuel pyrolysis and the formation of solid EC particles. High exhaust OC can occur if organic material separates from the cylinder walls during blow-down. Recent ARB testing of a limited number of vehicles with current wall-guided GDI technology suggests PM mass emissions levels on the order of 5 mg/mi on the FTP cycle.

Spray-guided GDI, also referred to as "jet" guided or "center-mounted" GDI, uses the design of the injector to control the shape of the spray. The injector is centrally mounted and located above the piston, which is similar to a diesel engine design. The resulting hollow cone of injected fuel avoids contact with the cylinder walls and leads to higher thermal efficiency and generally lower PM emissions. Spray-guided GDI can be a more complex system and a more expensive option if it requires engine block redesign. The same ARB testing referenced above determined spray-guided GDI nominal PM mass emission rates on the order of 1 mg/mi to 3 mg/mi. Both wall-guided and spray-guided GDI approaches increase power and lower carbon emissions relative to conventional PFI, but the spray-guided GDI option appears to be the preferred core technology in next generation engine designs, including those bound for the California LDV market. PFI, with optimization improvement (e.g., start-stop) will continue to play a key role in the low cost gasoline engine market segment.

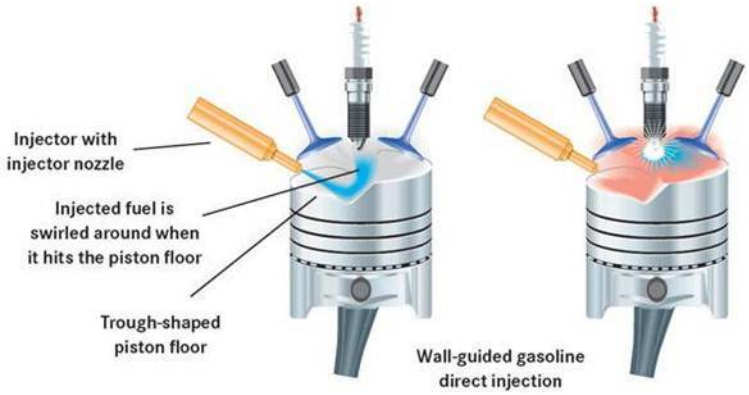


Figure 7. Wall-guided GDI
Source: http://www.greencarcongress.com/2006/02/mercedesbenz_pr.html

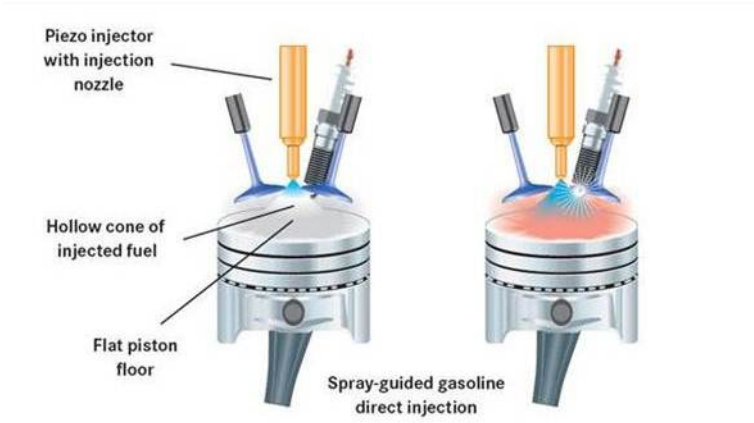


Figure 8. Spray-guided GDI
Source: http://www.greencarcongress.com/2006/02/mercedesbenz_pr.html

Boosting and Engine Downsizing

Turbocharging can effectively enable greater engine performance and/or downsizing. A turbocharger operates by drawing in ambient air and compressing it before introducing it into the intake manifold. This improves the engine's volumetric efficiency. The power needed to drive the turbocharger's compressor is derived from the engine's exhaust gases. Improved fuel efficiency from a turbocharger results from recovering a portion of the otherwise wasted thermal energy in the exhaust gas and improved combustion efficiency from a higher air density charge. One example of this commercially available technology comes from Ford Motor Company (Ford). Ford recently introduced EcoBoost engines that combine GDI, a downsized engine, and turbocharging (see Figures 9 and 10). EcoBoost, Ford's marketing term, is a good example of the potential for GDI turbocharged engines with greater fuel economy, power, and torque than conventional, PFI engines. The added cost of EcoBoost, generally stated in news reports is on the order of $700 over a conventional engine for a light-duty truck application and is offset by the improvement in fuel economy. The typical payback period at current fuel prices could be less than 2 years.

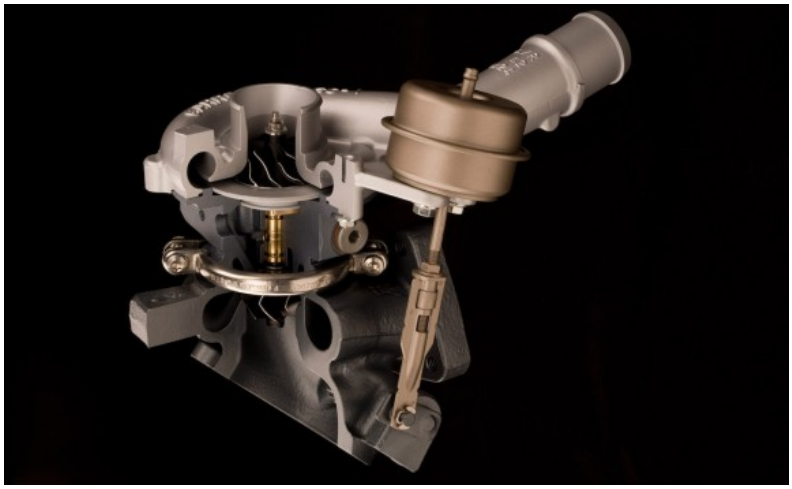


Figure 9. Ford EcoBoost turbocharger
Source: Car and Driver
http://www.caranddriver.com/features/08q3/five_fuel-saving_technologies-feature/gallery/ford_ecoboost_turbocharger_photo_20

Figure 10. Ford EcoBoost 4-cylinder engine
Source: Truck Trend
http://www.trucktrend.com/autoshows/coverage/163_2009_frankfurt_motor_show_2010_ford_cmax_ecoboost/photo_02.html

Advances in Diesel Technology

"Clean" diesel technology (CDT), a marketing term, seeks to optimize a diesel engine's efficiency by enriching the air/fuel mixture with added oxygen to form more

complete fuel combustion. CDT uses a common rail system (Figure 11) to supply fuel through fuel injectors at the same elevated pressure. A chemical membrane, held across a pressure differential, is used to separate the air stream into nitrogen-rich and oxygen-rich streams. Because oxygen dissolves and diffuses faster than nitrogen, oxygen-rich air is injected with the fuel. The common rail system then applies multiple injections per cycle so that timing and fuel flow are optimized for more complete fuel combustion. The injectors, which are mounted above each piston within the cylinder head, are accurately timed by a computer to precisely spray the fuel in finer quantities and result in improved atomization. The common rail system also decreases fuel variation between injectors because all are held at the same pressure. This results in more fuel that can be burned per each engine stroke and less is wasted. The net effect is that fuel consumption is lowered. The CDT engine is therefore more efficient and reduces overall PM and NO_x. CDT engines have shown increased engine performance, power, and fuel efficiency.

Research has shown that oxygen-enriched fuel mixture normally results in higher NO_x emissions. However, the clean diesel technology with the common rail system moderately increases the oxygen content so that an optimized fuel mixture is created. This results in less fuel that is not burned in the cylinder and wasted. The use of more fuel burned per stroke results in a reduction of NO_x per engine cycle.

Another benefit of CDT is that it does not require a redesign of the engine. It can be retrofitted on existing vehicles which does not require additional resources from the car itself. CDT is also relatively inexpensive and with the added fuel efficiency can be cost effective.

CDT vehicles are currently used in Europe as a way to meet stringent emissions standards. Not only are CDT vehicles fuel efficient and cleaner, but they are more powerful than hybrid vehicles. Volkswagen, Audi and Mazda have vehicles or plan to introduce vehicles in the American market that utilize CDT.

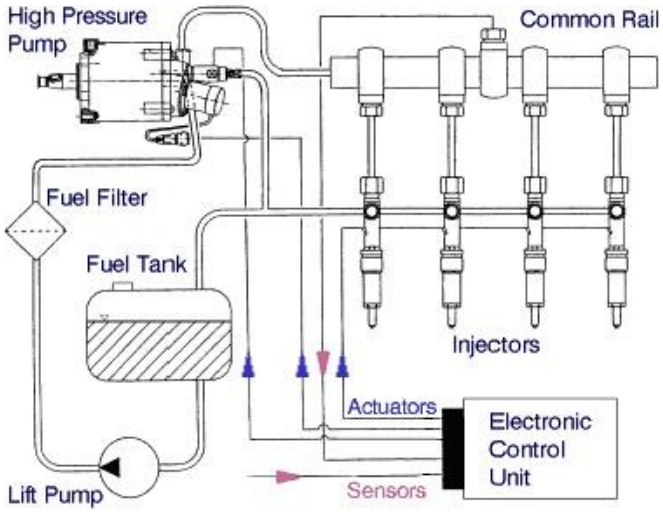


Figure 11. Common rail system
Source: Perkins Engines Company Limited
http://www.perkins.com/cda/components/fullArticle?m=114301&x=7&id=402734

Hybrid and Plug-in Hybrid Technology

Hybrid technology combines two different power sources, the ICE and an electric motor. It increases thermal efficiency and lowers GHG emissions from vehicles with power sources whose efficiency changes with power output, including ICEs that are commonly used in vehicles. Hybrid technology moderates engine load and, therefore, lowers overall PM emissions. In a fully-integrated hybrid, the electric motor is nearly the same size as the ICE and can be exclusively used to power the vehicle at low speeds. In other versions of hybrid vehicles, where the ICE is larger than the electric motor, the electric motor is used to "assist" the ICE during higher loads and optimize low load conditions (ARB, 2004).

The electric motor is powered by a large battery normally located near the rear of the vehicle. Currently, most hybrid vehicles use nickel metal hydride (NiMH) batteries. However, lithium-ion batteries provide an extended cycle life over the NiMH batteries and are expected to be cheaper because they have a higher energy density. With more energy density, the lithium-ion battery will deliver more power with less material (ARB, 2007). Some automakers are considering the lithium-ion battery as a lower cost alternative (Hyrbidcars.com, 2010). Although still relatively expensive, the fuel cost savings over the life of the vehicle is expected to offset the battery costs.

Newer hybrid technology vehicles may increase their fuel efficiency through a Power Split Transmission (PST) in place of a traditional transmission. The Toyota Prius, for instance, uses a planetary gear set that acts as a continuously variable transmission (CVT) but with a fixed ratio. The PST in the Prius allows the sharing of power between the electric motors and ICE combustion engine so that the ICE is running at its most efficient rate. The on-board computer determines the most efficient rate and

compensates by running the electric motors when it determines that the ICE does not need to be run. The Prius PST is shown in Figure 12.

Hybrid technology also takes advantage of dissipative energy sources with regenerative braking. Normally, kinetic energy is dissipated through heat from friction as brakes are applied to the brake rotor. However, regenerative braking uses coiled wires and magnets to induce a current in the opposite direction of the battery, and the change in current direction charges the batteries thus increasing its energy storage. The added charge improves the overall energy efficiency of the vehicle.

A variation of hybrid technology utilizes additional batteries to store electrical energy from the grid to power a vehicle's electric motor. Plug-in hybrids (PHEV) are charged while the vehicle is not in use. The additional battery capacity allows the vehicle to be operated solely on battery power over a greater distance than a traditional hybrid vehicle. The vehicle's range under battery-only operation can be as high as 35 miles depending on battery energy storage capacity. Less dependence on the ICE for propulsion or charging lowers overall PM emissions. This technology is also described in more detail in the staff's ISOR. The plug-in hybrids are also cost effective. The cost of the relatively small battery pack is offset by the lower operating cost of the vehicle (ARB, 2007).

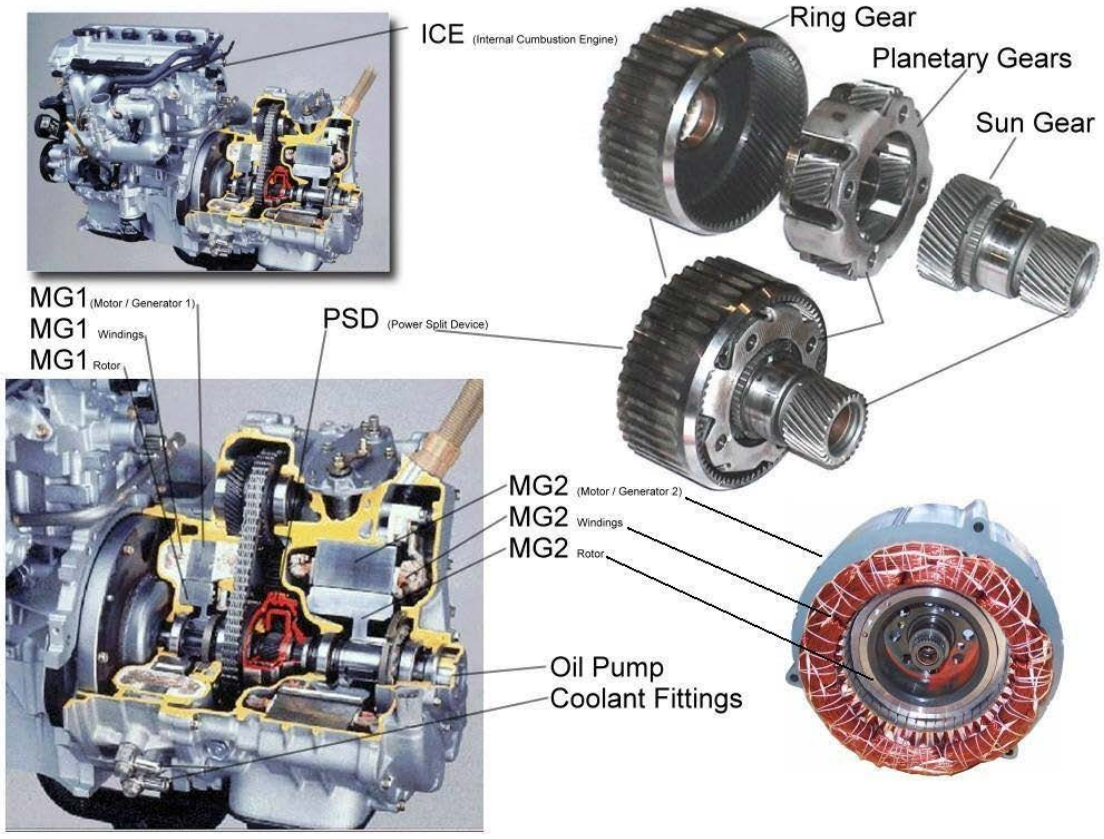


Figure 12. Toyota Prius power split transmission
Source: Oak Ridge National Laboratories

Zero Emission Vehicles

Zero emission vehicles (ZEV) refer to vehicles that emit no PM emissions. ZEV can encompass a wide variety of types of vehicle technology. The two most common types of ZEV are hydrogen fuel cell technology and battery electric vehicles (EV). In 1990, ARB adopted the ZEV program to incorporate ZEV into commercial production to significantly reduce the environmental impact of light-duty vehicles. ARB has been actively working to promote ZEV technology with its ZEV program and regulatory activities to date. ARB is also co-founder of the California Fuel Cell Partnership Program that promotes commercialization of fuel cell vehicles.

Hydrogen Fuel Cell Technology

Hydrogen fuel cell vehicles use hydrogen that is compressed into a fuel cell to produce electricity for powering a vehicle. Fuel cell technology uses the electric current created from a chemical reaction between hydrogen and oxygen. As the hydrogen is passed through the vehicle, it reacts with a catalyst to disassociate the positively-charged ions (protons) from the negatively-charged electrons of the hydrogen atoms. The positively charged ions then pass through a Proton Exchange Membrane (PEM) which impedes the electrons to the cathode. The electrons must then follow a path of a circuit to the cathode creating electric current to power the electric motor. Once the electrons arrive at the cathode and their electric potential energy is used, the hydrogen ions combine with oxygen to form water. A diagram of the fuel cell technology process is shown in Figure 13. However, the power provided from this cell alone is not enough to power a car and therefore multiple cells must be used. Any excess hydrogen that does not pass through the PEM will be re-used and directed through the PEM again.

Fuel cell vehicles have the potential to reduce our dependence on oil and reduce harmful environmental impacts. Since the by-product of the fuel cell process is only water vapor and heat, there are no pollution impacts with the emissions of hydrogen fuel cell vehicles. Also, fuel cells are roughly 68 percent efficient compared to nearly 19 percent for ICE (CAFCP, 2011) so less energy is wasted in the conversion to vehicle power.

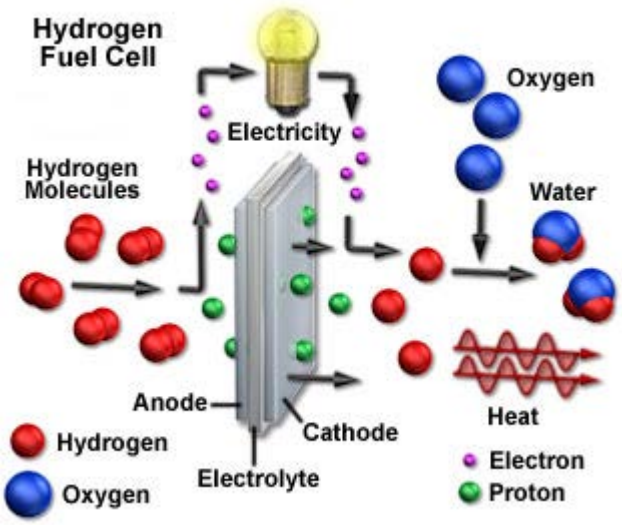


Figure 13. Hydrogen fuel cell process
Source: Microscopy Resource Center
http://www.olympusmicro.com/primer/java/fuelcell/

Hydrogen gas can be extracted from multiple means, such as from methane or fossil fuels. Research has been done to investigate solar energy as a way to re-disassociate water to hydrogen and oxygen with chemical catalysts (Rodríguez-Castellanos, 2007). This is done through electrolysis where an electric current created by the solar panel is sent through an anode into water creating hydrogen and oxygen gas. Another possible hydrogen source is through photosynthesis or artificial photosynthesis where water disassociation is done by biological means.

Battery Electric Vehicles

Similar to the PHEV, the battery electric vehicle uses a set of rechargeable batteries to power an electric motor. However, unlike a PHEV, the electric vehicle is solely powered by electricity. It uses a large set of batteries to store enough voltage to power a car. A diagram of the components of a battery electric vehicle is shown in Figure 14. To control the speed of an EV, the gas pedal is hooked up to a potentiometer so that the current to an electric motor is controlled. Depending on the amount of current released, the electric motor will speed up or slow down. EVs are commercially available and nearly every manufacturer has developed an EV.

Newer EVs have longer ranges and can travel significantly further on a single charge. Some electric vehicles can travel from 100 to 200 miles on a single charge. The EV provides convenience in the fact that it can be charged from a home electrical outlet. In addition, car manufacturers are planning to set up chargers at airports, highways, gas stations and shopping centers to make charging an EV more accessible. Unfortunately, it can take hours to charge the batteries as opposed to minutes to fill a car with gas. However, some EVs have fast charge systems, where batteries can be charged up to 80 percent in 30 minutes. Also, the battery packs can add weight to the vehicle. Battery materials and technology are constantly improving. Weight and

battery charge time is expected to be reduced with newer technology. For further discussion on electric vehicle batteries, see the PHEV section in this TSD.

Another benefit with the battery electric vehicle is that is does not need the same level of maintenance as an ICE. It does not require oil changes or smog tests or even major tune-ups that can be costly as a vehicle ages. The cost to charge an electric vehicle is also significantly lower than filling a car with gasoline. The cost to drive an electric vehicle is roughly 2 cents per mile as opposed to 12 cents for vehicles with an ICE.

Although no direct emissions are produced from the electric vehicle, most of the electricity used at power outlets is generated at fossil fuel burning power plants. The zero emissions from the vehicle are therefore offset by the emissions generated at power plants. However, with innovations in solar technology efficiency and renewable energy sources, there is expected to be less dependence on fossil fuel burning factories for EV so that emissions can be significantly reduced.

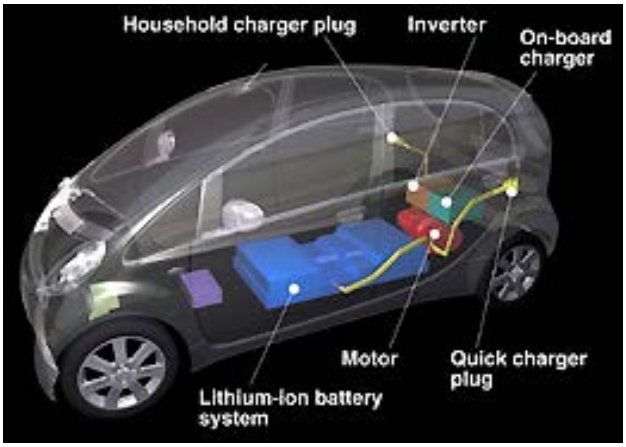


Figure 14. Electric vehicle components diagram
Source:
http://thefraserdomain.typepad.com/energy/2006/10/mitsubishi_i_mi.html

Particle Filtration for GDI Engine Applications

Particle filtration for a GDI engine via the use of a GPF is a viable means for achieving the desired PM emission reductions. The principles of operation and application of the GPF are very similar to that of the DPF, which has been extensively researched and reported on in the open, published literature. There are many similarities between GDI PM and conventional diesel PM, but also some important differences. Engine-out diesel PM is composed primarily of EC or soot as illustrated in Figure 15. The remaining fraction of emissions includes the organic components, metals, and ions from the fuel and the lubricant. As shown previously in Figure 4, gasoline GDI PM is also dominated by EC. But the remaining PM fraction is mostly high and low volatility organic compounds.

Most GPF development has occurred in Europe where lean-burn stratified GDI is favored. In addition, Europe has enacted a first-in-the-world regulation limiting the number of solid particles in the emissions (complementing the conventional PM mass limit also enacted) from both LDVs and heavy-duty engines (HDE). There, the GPF is being explored as the key enabling technology to concurrently meet the particle mass and the particle number standards. The GPF can be coated or uncoated and can be integrated into existing engine and TWC configurations. A recent investigation by Dow Automotive Systems found no negative impacts from the use of a GPF in terms of CO_2, NO_X (see Figure 16), and fuel consumption (see Figure 17). At the same time, the GPF evaluated by Dow showed significant PM filtration efficiencies similar to that of a DPF as illustrated in Figure 18. This study is a positive indication of the technical feasibility of the GPF for GDI applications with no significant negative impact on fuel use or other emissions.

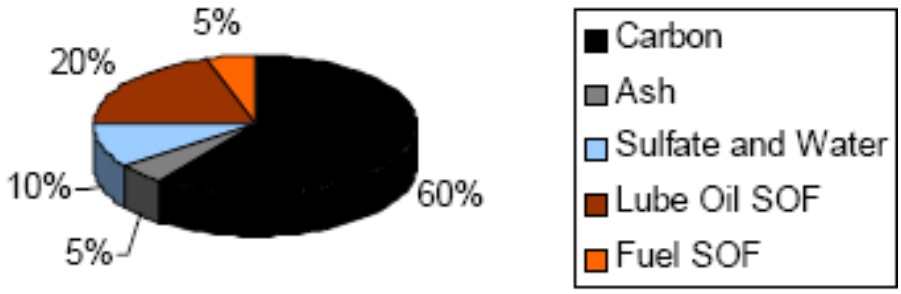


Figure 15. Composition of PM mass emissions from a conventional HD diesel engine without DPF. (SOF – Soluble organic fraction).
Source: adapted from Kittelson, 1998.

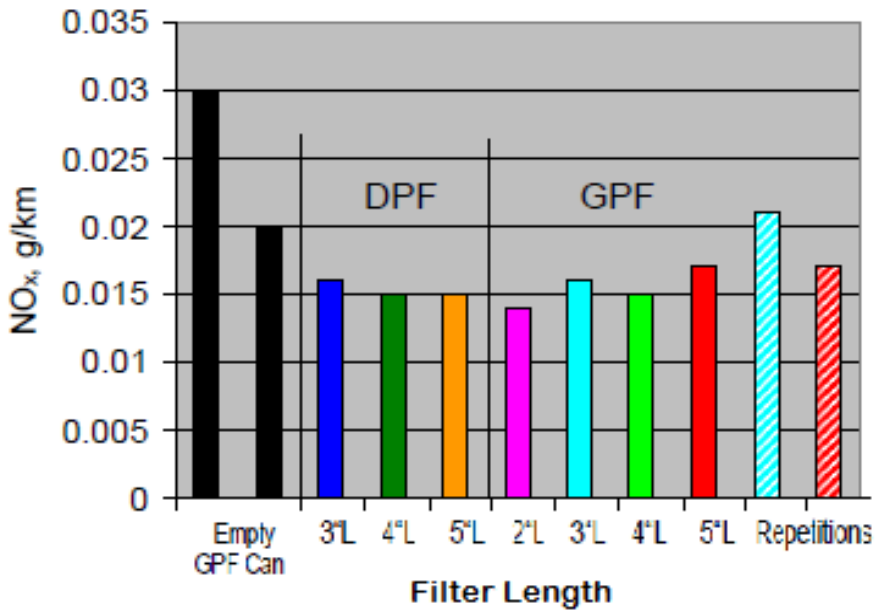


Figure 16. NO_X emissions comparison over the New European Driving Cycle from Dow Automotive Systems study of GDI particle filtration. Source: Mikulic et al., 2010.

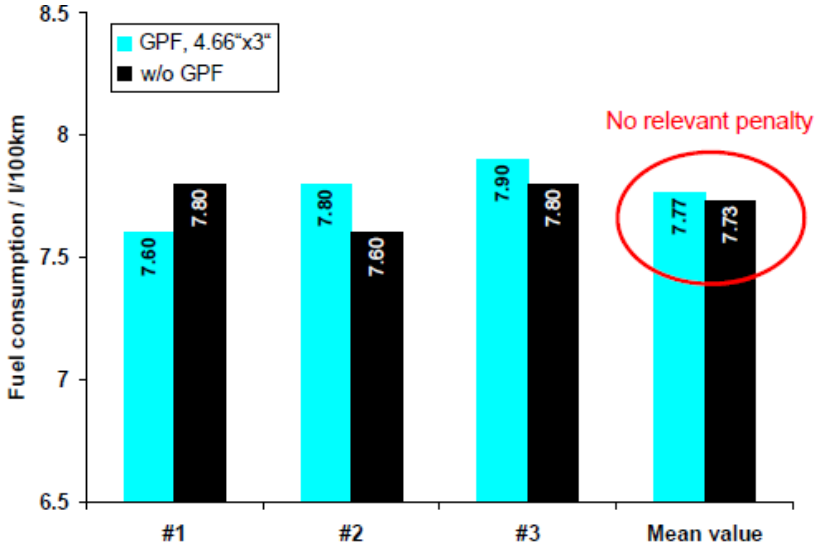


Figure 17. On-road fuel consumption from Dow Automotive Systems study of GDI particle filtration where no relevant penalty in average consumption with the use of a GPF was observed. Source: Mikulic et al., 2010.

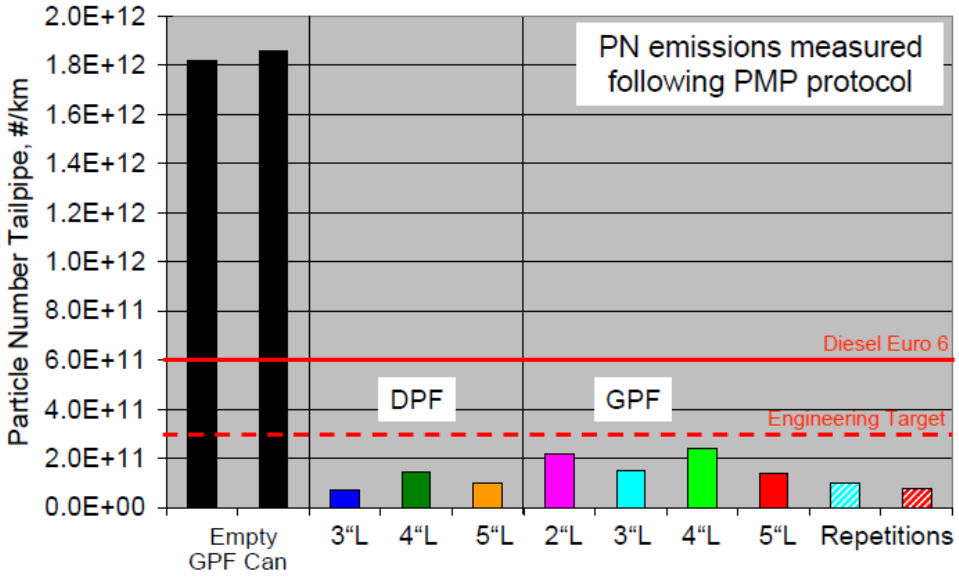


Figure 18. Tailpipe solid particle number emissions over the NEDC from Dow Automotive Systems study of GDI particle filtration. Source: Mikulic et al. 2010.

The DPF and Ultralow PM Emissions

The diesel engine is the most commonly applied engine for large, heavy-duty vehicle applications in California and has a proven track record of durability, superior torque performance, and high thermal efficiency. Today, there are more than 11 million engines in use in the U.S. and more than 12 percent of those are in use in California. A diesel engine can have 20 percent to 40 percent better fuel economy than a comparable gasoline engine, hence lower CO_2 emissions. However, high PM and NO_X emissions have been a notable challenge before the advent of improved combustion design, low sulfur fuel, exhaust gas recirculation, the DPF, SCR, and other technological advances. Combustion in a diesel engine produces high levels of PM because it is a diffusional process and the fuel has a low vapor pressure and a low octane number. In diesel combustion, a heterogeneous mixture of fuel is injected into hot, compressed air resulting in fuel rich/oxygen deficient regions where the fuel can break down before combustion pyrolyzing and readily forming EC, or soot. Diesel engines produce high NO_X because they run lean and have high combustion temperatures and pressures. To control PM and NO_X, new modern diesel engines use internal or external measures. Internal measures include improved combustion and engine design while external measures include the use of aftertreatment. Filtration, oxidation, and reduction are used for the control of PM and NO_X and the efficiencies of each of these processes in HDE applications are well documented. In filtration applications, a DPF can reduce PM emissions upwards of 95 percent. Reduction of NO_X via SCR can yield reductions of 80 percent. Modern MDV diesel engines use both aftertreatment devices to meet emission standards. Diesel powered vehicles configured with a DPF can yield very low PM mass exhaust emissions, well in the sub-10 mg/mi range as a recent ARB study of various heavy-duty diesel retrofit devices has determined (see Figure 19).

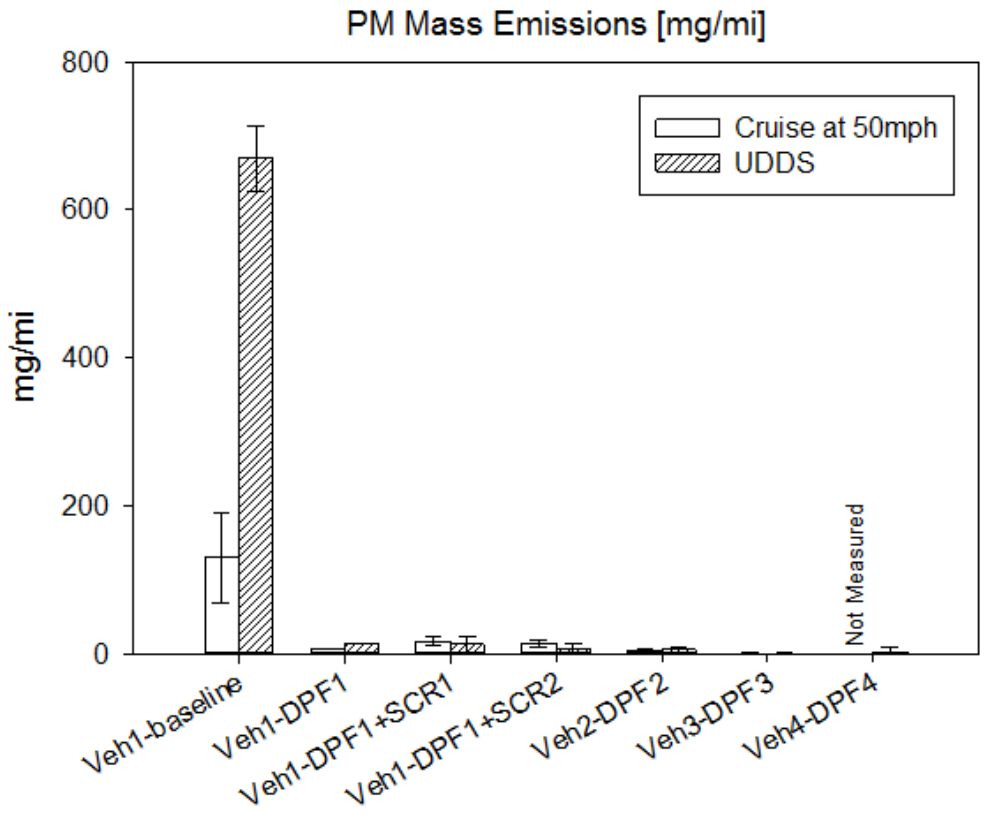


Figure 19. PM mass emissions measured for various types of diesel PM retrofit devices used in HDE applications in an ARB study.
Source: Herner et al., 2009.

Use of Alternative Fuels to Lower PM Emissions

Several other transportation fuels and technologies are also viable options for achieving GHG and criteria emission reductions. They have been extensively researched and analyzed. The State has an alternative fuels plan for increasing the use of non-petroleum fuels; focusing on key actions needed for progress in various areas including fuels and vehicles. Alternative fuels such as compressed natural gas (CNG) and liquefied petroleum gas (LPG) have a clear presence in the California vehicle fleet, both for LDV and HDE use, albeit in relatively small numbers. A CNG vehicle is an effective option to achieve reduced NO_X and PM emissions, and it also has lower CO_2 emissions than a comparable gasoline vehicle. Similarly, LPG offers some combustion and GHG benefits. In general, the current emphasis on efficiency, lower GHG impacts, and less reliance on foreign petroleum is promoting progress in many other areas: renewable diesel and biodiesel to replace conventional diesel, gasoline blended with 85 percent ethanol (E85) for flexible fuel vehicle use, and hydrogen powered vehicles, among others. E85 vehicles emit lower CO_2 emissions per mile and although they may consume more fuel due to the fuel's lower energy content, they do provide a net GHG benefit. With the growing interest in low carbon fuels, alternative fuels for transportation are expected to gain a growing share of the vehicle fleet.

Biodiesel

Biodiesel is an alternative fuel that is produced from products of renewable, domestic resources. Biodiesel is made through transesterification of methanol with fats and oils. Transesterification is the process of a triglyceride (fat/oil) reacting with an alcohol (methanol) to form esters and glycerin. The advantage of biodiesel is that compression-ignition engines can use biodiesel of any blend without significant modifications to the engine itself.

Biodiesel can be produced from plants or animals, which are substantial and sustainable resources. Most of the biodiesel produced in the U.S. is soybean oil or recycled cooking oil. However, biodiesel can be made from any type of feedstock material such as corn oil, sunflower oil, peanut oil, and animal fats. Biodiesel is also beneficial for diesel engines. Deposits left from conventional diesel gasoline are dissolved by the biodiesel resulting in cleaner and more efficient fuel systems. Fuel filters are not clogged from sediment and deposits.

Studies have shown a direct relationship between PM emissions and various blends of biodiesel. In 2002, the U.S. EPA performed a study on the emission effects of heavy-duty highway engines with different concentrations of biodiesel. Figure 20 shows the emissions effects with different blends of biodiesel. The results indicated a decrease in PM emissions with an increase in biodiesel blend (U.S. EPA, 2002; Graboski, 2003). Although conventional diesel can be blended with any percent of biodiesel, the most common blend is 20 percent biodiesel and 80 percent conventional diesel. Also shown in Figure 20, a 20 percent blend biodiesel reduces PM emissions by about 10 percent. However, Chien et al. (2009) indicates that although PM mass decreases with increased biodiesel blends, concentrations of ultrafine and nanoparticles increase. Graboski et al. (2003) also indicated that NO_x emissions may increase with biodiesel blends. Graboski (2003) concluded that NO_x emissions are dependent upon the characteristics of the type of fatty acids in the fuel. For example, unsaturated fatty acid chains produce significantly higher NO_x emissions than those that are more saturated.

Durbin et al. (2009) has conducted a comprehensive study of biodiesel and other alternative diesel fuels to better understand and, to the extent possible, mitigate any impact that biodiesel has on PM and NO_x emissions from diesel engines. The testing included a baseline ARB ultralow sulfur diesel (ULSD) fuel, two biodiesel feedstocks (one soy-based and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a gas to liquids (GTL) diesel fuel tested at 20%, 50%, and 100% blend levels.

Engine dynamometer testing was conducted on two on-highway heavy-duty engines, a 2006 Engine without DPF (2006 Cummins ISM) and a 2007 Engine with a DPF (2007 MBE4000). The results (Figure 21) demonstrated consistent and significant reductions of PM for the biodiesel blends for the engine without a DPF, i.e., the 2006 Engine, with the magnitude of the reductions increasing with blend level. For the DPF-equipped 2007 engine, the PM emissions were all well below certification limits and the emission levels for the 2006 Engine. For the most part,

PM differences between fuels were not statistically significant. Consistent and significant reductions of PM emissions were also observed for the chassis dynamometer testing of a 2000 Caterpillar C15-equipped Truck (without DPF, as shown in Figure 22), which were similar to or greater than the reductions seen in the engine testing for the non-DPF equipped engine for most testing combinations.

Besides the increase of NO_x emissions, biodiesel is facing additional obstacles before it can gain wide acceptance. These include lower energy density, current higher costs than conventional diesel, and a higher gel or freeze point than diesel, which poses added challenges for the fuel delivery system in colder climates. In general, biodiesel is a viable option for reducing PM and other pollution.

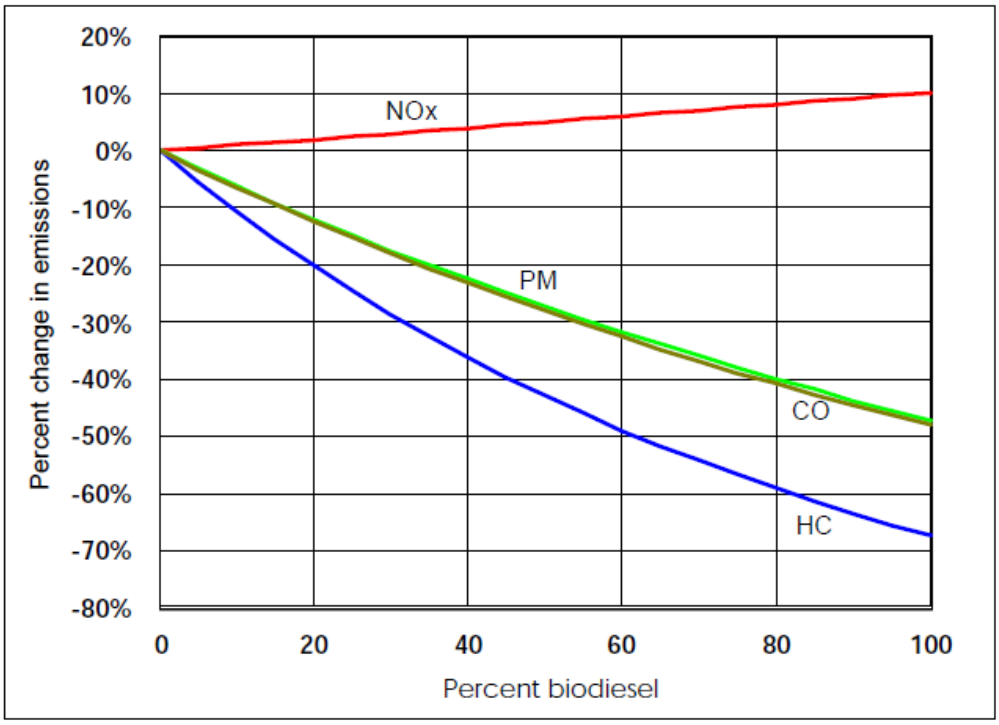


Figure 20. Average emission impacts of biodiesel for heavy-duty highway engines
Source: U.S. EPA. http://www.epa.gov/otaq/models/analysis/biodsl/p02001.pdf

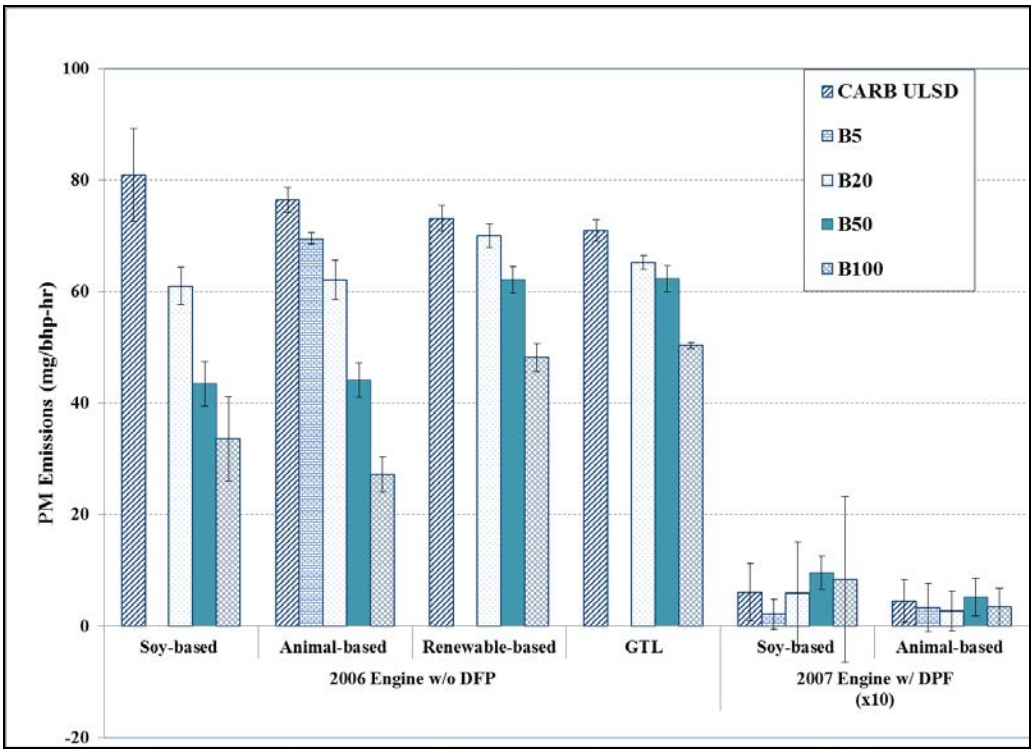


Figure 21. Average PM emission results for a 2006 engine (w/o DPF) and a 2007 engine (w/ a DPF) fueled with different blend of biodiesel, renewable diesel and GTL during FTP cycle. Source: Durbin et al., 2009.

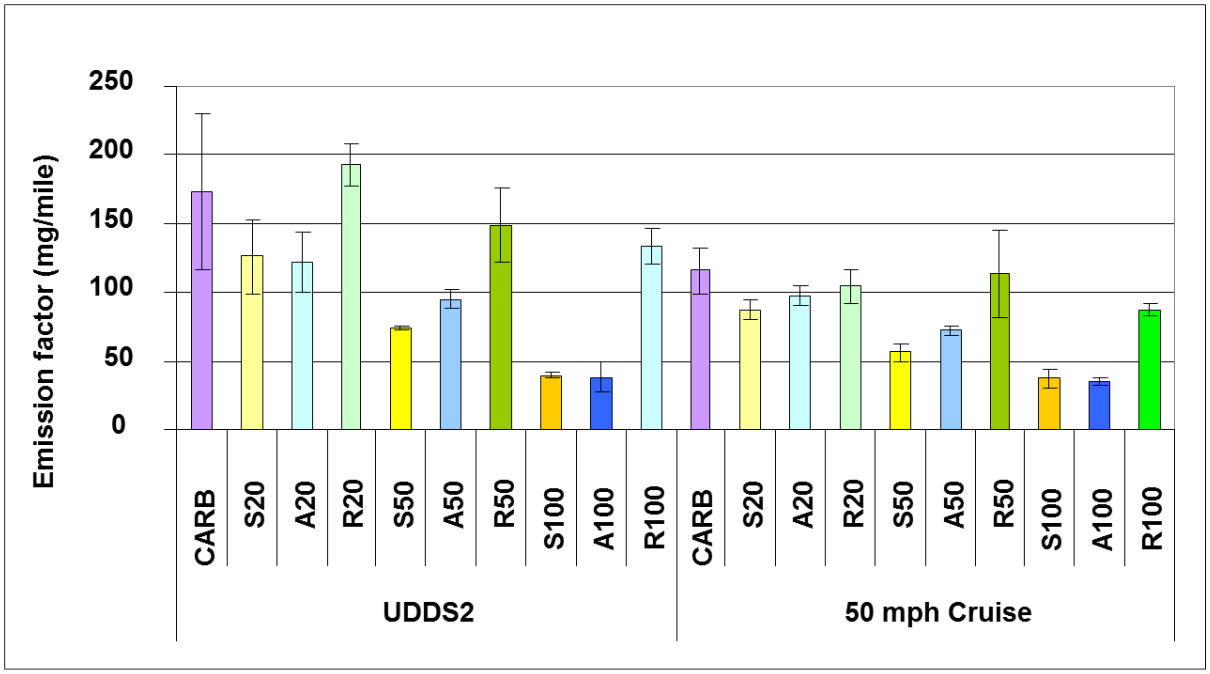


Figure 22. Average PM emission results for a 2000 Caterpillar C15-equipped Truck fueled with different blend of biodiesel and renewable diesel during UDDS and Cruise cycles. Source: Durbin et al., 2009.

Multiple Solutions for Reducing Vehicular PM Emissions

Ford has recently offered a general comparison of PM emissions (presented in terms of PM mass and particle number) for several relevant LDV engine technologies. This comparison is shown in Figure 23. According to Maricq (2009), the highest PM emissions come from diesels engines, followed by GDI, then DPF-equipped diesel, PFI, and finally CNG. Again, this is an illustration of what is possible with various technologies in terms of PM performance rather than an indication of actual average in-use fleet-wide emissions. Visual examples of the differences in PM emissions from PFI, GDI, conventional diesel, and DPF-equipped diesel vehicles are shown in Figure 24. These are filter media samples collected in the laboratory during testing conducted by ARB for gravimetric analyses. The carbonaceous nature of PM from conventional diesel and GDI PM mass emissions is evident. In contrast, PFI and DPF-equipped PM emissions are not discernable by visual inspection as the filter samples appear to be in their original, clean, and unused condition.

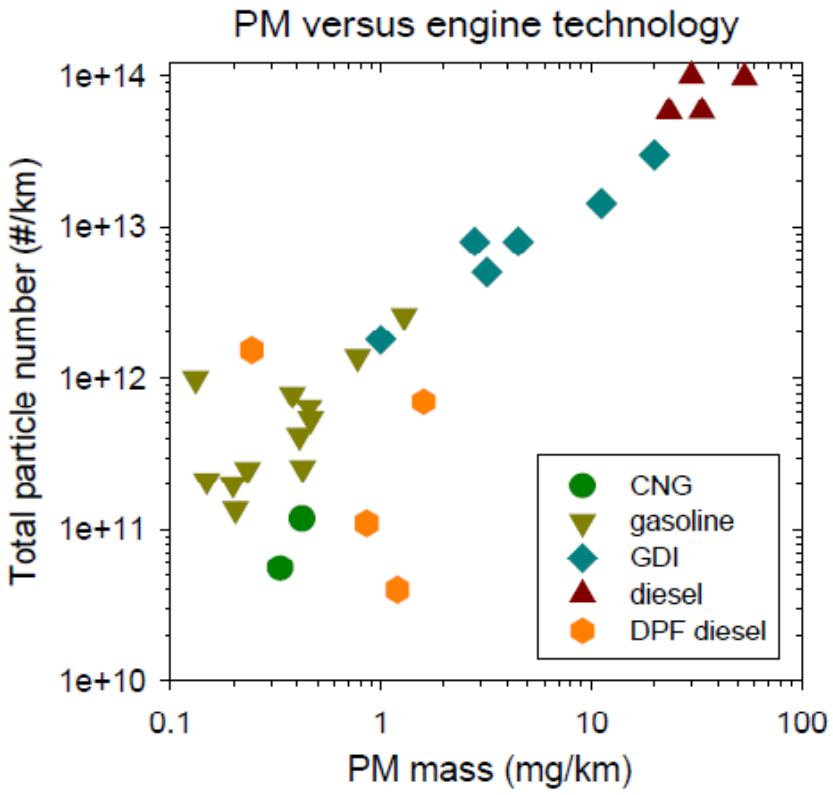


Figure 23. PM mass and particle number emissions for various LDV engine technology. Source: Maricq, 2009.
http://www.healtheffects.org/Slides/AnnConf2009/Maricq.pdf

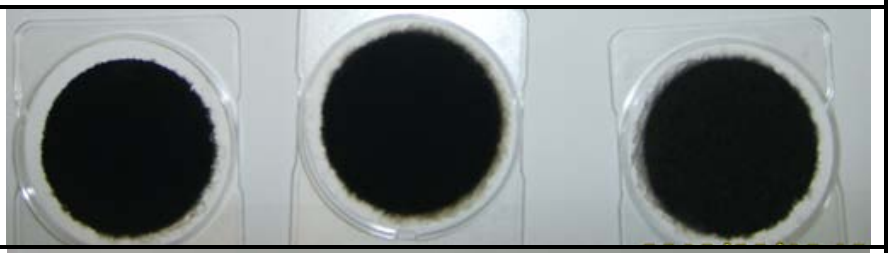
	Phase 1	Phase 2	Phase 3
Conventional Diesel			
LEV II GDI			
LEV II PFI			
DPF-equipped Diesel			

Figure 24. Visual comparison of PM filter samples for various LDVs. The phases refer to the portions of the FTP driving cycle.

3. Existing PM Mass Emissions Measurement Methods

The Conventional PM Mass Test Method

The vehicular emission of PM mass is operationally defined. It is based on precisely prescribed procedures covering vehicle and fuel preparation, vehicle testing protocols including emission sample collection, and the gravimetric determination of PM mass in the laboratory. This method is the original approach for measuring vehicle and engine PM emissions, where much of the early development was driven by the need to understand and control diesel PM mass emissions from HDE applications. The basic approach for determining vehicle PM mass is simple, as

Figure 25 shows. A vehicle or engine is exercised on a dynamometer over a prescribed duty or activity cycle. The entire volume of the vehicle exhaust is directed to a dilution tunnel using ambient air. A small sample of the vehicle's diluted exhaust is collected on filter media and the filter is weighed before and after the test. The difference in the filter weight is the legal definition of PM emissions. Every step of the method is prescribed precisely in regulation and in detail including: conditions for soaking the vehicle or engine, fuel, and lubricant prior to a test; the sequence of steps for conducting the actual emissions test; the sample train to be used prior to collection; the materials used for testing; the environmental conditions during testing; and the protocols for pre- and post-weighing of filter samples. In the past, the copious amount of PM mass emitted by early technology diesel rendered this method very effective because the sample signal was much larger than the measurement uncertainty or "noise" of the method. As diesel PM mass emissions began to decline in response to increasingly more stringent standards, the need for revisions and improvements to the method arose. These improvements began to occur again in the diesel arena, driven primarily by industry initiative and more specifically, in response to new diesel retrofit requirements and the 2007 HDE PM standards - these standards called for 90 percent reduction of PM mass emissions. The resulting wide introduction of diesel soot filtration marked a turning point for the need for improvements in the conventional PM measurement approach.

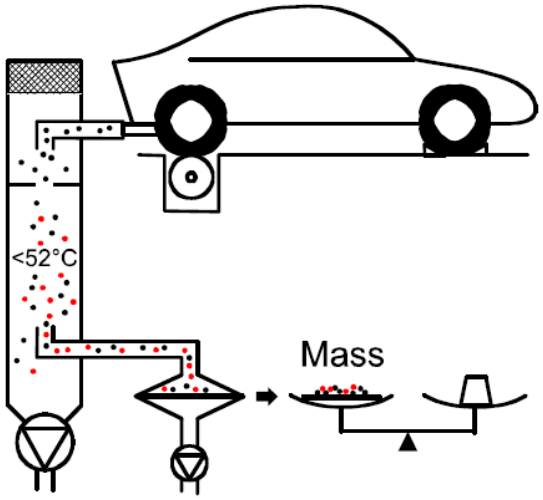
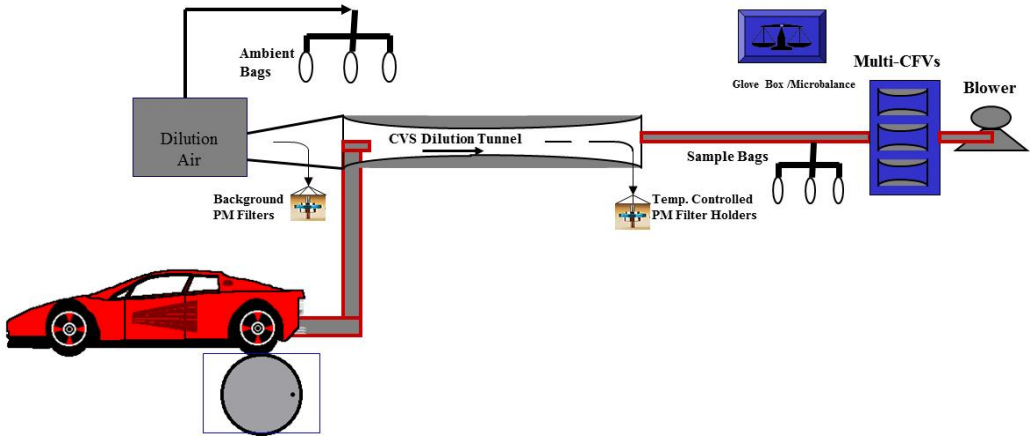


Figure 25. Simple illustration of the gravimetric method for determining PM mass emissions in vehicle exhaust.
Source: Mayer, 2006.

ARB's vehicle testing is conducted in a conventional chassis dynamometer test cell equipped with a Constant Volume Sampling (CVS) dilution tunnel and the associated equipment for gaseous and PM mass emission collection. The sampling system, calculation, calibrations, and quality control for the test cell conform to the requirements of 40 CFR Part 86 and to the improvements made in accordance with to 40 CFR Part 1065. The test cell is dedicated to clean vehicle testing and research and development. The laboratory is equipped for the measurement of

criteria emissions (CO, NO_X, hydrocarbons [HC]) and CO_2 using a Horiba analytical bench. Measurement capabilities also include GHG emissions. The test cell is equipped with a 1.22 m single-roll electric dynamometer and a driver's aid. The CVS tunnel is 0.254 m in diameter, and the total tunnel flow is controlled by a bank of critical flow venturis. Dilution air is room air filtered through a pre-filter, charcoal filter, and HEPA filter. The total tunnel air flow is controlled and is on the order of 400 cubic feet per minute (cfm), or approximately 12 cubic meters per minute (m^3/min). For PM, a temperature controlled (47±5 ^oC) secondary dilution PM filter sampling system at a nominal flow rate of 60 liters per minute (lpm) enables repeatable sampling of low PM filter mass from clean vehicles. The test cell is equipped for additional PM sampling for OC, EC, and metals. A simple graphic of the emissions laboratory layout is shown below in Figure 26a, followed by a corresponding picture in Figure 26b.

(a)



(b)

Figure 26. (a) Side view of ARB LDV emission laboratory setup shown the chassis dynamometer, the CVS dilution tunnel and the PM and gaseous emissions sampling trains. (b) Picture of test cell.

This test cell is also used for the development and investigation of alternative PM measurements such as particle counting. Specifically, this facility supported California's recent efforts on the international Particulate Measurement Programme (PMP) and the exploration of the new solid particle counting method for use for compliance with the European particle number emission limit. Additional details are provided later in this TSD document under the discussion of alternative PM measurements.

Once a PM sample is collected, ARB's PM gravimetric analysis is conducted in an environmentally controlled, dedicated clean room. The clean room is maintained at a temperature of 22±1°C and a dew point of 9.5±1.0°C, and the cleanness meets the Class 1000 Standard as established by the International Organization for Standardization (ISO). The PM sampling media used for vehicle PM emissions testing is a 47 mm Teflon filter with support ring (2 µm pore size, Pall Life Science/Whatman, or equivalent). Filters are equilibrated for a minimum of 30 minutes with the environment prior to carrying out the analysis on a seven decimal microbalance (UMX2, Mettler Toledo, Columbus, OH). The PM emissions are the difference between the pre-test and post-test filter masses, buoyancy corrected. The PM gravimetric analysis procedure is detailed in ARB SOP No. MLD 145 (MLD, 2011).

U.S EPA PM Test Procedures

The historical method for measuring PM mass emissions was contained in 40 CFR Part 86. The method described in 40 CFR Part 86 was subsequently modified by the Engine Emissions Measurement and Testing Committee and resulted in a new PM mass test procedure, 40 CFR Part 1065. The committee, which was collaboration between the industry, the regulatory agencies, academia, and other technical experts, focused exclusively on method revisions in order to improve emission measurement from low emitting engines such as those meeting the most recent and stringent NO_X and PM standards. The method revisions were originally adopted by the U.S. EPA in November 2002 and applied to non-road and stationary spark-ignition engines above 19 kilowatts (kW).

Although originally designed for heavy-duty vehicle PM measurement, the U.S. EPA decided that with the improved accuracy and repeatability of 40 CFR Part 1065, the PM sampling procedures could also apply to light-duty vehicles. In 2004, the U.S. EPA sent a guidance letter that allowed the option of using 40 CFR Part 1065 Heavy-Duty (HD) for measurement emissions from MY 2007 LDV. On May 25, 2006, several automobile manufacturers requested the U.S. EPA allow them the option of using PM sampling procedures in 40 CFR Part 1065 for light-duty vehicle testing in lieu of 40 CFR Part 86 Subpart B. On November 8, 2006, the U.S. EPA approved the request (U.S. EPA, 2006). In the 2006 approval letter, the U.S. EPA provided a list of applicable sections of 40 CFR Part 1065 for PM sampling procedures in light-duty testing. The sections listed in the approval letter include design specifications, testing procedures, equipment calibration procedures, and quality control practices. ARB first referenced 40 CFR Part 1065 in September 2006 during its adoption of the heavy-duty diesel in-use compliance regulation.

Currently, the U.S. EPA has included revisions to 40 CFR Part 1065 with the adoption of the Heavy-Duty GHG rulemaking which was signed on August 8, 2011. This rulemaking includes revisions to 40 CFR Part 1065 and the finalization of a new part for vehicle testing, 40 CFR Part 1066 HD, which applies to chassis certification of vehicles with a GVRW of greater than 14,000 lbs. Revisions included different options for calculating total flow of dilution air, an allowance for background correction, and validation of minimum dilution ratios for PM batch sampling. Also included are new methods for determining warm high-idle speed with a high-speed governor. We expect that manufacturers will be able to easily implement the LDV PM test procedure that U.S. EPA will release as part of their upcoming Notice of Proposed Rulemaking (NPRM) because it will be modeled on 40 CFR Part 1065, which the car manufacturers have already used extensively.

Applicable Test Procedure for Measuring PM Mass Emissions from LEV III LDVs and MDVs

The U.S. EPA is currently in the process of finalizing 40 CFR Part 1066 HD. This version will be the basis for modifications that results in a test procedure applicable to LDVs and MDVs in support of the upcoming Light-Duty Tier 3 NPRM. The modifications will improve the accuracy of measuring PM mass emissions from LDVs and MDVs at the proposed 3 mg/mi level. When U.S. EPA finalizes their Tier 3 emission standards and test procedures for certification of PM mass emissions from LDVs and MDVs, ARB will formally propose to adopt and incorporate U.S. EPA test procedures.

Test Cycles

Vehicle emission limits are prescribed over a specific test cycle. The drive cycle used to exercise a test vehicle on a chassis dynamometer or an engine on an engine dynamometer is one of the most critical elements for testing and determining emissions. The drive cycle is meant to represent the average duty or activity of a vehicle or engine during its normal operation. The drive cycle, by practical necessity, is a compromise or a representative snap shot of the multitude of possibilities of real-world vehicle/engine operation. The two relevant drive cycles that are required for LDV testing and certification are the standard FTP and the Supplemental Federal Test Procedure (SFTP or US06). Emissions tests results presented later will be given primarily for these two cycles. The California Unified Cycle (UC) was used developed by the ARB for ozone reduction strategies and is used for MDVs. The New European Driving Cycle (NEDC) is of interest for comparison to European vehicle emissions. Detailed speed profiles of the four cycles are provided in Figures 27-30.

Federal Test Procedure

The FTP consists of Urban Dynamometer Driving Schedules (UDDS) (see Figure 27). Each UDDS is divided into two portions; the first is a “start” section running for the first 505 seconds. The second portion is a transient section from 506 seconds to

the end at 1369 seconds. At this point the test stops and the engine is turned off. The first UDDS is considered a cold start test because the engine is tested in a "cold" condition. The second UDDS is a post-soak hot start test, which begins with a "hot" engine 10 minutes after the first UDDS ends. For both UDDS cycles it is assumed that the transient portion is the same, so it is not duplicated after the hot start test. The emissions result is a weighted average where the cold start and transient (first UDDS cycle) is weighted at 43 percent and the hot start and transient (equivalent to the second UDDS) is weighted the other 57 percent. The FTP profile is a relatively mild and low load profile. A vehicle is not challenged aggressively over this cycle. Excluding the cold start emissions; the PM emissions measured following the FTP are lower than those measured following the US06 profile.

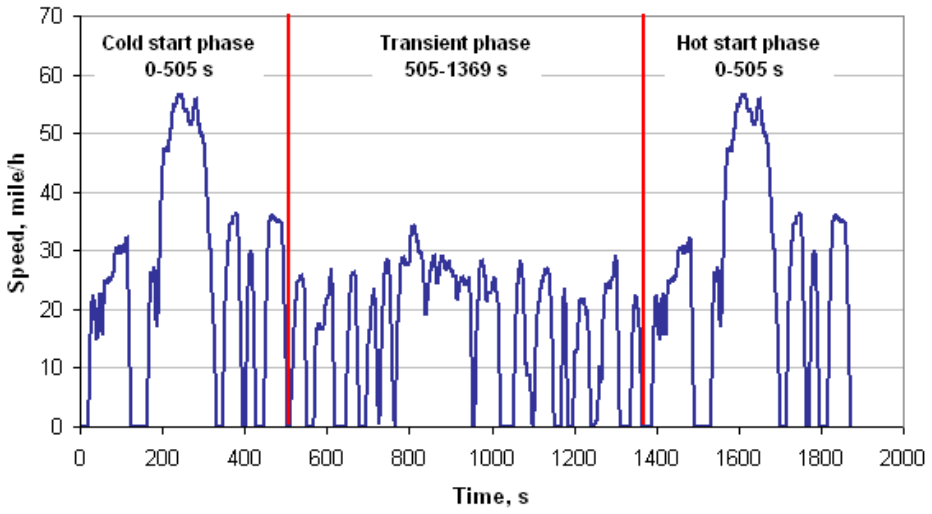


Figure 27. The FTP cycle speed trace.
Source: http://www.dieselnet.com/standards/cycles/ftp75.php

Supplemental Federal Test Procedure (US06)

The US06 was developed to more accurately represent the aggressive, high speed and high acceleration, driving behavior of an average driver today. The US06 driving cycle is shown in Figure 28. It is part of the SFTP and is a hot start test that is usually run following a 10 minute soak once the FTP is finished. The US06 cycle represents an 8.01 mile (12.8 km) route with an average speed of 48.4 miles/h (77.9 km/h), maximum speed 80.3 miles/h (129.2 km/h), and duration of 596 seconds. The higher acceleration and speed of the US06 cycle leads to higher engine loads, which produce more PM emissions. The proposed LEV III regulation requires supplemental PM testing using the US06 cycle, but adjusts the standards to compensate for the cycle aggressiveness.

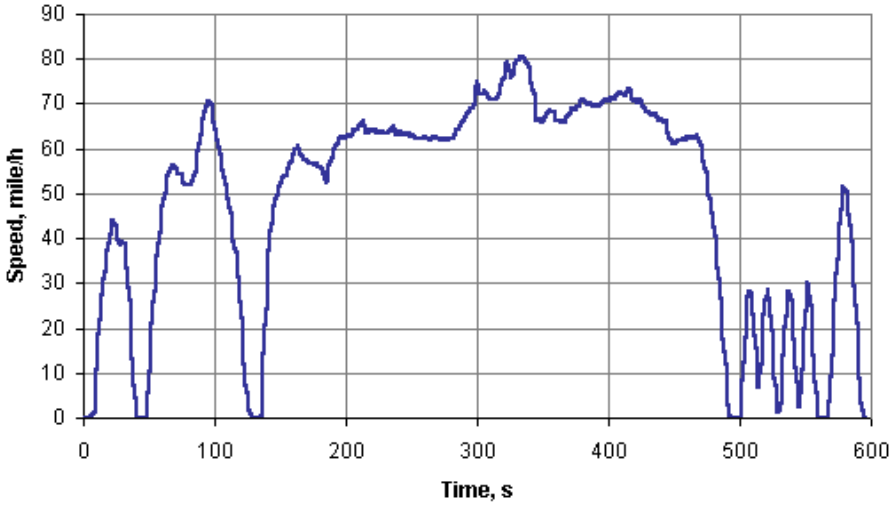


Figure 28. The US06 cycle trace of the SFTP.
http://www.dieselnet.com/standards/cycles/ftp_us06.php

California Unified Cycle

The California Unified Cycle (UC), as shown in Figure 29, is a dynamometer driving schedule for light-duty vehicles developed by the ARB. The test is also referred to as the Unified Cycle Driving Schedule (UCDS). One of the applications of the UC cycle is testing of vehicles fitted with direct ozone reduction technologies (the Supplemental Federal Test Procedure, SFTP, was previously used for that purpose).

The UC test has a similar three-bag structure, but is a more aggressive driving cycle than the FTP; it has higher speed, higher acceleration, fewer stops per mile, and less idle time. The UC test is run in the following manner: Bags 1 and 2 are run consecutively, followed by a ten minute hot soak, then Bag 3 which is a duplicate of Bag 1. Overall cycle emissions are calculated in the same manner as the weighted, overall FTP formula, taking actual mileage from the UC into account.

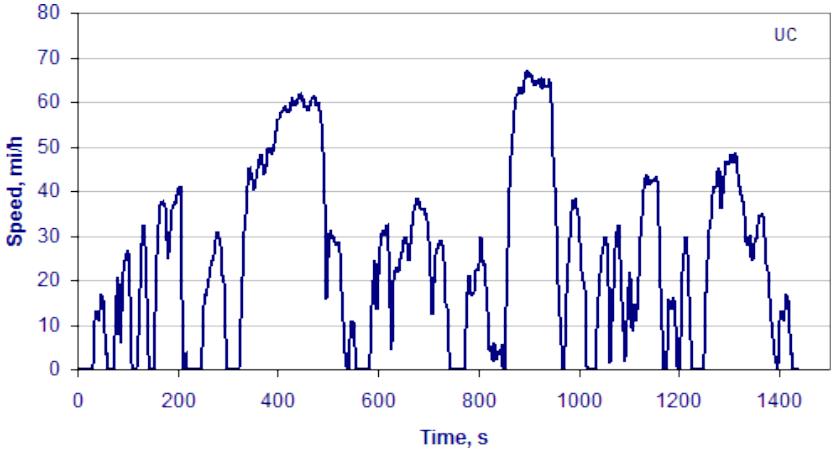


Figure 29. California Unified Cycle
Source: http://www.dieselnet.com/standards/cycles/uc.php

New European Driving Cycle

In Europe and other countries where the European standards have been adopted, the driving cycle for vehicle emissions regulation is the NEDC. The NEDC, as shown in Figure 30, is made up of four Urban Driving Cycles (UDC) followed by one Extra Urban Driving Cycle (EUDC). Similar to the UDDS, the UDC cycle is an urban driving cycle with characteristically low vehicle speeds, low engine loads, and low exhaust temperatures. The EUDC was added to more accurately represent the driving style of an average driver. It is the European counterpart to the US06 cycle. The only difference between the two is that the EUDC is integrated into the NEDC whereas the US06 is not integrated in to the FTP. The NEDC is the same as the European Driving Cycle, but does not allow an initial 40 second idle period. The NEDC is used for vehicle certification in Europe and has lower accelerations and speeds than the FTP. Being a moderately aggressive cycle compared to FTP, a vehicle subjected to a NEDC emits slightly higher CO_2 emissions as indicated by the International Council on Clean Transportation (ICCT, 2011). Dwyer et al. (2010) made a similar finding for CO_2 emissions, but noticed that the NEDC PM emissions are lower than the FTP. Further study has shown (Figure 31) that both the NEDC and FTP cycles have generated substantial amounts of both OC and EC during the cold start part of the cycle. During the latter phases of both cycles, the amount of EC decreases substantially, while OC decreases by a lesser amount. The amount of OC generated in the latter phases of the NEDC and FTP cycles is comparable with OC generated in the cold start part of the cycles, and this implies that semi-volatile and small particles are responsible for the OC in the latter phases.

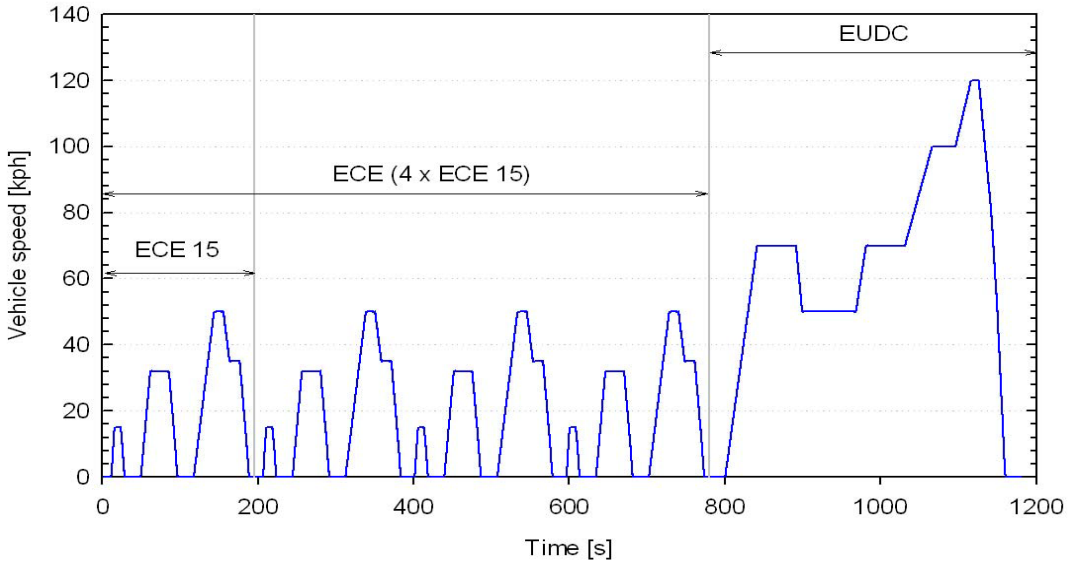


Figure 30. The NEDC cycle trace.

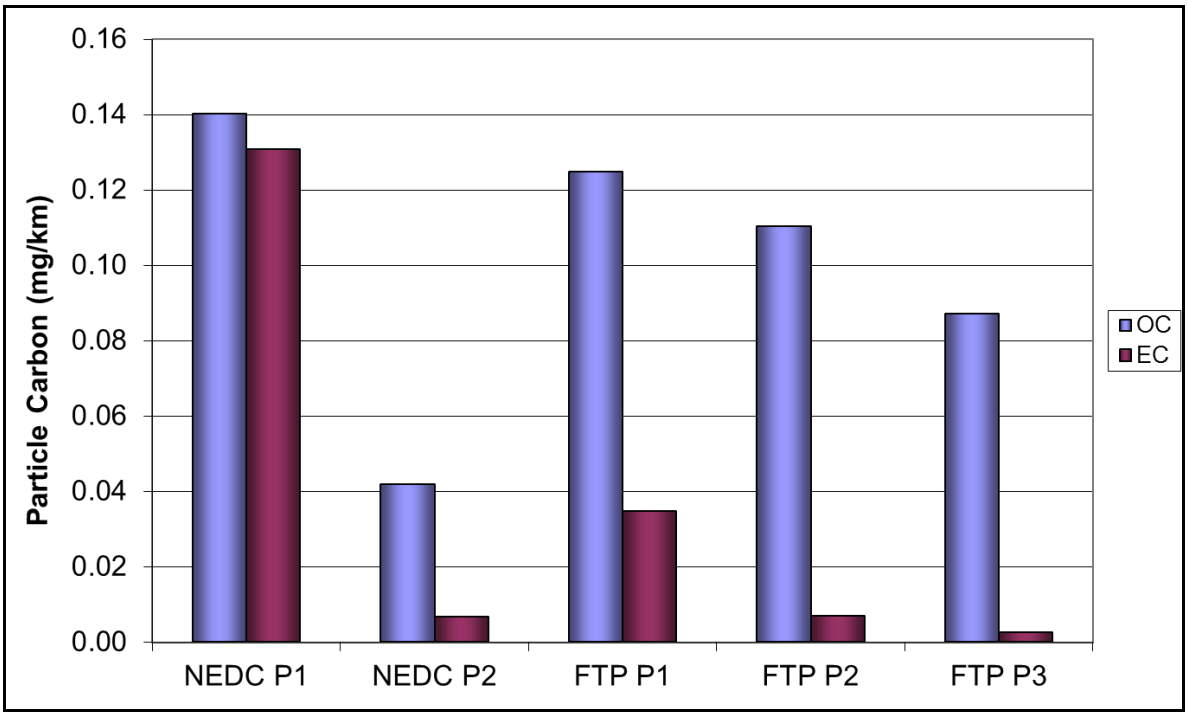


Figure 31. Comparison of PM mass emissions over FTP and NEDC cycles. Emission rates of organic and elemental carbon for NEDC and FTP cycles where P1, P2, and P3 denote the cycle phases: P1 – cold start; P2 – transient and hot running; and P3 is hot running for FTP.
Source: Dwyer et al., 2010.

4. Proposed Particulate Matter Mass Standards

Certification Requirements using the FTP

ARB is proposing more stringent PM mass standards for light- and medium- duty vehicles (PC/LDT1, LDT2 [LDTs with GVWR of less than 6,000 lbs.], and MDPVs) to prevent a potential backslide in PM emissions caused by new low-GHG engine technology. The proposed PM standards discussed below apply over the FTP and US06 cycles as currently applicable under the existing LEV II program.

Proposed LEV III Particulate Standards for Passenger Cars, Light-Duty Trucks, and Medium-Duty Passenger Vehicles (LDV)

Low PM emissions will be achieved by a vehicle in its new condition and throughout its useful life. To this end, as discussed in the staff's ISOR for this rulemaking, the proposed LDV PM emission standards are phased-in in two steps. The initial step of the proposed LDV PM standard is 3 mg/mi for the full useful life of a vehicle, defined as 150,000 miles starting with the 2017 vehicle MY. The 3 mg/mi standard is phased-in incrementally through MY 2021 when all new vehicles are compliant. The second and final step of the proposed LDV PM standard is a 1 mg/mi limit and is also phased-in incrementally through MY 2028. The PM standards for LDVs are shown in Table 1.

Table 1. LEV III PM Standards for LDVs

LEV III Particulate Emission Limits and Phase-in for Passenger Cars, Light-Duty Trucks, and Medium-Duty Passenger Vehicles		
Model Year	**% of vehicles certified to 3 mg/mi**	**% of vehicles certified to 1 mg/mi**
2017	10	0
2018	20	0
2019	40	0
2020	70	0
2021	100	0
2022	100	0
2023	100	0
2024	100	0
2025	75	25
2026	50	50
2027	25	75
2028 and subsequent	0	100

This is an ambitious goal meant to promote the development and wide adoption of ultralow PM technology in the future. This represents an aggressive fleet-wide

reduction of 90 percent below the current LEV II PM limit. Because of the significant technical and practical challenges associated with the development of new car technology that can meet this very low PM mass emission standard on a fleet-wide basis, a phase-in approach and substantial development time are necessary. Therefore, in the MY 2017, it is proposed that one tenth of LDVs sold in California comply with the new PM mass standard of 3 mg/mi, which is 70 percent lower than the current LEV II limit. The fraction of compliant vehicles will increase each successive year. By MY 2021, all new LDVs will emit PM mass at no more than 3 mg/mi.

In addition, the proposed 2025 PM mass limit presents new significant and unique emission laboratory measurement challenges that require further investigation. PM mass emissions at the 1 mg/mi level can be very difficult to distinguish from background concentrations. Thus, tailpipe PM emissions measurements will become increasingly more difficult to conduct with the necessary rigor for regulatory compliance. Improvements in laboratory best practices for vehicle emissions testing and PM measurement equipment and procedures will be needed before the new 2025 PM mass limit can be applied consistently and universally. It is possible that a new and superior PM emission measurement method may be needed, one that is based on particle number, like in Europe, or some other representative metric rather than exclusively on the conventional particle mass.

Proposed LEV III Particulate Standards for Medium-Duty Vehicles other than Medium-Duty Passenger Vehicles

The proposed PM emission standards for MDVs are based on the GVWR of the vehicle. For MDVs with GVWR of 8,501 to 10000 lbs., the proposed PM standard for MY 2017 and subsequent MYs is 8 mg/mi. For MDVs with GVWR of 10001 to 14000 lbs., the proposed MDV PM MY 2017 standard is 12 mg/mi. The 12 mg/mi PM standard is also phased-in incrementally through MY 2021. The PM standards for MDVs are shown in Table 2.

Table 2. LEV III PM Standards for MDVs

LEV III Particulate Emission Standard Values and Phase-in for Medium-Duty Vehicles Other than Medium-Duty Passenger Vehicles			
Vehicle Type	**Model Year**	**% of vehicles certified to 8 mg/mi**	**% of vehicles certified to 12 mg/mi**
MDVs 8,501 - 10,000 lbs. GVWR, excluding MDPVs	2017	10	n/a
	2018	20	n/a
	2019	40	n/a
	2020	70	n/a
Vehicles in this category are tested at their adjusted loaded vehicle weight	2021 and subsequent	100	n/a
MDVs 10,001 - 14,000 lbs. GVWR	2017	n/a	10
	2018	n/a	20
	2019	n/a	40
	2020	n/a	70
Vehicles in this category are tested at their adjusted loaded vehicle weight	2021 and subsequent	n/a	100

LEV III Particulate Intermediate In-Use Compliance Standards for Passenger Cars, Light-Duty Trucks, and Medium-Duty Passenger Vehicles

Because in-use, real-world vehicle activity can result in higher emissions, the proposed intermediate in-use compliance standard for MY 2017 through MY 2021 vehicles certifying to the 3 mg/mi particulate standard shall be 6 mg/mi. For the MY 2025 through 2028, the intermediate in-use compliance standard for vehicles certifying to the 1 mg/mi particulate standard shall be 2 mg/mi.

LEV III Particulate Intermediate In-Use Compliance Standards for Medium-Duty Vehicles, excluding Medium-Duty Passenger Vehicles

For the MY 2017 through 2021, the intermediate in-use compliance standard for vehicles certifying to the 8 mg/mi particulate standard shall be 16 mg/mi and the intermediate in-use compliance standard for vehicles certifying to the 12 mg/mi particulate standard shall be 24 mg/mi.

Proposed LEV III Particulate Standards for Passenger Cars, Light-Duty Trucks, Medium-Duty Passenger Vehicles and Medium-Duty Vehicles Following the US06 Supplemental Federal Test Procedure

The LEV III regulations include a new proposed requirement that vehicles to certify PM emissions using the US06 drive cycle, which simulates the high vehicle loading

and accelerations of an aggressive driver. The proposed standards require that LDVs and MDVs comply for the full useful life of 150,000 miles. The phase-in of US06 PM standards will be tied directly to the FTP PM certification. Phase-in of the standards will follow the FTP PM phase-in (20%/year starting in 2017 for light-duty, MDVs still TBD). In addition, ARB will be offering 5 mg/mi of in-use relief for the first 5 model years. The PM standards following the US06 drive cycle are shown in Table 3. In the composite formula for MDVs, OEMs may use the FTP PM value in lieu of an SFTP SC03 cycle PM value.

All PCs with GVWR 8,500 lbs. or less must meet a 10 mg/mi PM standard. For LDTs with GVWR less than 6,000 lbs., LDTs would need to comply with a 10 mg/mi PM standard. For LDTs with GVR of 6,001 lbs. or more and MDPVs with a GVWR between 8,501 lbs and 10,000 lbs., they both would need to comply with a 20 mg/mi PM standard. For MDVs with loaded and adjusted loaded vehicles weights of GVWR of 8,501 to 10,000 lbs., with an HP/GVWR ratio > 0.024, the PM standard for compliance is 10 mg/mi. All other MDVs with GVRW of 8,501 lbs. to 14,000 lbs. must meet a PM standard of 7 mg/mi. The percentage of compliant MDVs for both categories is increased each year with full implementation by MY 2021.

Table 3. LEV III PM Standards for MDVs following US06

Vehicle Type	Test Weight	Test Cycle	Mileage for Compliance	PM Standard (mg/mi)
All PCs 8,500 lbs. GVWR or less & LDTs 6,000 lbs. GVWR or less	Loaded vehicle weight	Full US06	150,000	10.0
LDTs 6,001 lbs. GVWR or more & MDPVs 8,501–10,000 lbs. GVWR	Loaded vehicle weight	Full US06	150,000	20.0
MDVs 8,501–10,000 lbs. GVWR (HP/GVWR $\leq$ 0.024)	Adjusted loaded vehicle weight	0.28 x US06 Bag 2 + 0.37 x SC03 + 0.35 x FTP	150,000	7.0
MDVs 8,501–10,000 lbs. GVWR (HP/GVWR > 0.024)	Adjusted loaded vehicle weight	0.28 x US06 + 0.37 x SC03 + 0.35 x FTP	150,000	10.0
MDVs 10,001–14,000 lbs. GVWR	Adjusted loaded vehicle weight	0.28 x UC (LA92) + 0.37 x SC03 + 0.35 x FTP	150,000	7.0

5. Feasibility

ARB and U.S. EPA performed studies that measured the PM emissions from LDVs and a MDV to support this rulemaking. ARB's study primarily focused on newer low mileage LDVs. The performance of current technology high-mileage PFI and GDI vehicles is of high interest as a predictor of performance over the useful life of the vehicle. For that information, ARB is relying on test results obtained by the U.S. EPA. Both programs measured PM emissions over the FTP and the US06 cycles. However ARB's US06 testing was limited to only five of the nine GDI vehicles and only three of the ten PFI vehicles. The U.S. EPA test program included both cycles for all 17 vehicles. Both studies showed the many existing newer and high mileage vehicles already can meet the proposed standards. Thus, the proposed new PM limit seeks to promote wider application of this existing low emitting technology. This section details ARB's and U.S. EPA's LDV testing efforts.

ARB Test Program

ARB recently measured PM emissions from 19 LDVs. All 19 vehicles were tested using the FTP cycle, and eight vehicles were tested on both the FTP and US06 cycles. Nine GDI – stoichiometric (homogeneous) vehicles, MY 2007 through 2010, and ten PFI vehicles, MY 2000 through 2009, were tested at ARB's Haagen Smit Laboratory for PM emissions using California Phase 3 commercial summer fuel containing 6 percent by volume ethanol. The test vehicles were all relatively low mileage vehicles. With two exceptions, all vehicles had odometer readings of 67,000 miles or less. One GDI vehicle and one PFI had odometer readings of 124,000 miles and 115,000 miles, respectively. Seven of the GDI vehicles were equipped with wall-guided fuel injection while the remaining two used spray-guided, center-mounted fuel injection.

The ARB tests were conducted by adhering to 40 CFR Part 1065 where applicable for LDV testing. Each vehicle was tested with minimum of three repeat tests. It is well known that cold-start emissions, whether they be for PFI, GDI, or any other type of ICE, are higher than emissions when the vehicle is running hot and stabilized. In fact, cold start emissions are typically one of the most pressing design challenges for car makers. In the FTP results presented here for the nine GDI test vehicles (Figure 32), PM mass emissions were highest for Phase I (cold start), with PM emissions ranging from 4 to 35 mg/mi and an average PM emission rate of 14 mg/mi. In Phases 2 and 3 after engine warm up, PM emissions were significantly lower with an average PM emission rate of 1.1 mg/mi for Phase 2 (hot running) and 1.5 mg/mi for Phase 3 (warm start). For the nine GDI vehicles tested, the FTP weighted PM emissions ranged from 1.6 to 8.4 mg/mi with an average FTP weighted PM emission rate of 3.9 mg/mi. For comparison, the average, FTP weighted PM emissions for the 10 PFI vehicles tested were 0.5 mg/mi with a range of 0.16 mg/mi to 0.99 mg/mi. The individual test results are summarized in Table 1 of the Appendices.

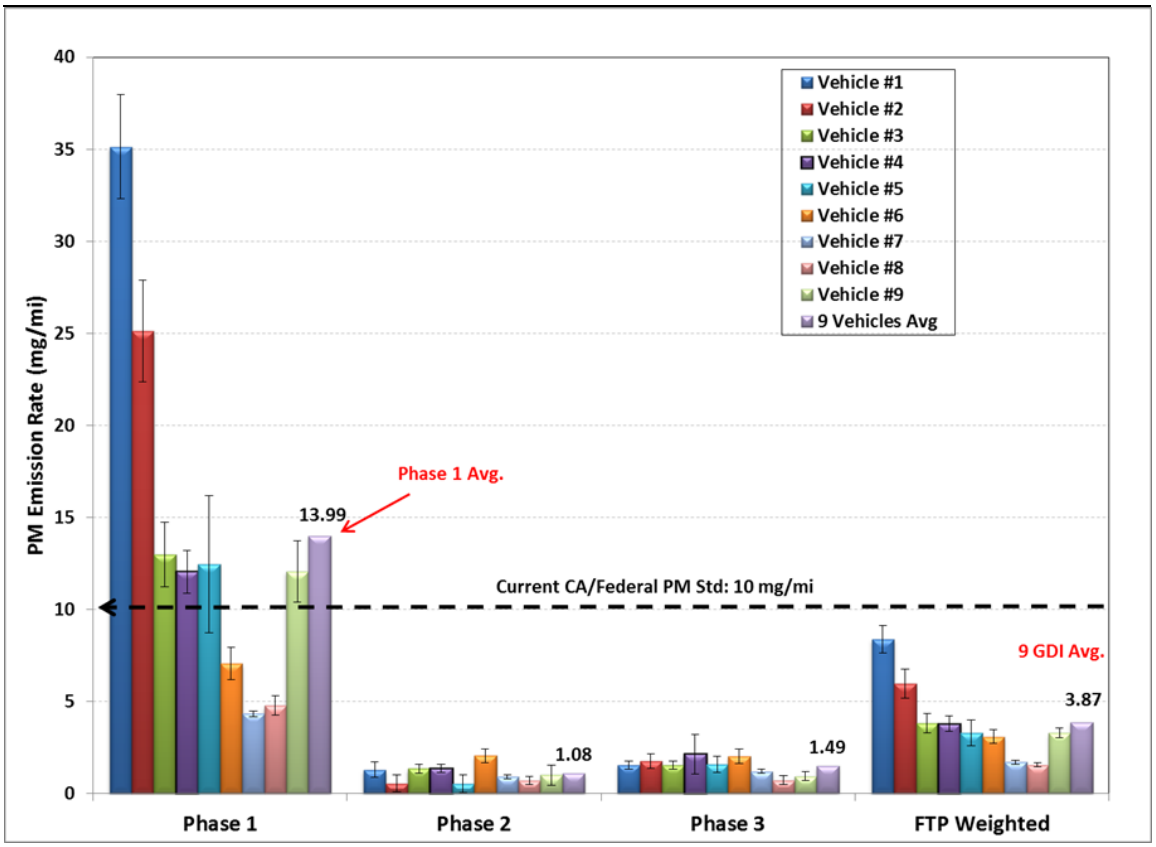


Figure 32. PM Mass Emission Rates on FTP cycle for 9 GDI Vehicles Using California E6 Summer Fuel

The proposed new PM standards are also applicable over the US06 cycle to ensure that there is no backslide in PM emissions from the lack of adequate control over vehicle operation outside of the narrow, mild driving range captured by the FTP cycle alone. As discussed above, PFI vehicles have higher emission levels on the US06 cycle compared to GDI vehicles possibly due to the higher combustion chamber temperatures and less precise fuel control. The fueling control of a PFI engine may not respond as effectively as a GDI fueling system to transient loads, which can lead to fuel collecting in the intake manifold and fuel-rich combustion. GDI vehicles use a more sophisticated fuel metering algorithm and inject fuel directly into the combustion chamber so they do not appear to run rich during more aggressive driving. Also, the US06 cycle subjects engines to higher loads that increase oil consumption and, consequently, PM emissions. As a result, manufacturers are now asked to design their engines to control oil consumption over the useful life. ARB conducted limited testing of vehicle emissions over the US06 cycle and the results are presented in Figure 33. Eight different vehicles, five GDI and three PFI, were exercised over the US06 and their PM emissions were measured. The GDI PM results over the US06 ranged between 0.14 mg/mi and 2.7 mg/mi. The emissions from two PFI vehicles were measured at 0.7 mg/mi or lower. One notable exception, as shown in Figure 33, are the results for a 2009 Hummer, which yielded PM emissions of nearly 8 mg/mi. For this particular vehicle, the FTP PM emissions were not particularly extraordinary at 0.99 mg/mi. The observed eight

fold increase in PM emissions over the US06 serves as a reminder that all vehicle categories need adequate piston and ring design and tight cylinder tolerances over a wider range of engine operation in order to maintain low oil consumption and low PM emissions. The rest of the results presented below demonstrate the technical feasibility of the proposed 10 mg/mi US06 PM standard because current-generation technology performs at or below this limit. Thus, the limit is meant to minimize the impact of outliers that can emit, as test results show, well above the proposed standard.

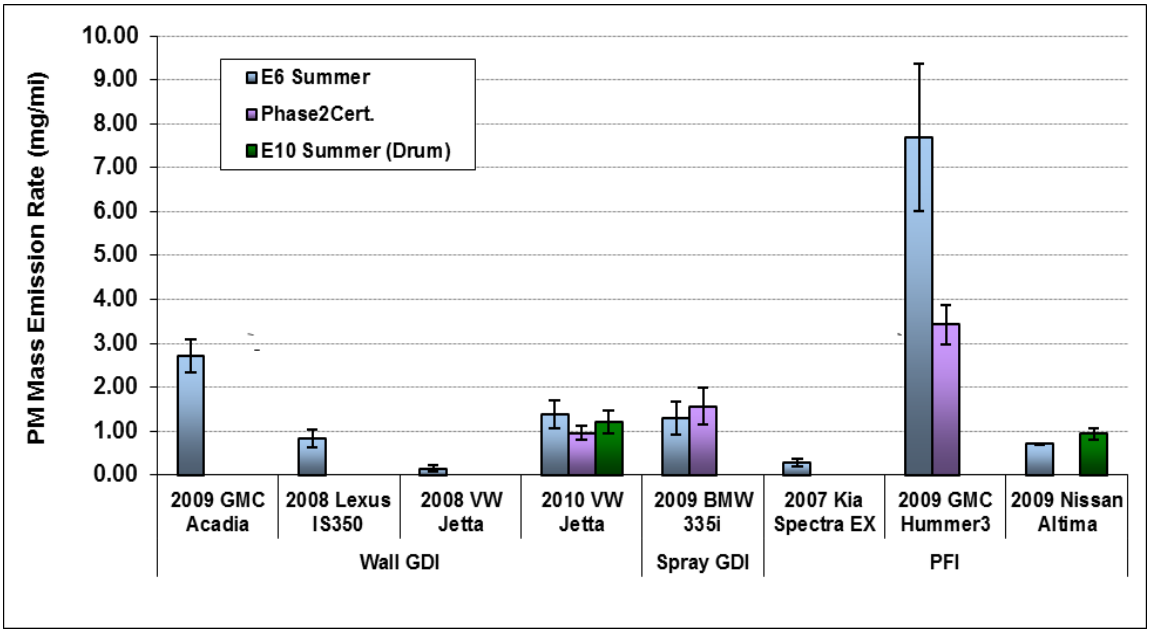


Figure 33. PM Mass Emissions on US06 cycle for GDI and PFI Vehicle using 3 Fuels.

ARB MDV Test Results

ARB has conducted testing of a 2007 Ford E250 Cab Chassis MDV following 40 CFR Part 1065 and ARB's SOP No. MLD 145. The vehicle contained a spark-ignited 4.6-L PFI engine certified to ULEV II standards. The vehicle's GVWR was between 8,501-10,000 lbs. A total of three FTP, three UC and four US06 tests were performed. In addition to measuring PM mass emissions, solid particle number emissions were measured with an AVL PMP solid particle counter. The test fuel used for all tests was E10 summer fuel. The results of the testing are shown in Table 4 and Figures 34 and 35.

The average PM mass emissions are 1.7 mg/mi for the FTP cycle with reasonable repeatability (coefficient of variability of 25%), and 0.8 mg/mi for the USO6 cycle. The FTP PM results are comparable to those measured from current light-duty vehicles. The low results can be potentially explained by its low mileage (approximately 50,000 miles) and precise fuel control. The US06 results are much lower. The US06 test results also indicate good combustion preparation mixing, no

impingement on any combustion chamber parts, and no over fueling on acceleration.

The test results clearly show that the proposed PM mass standards for MDVs are achievable with the technology used on some vehicles currently produced. In the future, with years for further development, manufacturers should be able to comply with the proposed standards as they migrate to low carbon technology.

Table 4. MDV PM mass and SPN test results for 2007 Ford E250

	Total PM Mass(mg/mi)				Solid Particle Number (#/mi)			
Test Cycle	**Phase 1**	**Phase 2**	**Phase 3**	**FTP Weighted**	**Phase 1**	**Phase 2**	**Phase 3**	**FTP Weighted**
FTP-1	1.7	1.0	1.1	1.2	4.0E+12	2.2E+10	1.9E+11	8.8E+11
FTP-2	3.7	1.8	1.2	2.0	3.5E+12	4.4E+10	1.7E+11	7.8E+11
FTP-3	4.5	1.0	1.1	1.7	3.7E+12	3.5E+10	2.5E+11	8.5E+11
Avg.	**3.3**	**1.2**	**1.1**	**1.7**	**3.7E+12**	**3.3E+10**	**2.0E+11**	**8.4E+11**
SD	1.4	0.4	0.1	0.4	2.5E+11	1.1E+10	4.0E+10	4.8E+10
US06-1	0.7	na	na	na	2.5E+11	na	na	na
US06-2	1.0	na	na	na	3.8E+11	na	na	na
US06-3	0.4	na	na	na	4.9E+10	na	na	na
US06-4	1.3	na	na	na	1.9E+11	na	na	na
Avg.	0.8	na	na	na	**2.2E+11**	na	na	na
SD	0.4	na	na	na	1.4E+11	na	na	na

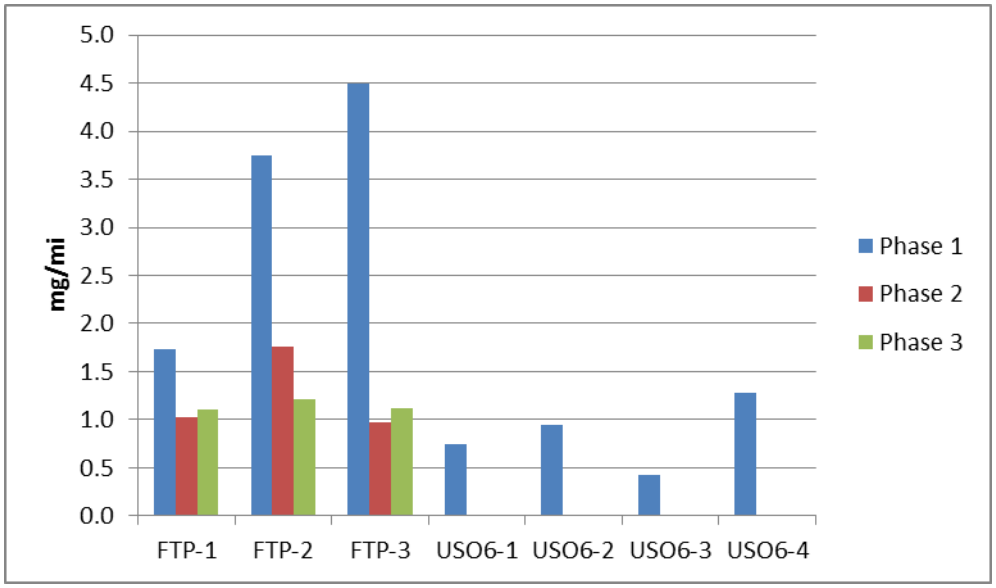


Figure 34. MDV PM mass results

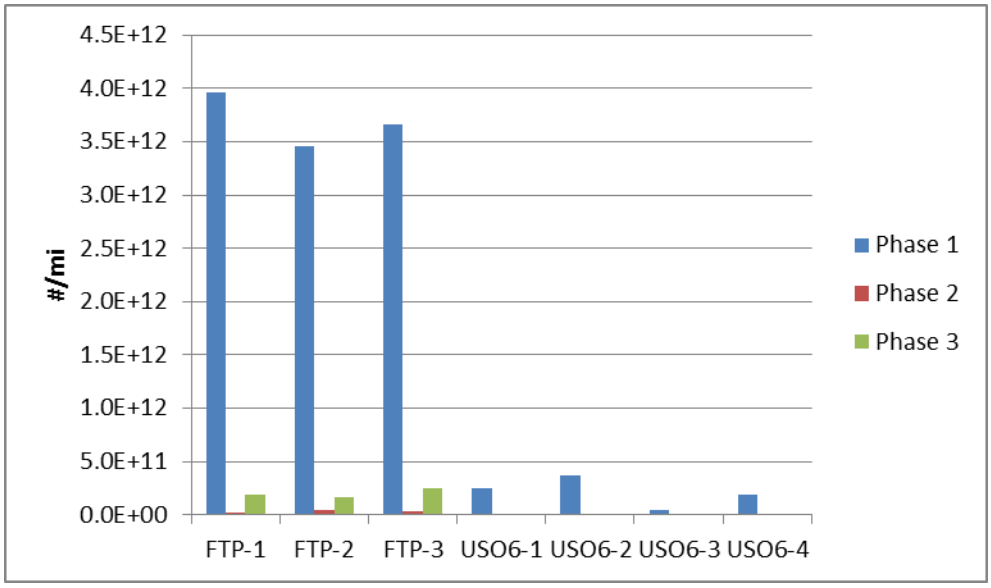


Figure 35. MDV SPN results

U.S. EPA Test Program

The U.S. EPA study investigated various aspects associated with vehicle age, deterioration, oil consumption, and aggressive driving. The U.S. EPA test program included a total of 17 vehicles, 15 PFI and two GDI. Five of the 17 test vehicles were oil burners. All vehicles were MY 2005 and newer and had 100,000 miles or more on the odometer. The vehicles were designed to meet the 10 mg/mi Tier 2 PM standard and were tested using the FTP and the US06 cycles. Figures 36 and 37 below summarize the test results of the U.S. EPA test results for FTP and US06 cycles. The results show that PFI emissions are approximately 5 mg/mi when subjected to the FTP cycle. However, the data shows that PFI engine PM emissions are considerably higher when subjected to the US06 cycle. It is also worthy to note that GDI engines performed much better than PFI engines on the US06 cycles. In general, high mileage and oil burning vehicles had much higher emissions when tested on the US06 cycle. Tighter ring tolerances and high compression ratios for the two GDI engines tested on the US06 cycle may account for the much lower test results. Overall, 15 of the 17 vehicles tested under the U.S. EPA test program had PM emissions lower than the 3 mg/mi proposed PM standard for MY 2017 LDVs when subjected to the FTP cycle. Ten of the 12 LDV/LDT2 vehicles tested had PM emissions lower than the proposed in-use PM standard of 10 mg/mi for MY 2017 when subjected to the US06 cycle. Three of the five LDT3/4 (LDTs with GVWR of 6,000 to 8,500 lbs.) vehicles tested had PM emissions lower than the proposed in-use PM standard of 20 mg/mi for MY 2017 when subjected to the US06 cycle.

The federal test data is very useful because it highlighted a number of key potential issues not shown by the ARB test program. First, aggressive driving can clearly deteriorate the low PM performance of a PFI vehicle. The same is not true for a GDI engine. Second, vehicle age and increased oil consumption are also factors that

can drive up the typically low PM emissions of the PFI vehicle. For its part, the GDI engine still will need some improvement, perhaps in terms of wider utilization of spray-guided injection, to lower PM emissions over both FTP and US06 conditions. The more stringent proposed FTP limits and the addition of new in-use limits as well as new limits over the US06 are meant to work in concert to promote low emitting technology and to drive down and maintain real-world low PM emissions for the life of the vehicle.

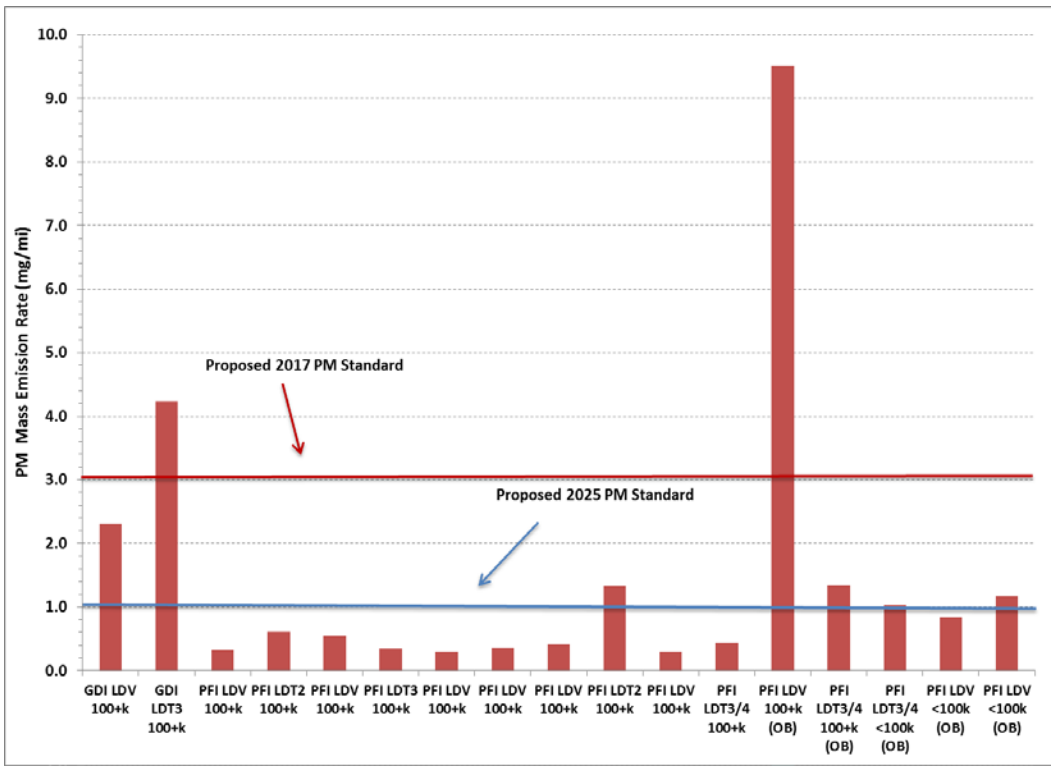


Figure 36. U.S. EPA Test Results (FTP cycle). OB designates vehicles identified with excessive oil burning.

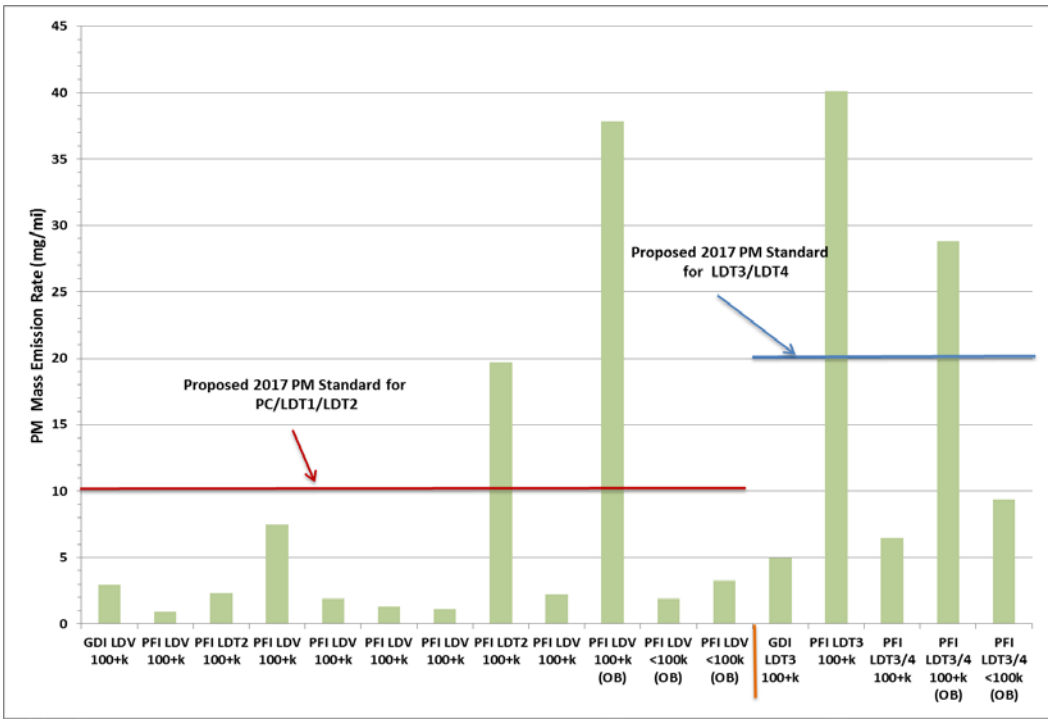


Figure 37. U.S. EPA Test Results (US06 cycle).

6. PM Benefits and Impacts

PM emissions reductions

Test results to date suggest that a PFI vehicle is much more susceptible to driving effects (i.e., duty cycle) than a GDI vehicle. Deterioration with vehicle age and excessive oil burning can exacerbate this effect. A current technology PFI engine can be extremely low PM emitting and in the sub-4 mg/mi range as discussed previously. But these low emissions are typically observed for a newer vehicle and during vehicle operation over the relatively mild FTP cycle. When faced with more aggressive driving such as that represented by the US06 cycle; calibration, fueling control and other design factors of the PFI engine appear to lag, resulting in higher PM emissions. In contrast, a GDI vehicle may not achieve the very low emissions of the PFI vehicle over the FTP, but it appears to have superior fueling control over a wider range of operation. Limited data also suggest a smaller high mileage effect than that observed for PFI vehicles. The result is the GDI engine is able to moderate the impact of aggressive driving (i.e., US06) and natural deterioration. Consideration of these factors and the supporting staff analysis for present conditions described in section V: Emissions Impacts of the ISOR, leads to an average baseline (i.e., no new policy) in-use emission level of 4 mg/mi. This baseline emission factor is needed for purposes of inventory and benefit calculations. In both vehicle type cases, technology improvements in response to the proposed standards will drive this level of emissions down and allow for compliance with the new limits. Specifically, in the case of the PFI engine, the new standards will promote improved oil consumption and fueling control, particularly as

the vehicle ages (a necessity in order to meet the proposed useful life limits). In the case of the GDI engine, the new standards will encourage further improvement towards spray-guided injection or other solutions for reducing PM emissions. These interpretations of the PM performance of GDI and PFI engines based on the test data collected by ARB and by the U.S. EPA are the technical underpinning of the proposed regulation.

The benefits of the proposed standards become the difference between the baseline emission level and the new limits. For illustration, Figure 38 is a graphical representation of baseline PM emissions from vehicles under a business-as-usual scenario (BAU) without the proposed LEV III rule and one scenario where the new policy is adopted. Under BAU, the progression of emissions growth is driven by conventional vehicle population and vehicle miles travelled (VMT) growth assumptions. The move to GDI is still expected given an interest in fuel efficiency improvements. However, this GDI technology is not of the type where PM emissions can be minimized. Some fraction of the fleet still includes PFI technology and the confounding effects of deterioration, oil consumption and real-world driving (i.e., US06 effects) are still present. In the alternative case "with control," the LEV III standards are expected to drive PM emissions down and the emphasis of low carbon options promotes the wider introduction of "cleaner" GDI technology in the form of spray-guided GDI engines. The result, as desired, is the LEV III regulations prevent the proliferation of higher PM emitting technology in the vehicle fleet and promote a change towards air quality improvement and a future downward trend in emissions.

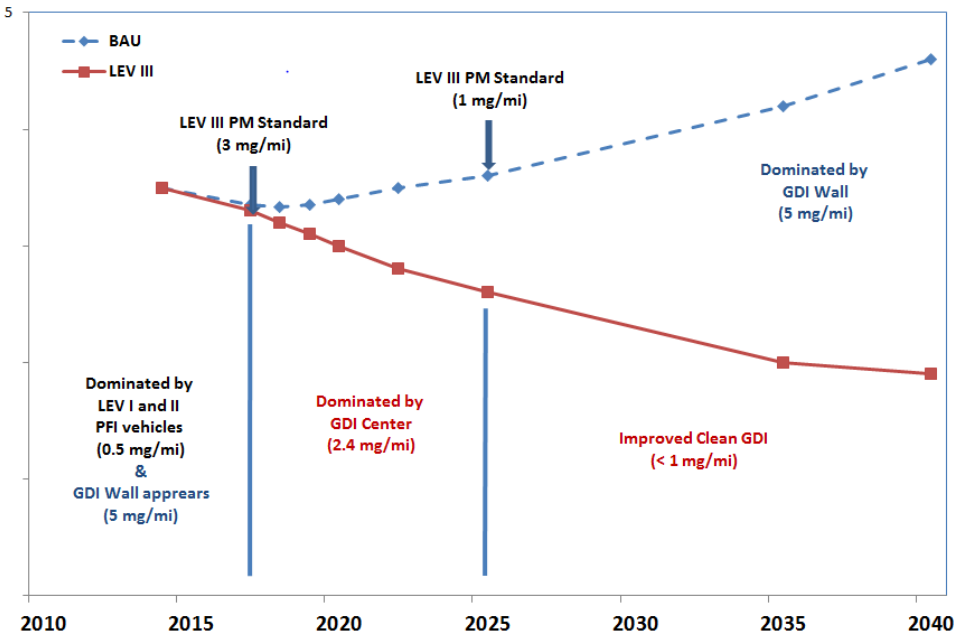


Figure 38. Trend in PM emissions baseline (BAU cases) and the proposed effect of control (with new LEV III policy).

Cost Impacts

Market and regulatory forces are encouraging car manufacturers to move towards wider adoption of GDI technology. Most GDI vehicles currently being produced for sale utilize wall-guided fuel injection. Placement of a side-mounted injector is a relatively straight forward and cost-containing option as it does not require major engine block modification or significant re-design. However, the downside is lower volumetric efficiency than a center-mounted injector for spray-guide GDI design. Given the emphasis on CO_2 reductions, the expected trend is for new GDI vehicles to move towards spray-guided GDI engines.

A center-mounted injector involves more complex engine re-engineering given the need to move the spark plug to the side and make engine block modifications to accommodate the injector. Logically, the necessary modifications come at an incremental cost relative to the other GDI option. The benefit is greater volumetric efficiency and improved CO_2 and PM performance.

Industry information suggests that price structures and cost impacts may be more heavily influenced by other market forces rather than regulatory mandates for emission reductions. Injector price may not be as closely tied to spray-guided versus wall-guided injection as originally thought, although spray-guided injectors may have to be slightly longer to reach into the combustion chamber from the top of the cylinder head. It is expected that current injector design can be used for spray-guided applications so there would be no cost differential for the injector itself. Spray-guided GDI systems supporting stratified lean-burn combustion are not likely to be introduced in California due to the challenge of cost-effectively meeting NO_x emissions requirements. The majority of spray-guided GDI systems will be homogeneous, stoichiometric combustion that can use solenoid-based high pressure injectors with smart control and mixing strategies rather than the more expensive piezo injectors used on stratified combustion engines.

An additional option to controlling PM from LDVs and MDVs is a gasoline particulate filter. Emissions control manufacturers have suggested that the cost increase for production quantities of GPFs may be on the order of 100 dollars. Integration of the DPF into an existing TWC package or as a separate, add-on component will determine, in part, the final cost. It is not projected that manufacturers will need GPFs for well-designed spray-guided GDI systems. However, the GPF remains a viable option for manufacturers.

In summary, compliance with the proposed PM standards is not expected to impose a cost increase to vehicle manufacturers. By 2025 due to market forces, a majority of new GDI engines are expected to have migrated to spray-guided GDI on small and medium-duty vehicles. Meeting the proposed PM standard will only require that manufacturers include compliance with the PM standard as an objective during engine hardware and software design. The use of a GPF will remain purely a business decision since it is not necessary for meeting the proposed emission limits.

B. Test Method Improvement

Measuring PM mass emissions in the range of 3 mg/mi to 1 mg/mi requires a robust test procedure that is theoretically correct, practical, and carefully executed. Measuring PM mass on the order of 1 mg/mi presents additional practical challenges because at this level of emissions the current CVS tunnel-based measurement background can introduce a bias or "noise" in terms of measureable PM mass that is attributable to the test vehicle. This background PM can be of the order of the actual PM emissions from the vehicle. However, it must be acknowledged that various testing efforts in academia and elsewhere do routinely report, in the published literature, vehicle emissions in this low range. What that says is that the measurement can be done with current laboratory practices. What is needed is standardization and resolution of knowledge gaps as discussed here. Thus, given these challenges, a consortium of government and industry experts are active in research in this area. The focus is to determine the most appropriate technical improvement to current best laboratory practices that can yield a PM measurement that is accurate, repeatable, and reproducible in various laboratory settings involved in compliance testing. The U.S. EPA is leading this effort and is expected to soon publish method revisions in the CFR to establish an improved procedure for vehicle testing. Internationally, there is also on-going work under the auspices of the United Nations Economic Commission for Europe. This group is developing a Global Technical Regulation for emission test procedures applicable to compliance testing for passenger cars and other light-duty vehicles. In both cases, the intent is to improve the measurement approach for PM emissions for the very low emitting regime anticipated from future vehicles so that the measurement can be made universally, accurately, and consistently. The U.S. EPA already developed the procedures presented in 40 CFR Part 1065 to provide improvements in heavy-duty engine testing, particularly in the areas of repeatability and accuracy of the PM mass measurement for heavy-duty diesel engines. The procedures are also applicable to LDV PM testing and certification as described in 40 CFR Part 86. It is expected that upon finalization of the federal Tier 3 rule for LDV, the U.S. EPA will also finalize new test procedures in 40 CFR Part 1066 to be used, from that point on, in the U.S. for demonstration of compliance with new proposed federal PM mass standards. ARB intends to adopt those procedures once finalized to show compliance with the applicable new proposed PM standards for California.

1. Areas of Improvement in the PM Mass Method

Two of the principal challenges associated with the PM mass measurement at the 1 mg/mi level are related to dilution tunnel and filter media "artifacts" (Chase et al., 2004). Artifact in this context refers to a measurable amount of PM mass that is attributed to emissions, but that it is not material emitted directly by a test vehicle or engine. Sample train artifact relates to PM measurement variability observed due to adsorption and desorption of particulate from the PM sample train. Sample train artifact can come from anywhere in the sample train, but a majority comes from three areas: the vehicle exhaust system, the transfer tube between the vehicle and the dilution tunnel, and the dilution tunnel.

Filter media artifact relates to the potential adsorption (positive) and desorption (negative) of material depending on the sampling conditions that introduces additional PM mass measurement variability. This variability can bias the weight of filter media used for gravimetric analysis, particularly at very low emission regimes from 1 mg/mi compliant vehicles. Filter media was shown previously in Figure 24. Teflon is a filter material of choice for conducting vehicle emissions testing. Average Teflon filter bias of 0.5 ± 0.5 mg/mi has been noted for exhaust testing (Maricq et al., 2011). For very low emitting vehicles, the magnitude of this filter artifact can approach the actual PM mass emission from the vehicle (Li et al., 2006). The following issues emerged from discussions between industry and the regulatory agencies related to potential areas of improvement to PM test methods.

Dilution air and dilution tunnel

The development and adoption of good laboratory practices can control sample train artifact. Temperature and dilution must be carefully controlled to prevent aqueous condensation. When measuring emissions, the exhaust transfer tube and the inner wall of the sample train should be kept clean. Additionally, variability can be introduced by testing dissimilar vehicles or cycles in sequence. This can cause transfer tube and tunnel surfaces to adsorb or desorb material that can later be counted as mass. Testing a higher emitting vehicle just prior to a lower emitting vehicle can also bias the test result.

Dilution air artifact is mass collected on the filter media used for vehicle sampling from lack of adequate filtration of dilution air and adequate scrubbing of gases. 40 CFR Part 1065.140(b)(3) offers the option of dilution air filtration using a High Efficiency Particulate Air (HEPA) filter. Dilution air background correction is an option for improving the PM mass measurement. Background correction for the dilution air involves sampling downstream of the HEPA filter and upstream of where the vehicle exhaust is introduced into the dilution tunnel. The background air correction should be run at the same time as the actual emission test for which the background will be used to correct the PM emission result.

When measuring emissions at or below 3 mg/mi, the exhaust transfer tube and the inner wall of the sample train must be kept clean. Variability can be introduced by testing dissimilar vehicles in sequence. Care must be taken to make sure the sample train is properly conditioned for the test being conducted.

Filter media

Adequate filter media handling practices are also needed to control for measurement variability. ARB test results confirm that using the PM gravimetric analysis procedures detailed in ARB SOP No. MLD 145 (MLD, 2011) can control for some of the observed variability.

Filter media artifact is the mass that is adsorbed or desorbed on the filter from emissions that start in the gas phase. Absorption desorption also introduces variability. Recent information provided by industry suggests that the filter artifact

may not correlate directly or entirely with driving cycle duration or the total amount of PM mass collected on the filter. But the filter artifact can be minimized by increasing the mass collected on the filter (Maricq et al., 1999). This can theoretically be accomplished in multiple ways including increasing the duration of the test, reducing the dilution ratio, or by compositing multiple test cycle phases onto a single filter.

Increasing the duration of the test is only practical for Phase II and III because the Phase I cold start test requires a cold soak immediately prior and therefore cannot be extended. Reducing the dilution ratio has limited applicability because 40 CFR Part 1065.140(c)(6)(ii)(C) requires identification of the maximum potential mole fraction of dilute exhaust lost on a continuous basis during the entire test interval. This value must be less than or equal to 0.02. This means that no more than two percent of the water in the CVS can be in liquid phase at the minimum wall temperature. This limitation means that a lower dilution ratio could be used in conjunction with dilution tunnel heating.

Increasing the mass collected on a filter can be accomplished by reducing the number of filters used for a FTP test. For example, rather than using a single filter for each of the three phases of the FTP cycle, two filters can be used over the cycle instead. Specifically, one filter can be used to measure Phases I and II (cold-start and transient) emissions while a second filter can be used to measure Phases II and III (transient and hot start) emissions. This modification will not affect the current weighting of the FTP cycle by each of its phases. Thus, this is a potential modification that could be used to improve existing and future PM test procedures.

Similarly, a single filter for PM mass collection can be used over the entire test cycle. However, this can be problematic as cold start emissions, which would dominate the sample signal, would be difficult to tease out and the results need to be weighted properly. One way to use a single filter and still properly weight the cold start and hot start emissions would be to adjust the filter media face velocity to obtain the proper weighting of the various cycle phases. One significant advantage of this approach is that a single filter can be used for collection of PM mass over the entire test cycle. For instance, assuming a maximum filter face velocity of 100 centimeters per second (cm/s), collection of a cold start UDDS sample would occur using a filter face velocity of 75 cm/s (43%/57%*100 cm/s = 75cm/s) whereas the hot-running UDDS emissions would be determined using a filter face velocity of 100 cm/s. This approach is attractive as it would cut by two thirds the uncertainty associated with filter media conditioning, handling, and analysis. Admittedly, there are practical challenges associated with the modifications to the CVS PM sampling train that would be required to allow for modification of face velocity over a transient test. Using this approach would eliminate the ability to discriminate cold start from hot running PM emissions. This suggestion is made as a potential area for future research. But a number of efforts on PM test method improvement are already underway which are projected to improve the test method for ultra-low emissions testing.

Reducing the number of filters used for a drive cycle makes it easier to meet the two percent liquid phase water limit. By using fewer filters, the cold start and transient

portions of the FTP could be combined into a single phase which would allow the water in the CVS tunnel to stay in the vapor state. This would not be the case if running a cold start phase alone, which may require CVS heating or insulation. However, there are technical considerations such as how to adjust the flow rate between phases and what effect flow rate has on the filters ability to trap and retain semi-volatile PM emissions that still need to be evaluated. Additional research needs to be conducted in this area to determine if it is a viable option for accurately measuring PM emissions at very low levels.

2. Additional Industry Recommendations

During the course of development of the new PM standard in the LEV III regulatory proposal, ARB has worked extensively with stakeholders to develop a regulation that achieves the reductions that California needs while minimizing the burden on the industry that has to comply with the new limits. This government-industry dialogue was fruitful and led to meaningful advances in the technical aspects associated with PM emission testing. This collaboration has also identified a number of areas where future testing and research are necessary.

Artifacts

Precise measurement of PM mass emissions in the range of 1 mg/mi may be statistically limited due to measurement artifacts as described above and to potentially strong fuel effects – fuel differences that can lead to large PM emission differences. The statistical limit for filter-based PM mass measurement is dominated by the filter blank variability. Improved laboratory practices will greatly reduce variability and therefore lower the statistical limit. Using the ARB laboratory standard operating procedures, ARB has generated PM mass data sets below 1 mg/mi with minimal variability. The PM variability due to fuel characteristics identified by industry research is not a factor for certification fuels used in California as discussed in section III of this document.

Filter Artifact

Gaseous adsorption based filter artifact can be substantial compared to the PM mass for very low standards (Maricq, 2011). Industry suggests that a PM filter artifact compensation algorithm to correct for PM filter artifact should be used. Further studies are needed on gaseous phase adsorption at concentrations similar to those in diluted exhaust.

Sample Train Artifact

In addition to sample train artifact as described previously, industry argues it is virtually indistinguishable from vehicle PM and can be positive or negative as shown in Figures 39 and 40. Since filter artifact is not measured by instrumentation, the additional mass collected on TX40 and Teflo filters is assumed to be artifact (Chase et al., 2004). Measurement of particle distributions using partial flow dilution and through other dilution tunnel techniques shows that the tunnel can be a substantial

source of PM emissions (Maricq et al., 1999). The total PM dilution ratio amplifies artifact. The ARB PM testing laboratory has controlled artifact by using proper maintenance and laboratory practices pursuant to ARB SOP No. MLD 145 (MLD, 2011). This is especially important during the more aggressive US06 driving cycle which can cause desorption from the sample train as shown in Figure 41 or when measuring a sample with a high fraction of semi-volatiles.

Industry has suggested additional areas of future research including minimizing the length of the transfer tube, utilizing various conditioning approaches for the dilution tunnel prior to performing a vehicle test, and using partial flow dilution systems which will theoretically reduce artifact by better managing temperature and humidity.

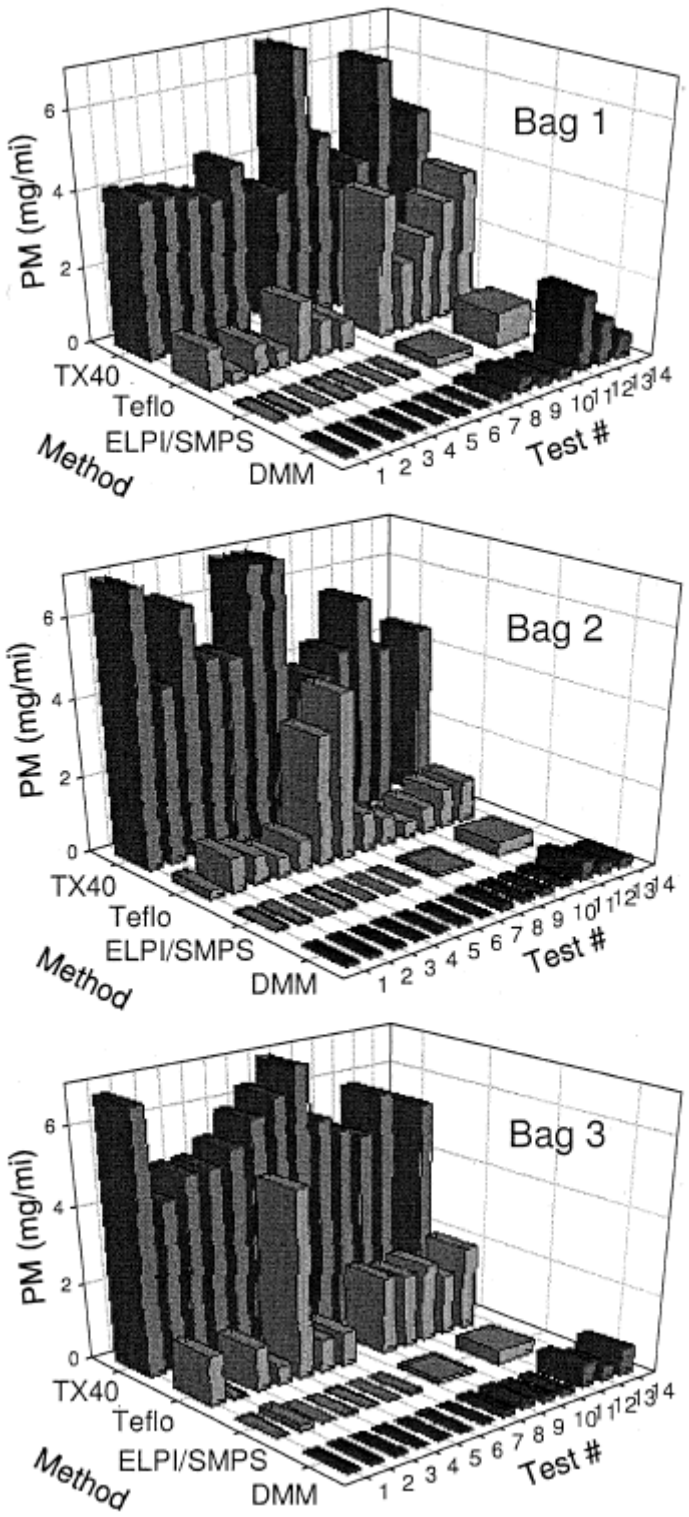


Figure 39. PM mass emissions measured using different filter media and instruments
Source: Chase et al., 2004.

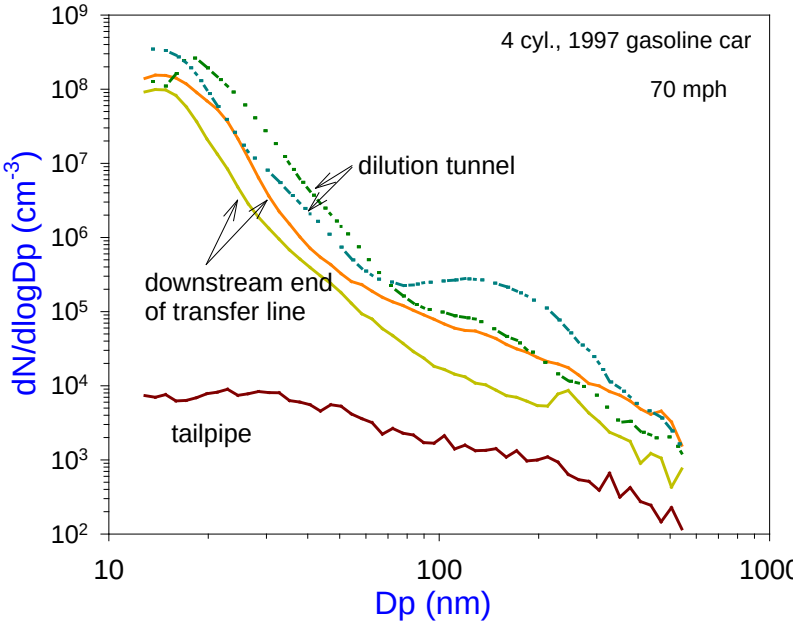


Figure 40. Sample Train vs. Partial Flow Diluter (tailpipe) particle size distributions
Source: Maricq et al., 1999.

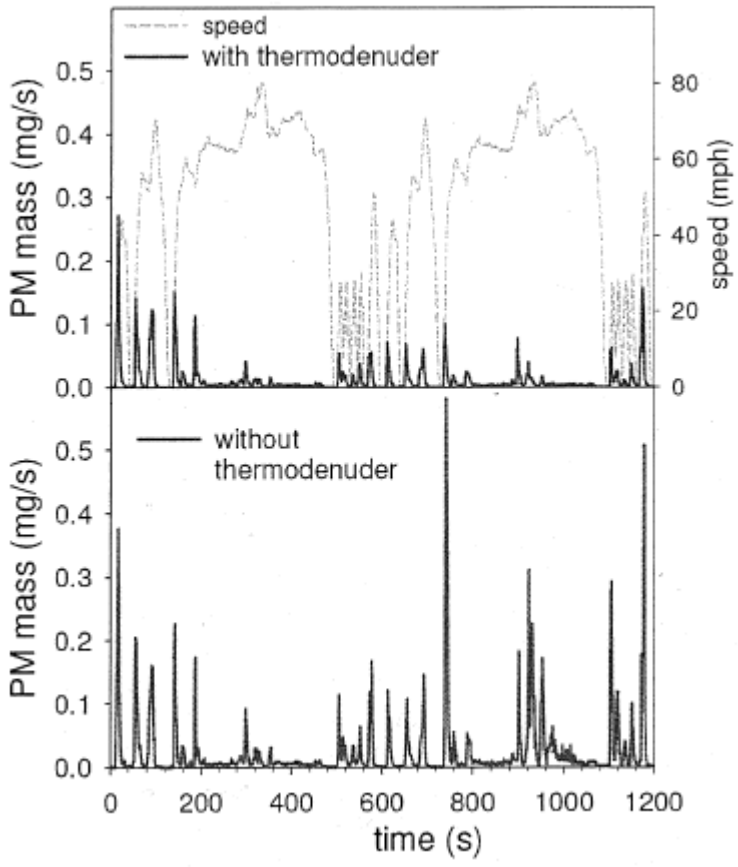


Figure 41. Effect of sample train desorption on PM mass
Source: Maricq et al., 2011.

3. Advances in PM Measurement from the U.S. EPA Test Program for Development of a PM Generator

The CVS tunnel artifact described above can present a mass closure problem in that the true PM emission factor for a vehicle or engine may be numerically different when determined from the emissions measured after dilution and sampling from a CVS tunnel. Generally this measurement uncertainty did not play a large role in the past since it appeared in the noise of the mass measurement when the magnitude of emissions from older engine technology was much greater than the magnitude of this artifact mass. As emissions began to decrease, this measurement uncertainty became a relatively more important factor in the measurement. The U.S. EPA is developing an approach to address this issue and has begun work on a PM generator (PMG) during the EPA/ARB/EMA Measurement Allowance Program. This program was conducted to determine the on-road heavy-duty diesel engine in-use compliance measurement allowance for PM mass emissions. Measurements were made using portable emissions measurement systems (PEMS).

The intent of the PMG is to generate a known, quantifiable, and repeatable amount of PM combustion products traceable to the fuel and oxidant. The PMG works by mixing EC generated in a mini Combustion Aerosol Standard (CAST) with hydrocarbons of different molecular weights which are introduced using a series of ovens. The PMG is intended to address the EPA's interest in studying both the solid and volatile components of combustion source PM emissions. The original goal for the PMG was to develop a National Institute of Standards and Technology (NIST) traceable PM standard, but more recently the emphasis has shifted towards using the PMG for more basic aerosol research, such as to pursue a better understanding of the processes governing sorption of volatile and semi-volatile species using a simulated exhaust mixture. The EPA believes the PMG will provide a foundation for future PM regulatory framework, and expects PMG research to help guide improvements to the current CFR CVS sampling system and methods. Specifically, the U.S. EPA is currently conducting experimental studies focused on complete characterization of sampling losses from the PM sampling system, determination of the system’s dynamic range, repeatability, and fundamental PM formation experiments for isolating multi-component effects. Presently, the U.S. EPA is seeking to fund improvements to a prototype PM generator (shown as a diagram and photo in Figures 42 and 43).

Theoretical work includes PM and gas transport modeling to simulate losses among other issues. Therefore, given the emphasis of key areas that require additional study, the U.S. EPA PMG program may prove to be a very useful effort for advancing our understanding of PM as an air pollutant and as a regulated emission for which a robust measurement method becomes a foundational element. It is anticipated that by the end of 2011 the project goals described above will be complete. ARB intends to follow these developments in the event that the PMG offers opportunities for PM test method development and improvement.

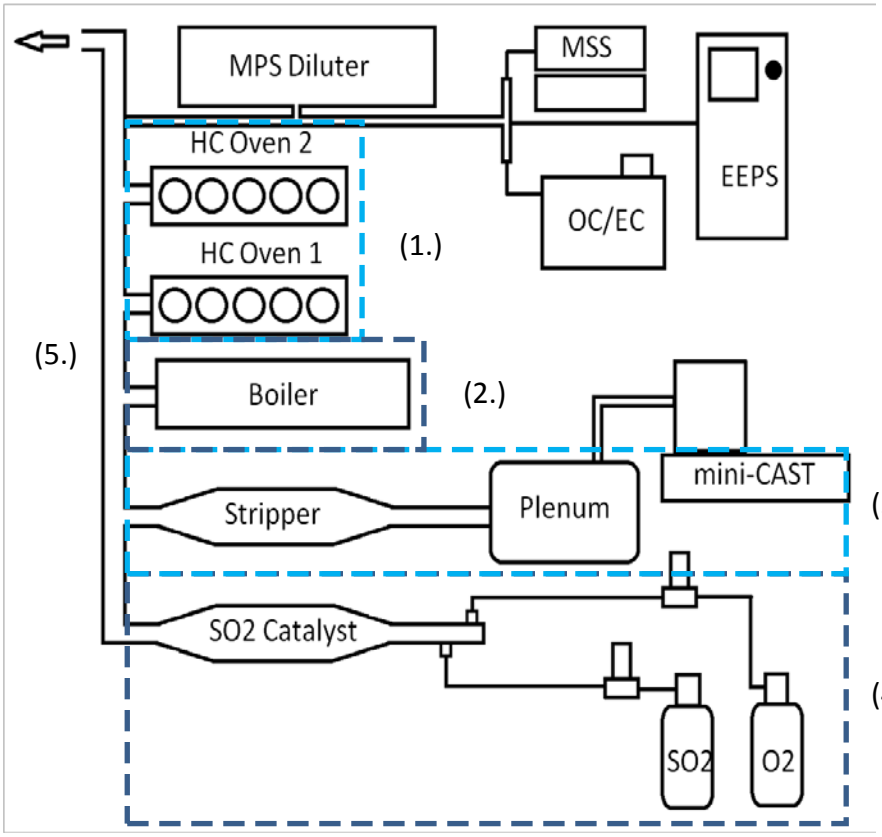


Figure 42. PM Generator Diagram

1. HC source
2. H_2O source
3. Soot source
4. SO_3 source
5. Mixing manifold

Source: Bougher et al., 2010.

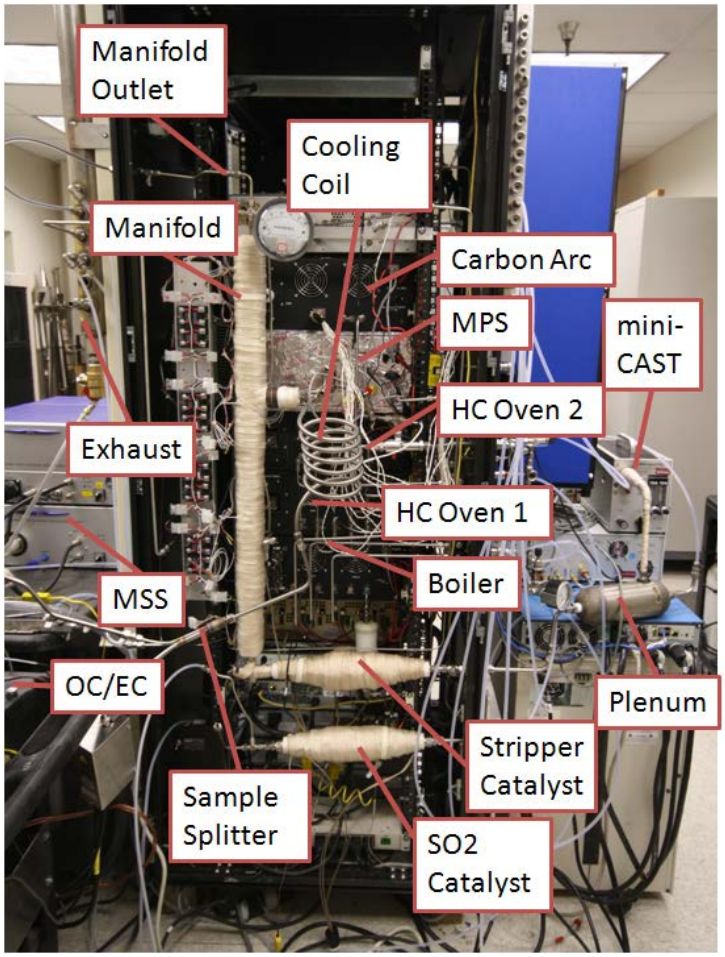


Figure 43. Prototype PM Generator
Source: Bougher et al., 2010.

4. Promising Complementary PM Methods

Several factors are driving the interest in complementary test methods to the conventional PM mass measurement. First, as scientific evidence continues to emerge linking various adverse health effects and exposure to the smallest of the fossil fuel combustion-generated particles, the so-called ultrafine particles (UFP) or those with an aerodynamic diameter of 0.1 micrometers or less (PM0.1), there is increasing attention to technology options for their control from all sources, not just vehicles. In parallel, there is also emphasis in defining a test method(s) that can provide a direct measurement of those particles. Second, as vehicle PM mass emissions trend downward and start to approach levels around the proposed 1 mg/mi standard, the gravimetric measurement becomes increasingly challenging for the reasons previously discussed. This measurement challenge can be exemplified by results shown in Figure 44. The data from the PMP program, which shows that as the particle emissions per distance driven decrease with the use of technology like a DPF, and the measurement of those particle emissions becomes increasingly more sensitive to various factors that lead to larger variability in the measurement.

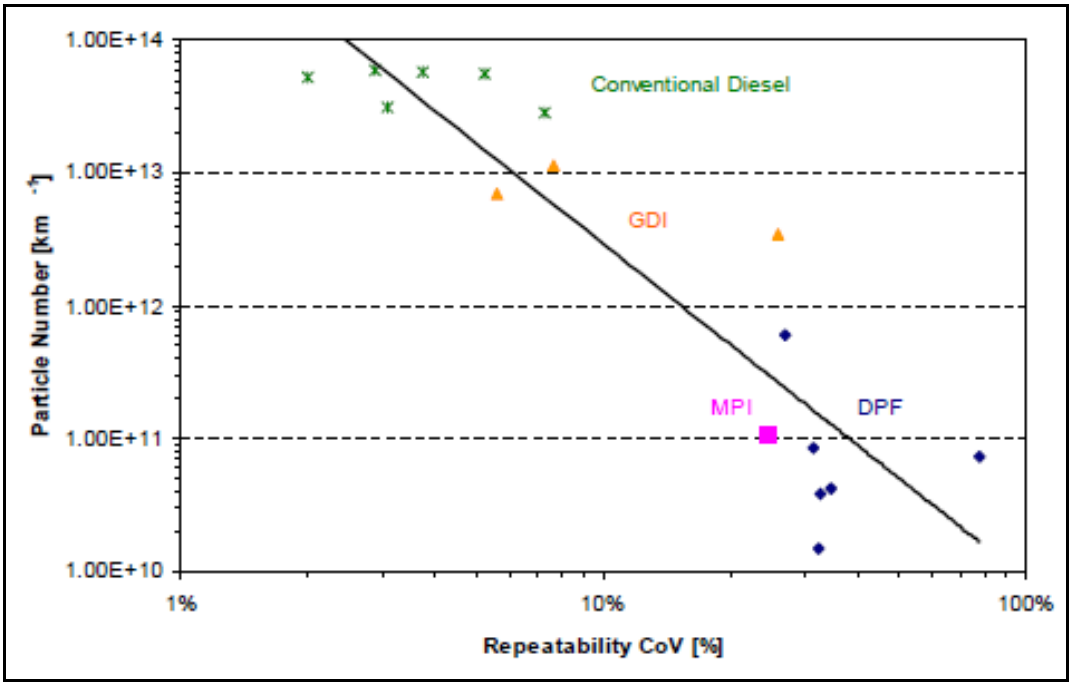


Figure 44. Particle number emissions for various vehicle technologies and the repeatability in that measurement in terms of the Coefficient of Variance. Source: Andersson et al., 2007.

The necessary improvements to the PM mass measurement were first brought to light by the diesel engine development and the strategy for particle filtration via a DPF. In the U.S., ARB, along with many others from industry, academia, and government, invested heavily in understanding and improving the PM measurement from the heavy-duty DPF-equipped engine. One prominent effort in the area of particle emissions and measurements was the Coordinating Research Council's E-43 Project, Diesel Aerosol Sampling Methodology (CRC, E-43, 2002). The lessons from this study of diesel aerosols in the low PM emitting regime are applicable to gasoline emissions because consideration of the particle characteristics in terms of size and number aids greatly in understanding distinctions between technologies, fuels, and PM mass emissions. Figure 45 compares the average particle size distributions for test fleets of gasoline and diesel vehicles. The diesel results are those of CRC E-43 while the SI results were measurements conducted on Minnesota roadways in a project sponsored by the United States Department of Energy (U.S. DOE). The data shows the clear difference in the size distribution of the larger particles, those that account for most of the PM mass, between gasoline and diesel emissions. However, those differences can disappear under certain vehicle operating conditions. Acceleration for the gasoline test fleet increased its emissions to a level that exceeded the diesel test fleet emissions. If considering nanoparticles only, those in the sub-50 nm size range that contribute almost null to PM mass; the emissions are similar for both cases. These findings and various other similar reports from many parallel or subsequent studies to those cited above are the evidence that points to the need for complementary or alternative test

methods in order to improve the assessment of the PM emissions from future clean vehicles.

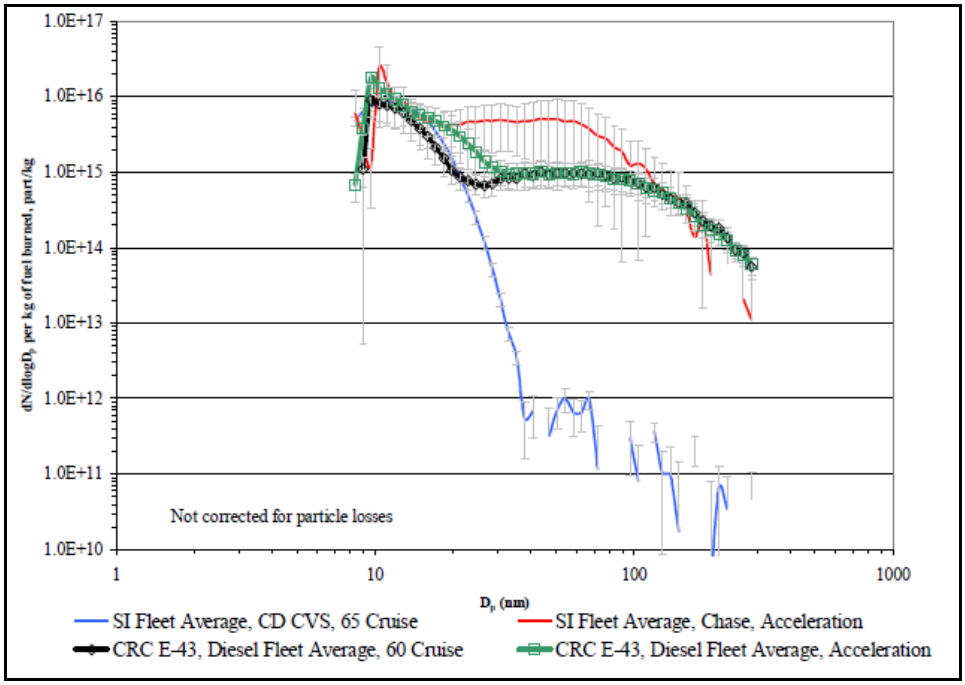


Figure 45. Particle size distribution (particle number concentration against particle size) from on-road measurements with a mobile laboratory for chasing vehicles. Source: Kittelson et al., 2004.

The practice of counting and sizing aerosols to support the study of airborne particles in indoor and outdoor air is an area of science that has been around for a long time. This means the instrumentation and the laboratory measurement practices for conducting an accurate measurement are familiar and mature. They are also practical and can be applied readily to the study of vehicle emissions as evidenced by the sum of the work cited in this TSD. There are many other descriptors of PM emissions that are of interest such as particle surface area, density, volatility, or chemical composition among others. However, the physical characterization of the particle emissions in terms of size and concentration is the most widely used and referenced approach. The experience in aerosol science and air pollution is proving very useful for application to the area of source-specific pollution measurements, most notably vehicle and engine emissions. One of the best examples of the recent advances in metrology for PM emissions is described in the next section.

The European Particle Measurement Programme

The Particle Measurement Programme was launched in 2001 under the auspices of the United Nation's Economic Commission for Europe - Group of Experts on Pollution and Energy (UN-ECE-GRPE). This program was designed to deliver a regulatory procedure for Europe that would either replace or complement the existing procedure used for PM mass measurement for vehicle emission certification. The principal driver for the initiation of PMP was the realization that a PM mass-based standard alone may not be sufficiently sensitive to be able to discern conclusively the differences between the filtration efficiency of various diesel control aftertreatment options. In an effort to promote only the best available control technology for diesel vehicles, a solid particle number (SPN) based limit was devised along with the associated test protocols, measurement procedures, and instrumentation requirements suitable for compliance verification and certification. The PMP working group devised a three-phased approach. In the first two phases of the program, a wide range of measurement instruments and sampling systems were assessed over standard regulatory tests. During the third phase, an inter-laboratory correlation exercise was conducted. Confirmatory testing was conducted for repeatability, reproducibility, and practicality on various vehicle and engine technologies. During the first phase, measurement systems addressing several key particle properties were evaluated. In addition, dilution methods, sample conditioning and costs were assessed. The second phase subjected the best performing systems from the first phase to a more rigorous evaluation. The aim was to confirm the results of first phase and determine fundamental levels of repeatability. The second phase testing confirmed that the revised filter mass measurement method and the particle number method met the original objectives of the program, which were to identify the best metrics for future particle measurements, to determine the instruments and methods needed to determine those metrics, and to investigate the potential of these advances for "type approval" testing, or certification testing as is more commonly referred to in the U.S. The project showed, in the end, that improvements to the PM mass measurement were feasible and that a SPN-based limit was also able to distinguish between the emitting regimes of various technologies as shown in Figure 46. The program produced the scientific basis for the Euro 5/6 limits for particle number and PM mass for EU type approval. The findings may be integrated into the test methods and PM standards applicable to future heavy-duty engines.

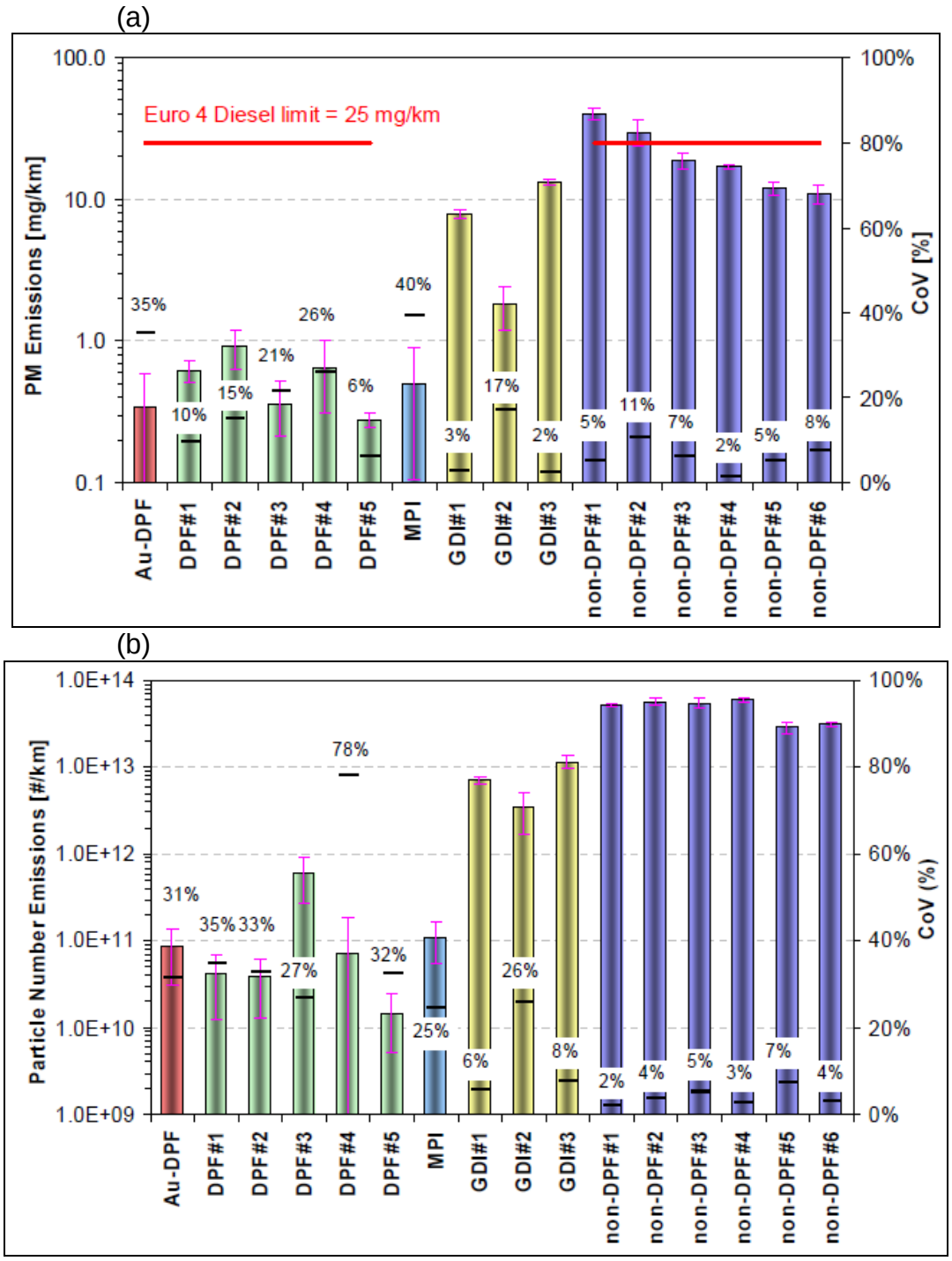


Figure 46. Final results for the inter-laboratory correlation exercise of the light-duty vehicle transfer standard (i.e., the golden vehicle) presented in terms of PM mass (a) and particle number (b) emissions.
Source: Andersson et al., 2007.

The PMP test protocol contains a number of elements, including efficient dilution air filtration, size pre-classification (50 percent particle size cut-point at 23 nm), hot

dilution, semi-volatile particle removal, and particle counting. Semi-volatile nucleation mode particles are generally less than 20 nm. Conversely, most solid particles are larger than 20 nm. Volatile particles <23 nm are excluded to reduce measurement variability caused by particle formation that is strongly dependent on sampling conditions. Figure 47 shows a diagram of the principal sampling elements necessary to conduct solid particle counting in accordance with PMP recommendations.

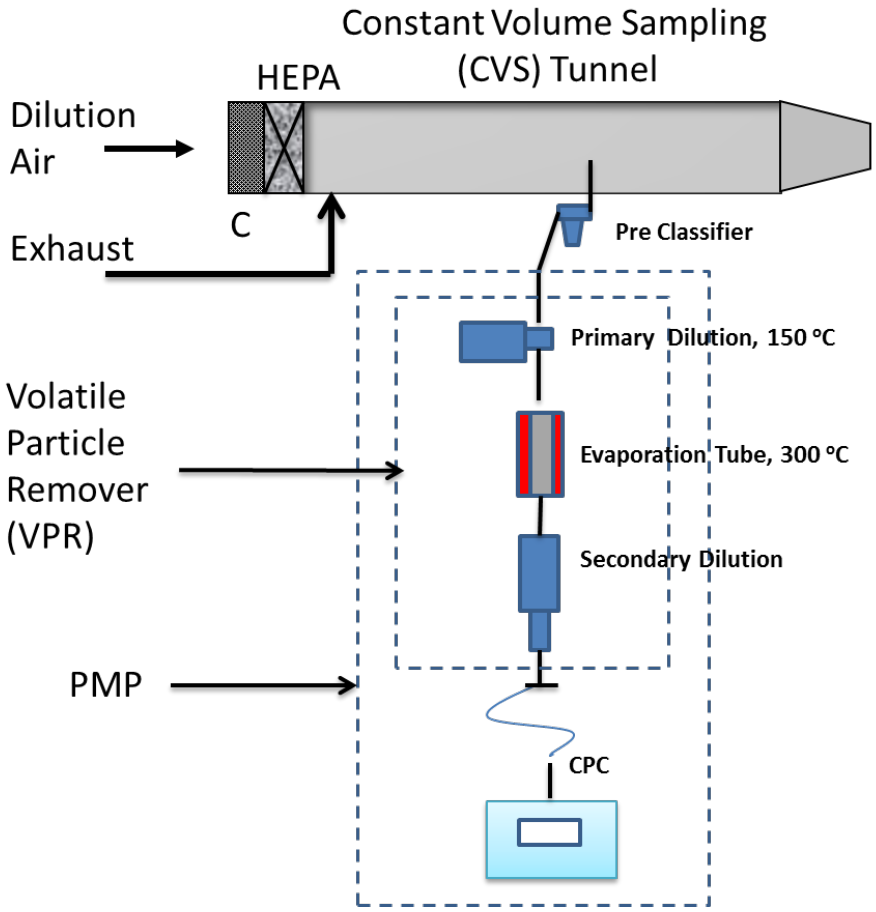


Figure 47. Conventional PMP sampling protocol

Because of the success of PMP, the recognized practical advantages offered by the SPN measurement procedure, the advantages of one common test procedure for a global car industry, and the emerging and specific interest in UFP emission measurement and control, ARB originally proposed the adoption of a new and optional PM SPN standard based on the PMP test method. The PMP method was selected because it offers superior flexibility and ease of use over the gravimetric measurement without backtracking on the needed accuracy for a regulatory method. Another advantage is that it is the only new measurement method that has undergone rigorous and extensive international study and scrutiny. ARB gained experience with PMP by participating informally in the inter-laboratory comparison of the transfer test vehicle standard, the Golden Vehicle, in 2007 (ARB, 2008). ARB

and the Joint Research Center of the European Commission (JRC) have collaborated on a number of research areas of mutual interest under a Memorandum of Understanding on Emissions from Transport. One of those research topics is the PMP measurement method. ARB's participation was an informal part of the light-duty vehicle Inter-laboratory Correlation Exercise (ILCE_LD) that PMP conducted formally at 11 laboratories from Europe and Asia. The GV was a reference standard that was evaluated at all of the participating laboratories. The California testing was unique and expanded the ILCE_LD by including PM emissions testing for soaks cycles, and fuels, which were not originally part of the PMP. ARB staff evaluated the effects of vehicle soak-time and pre-conditioning on PM and particle number results, and compared various particle sampling instruments for PMP method (Ayala et al., 2008; Dwyer et al, 2010). The effort was greatly beneficial for ARB and our work for PM test method development. It also gave the agency an opportunity to compare, one-to-one, our measurement capabilities for low emissions against those of other laboratories from around the world. It showed that the test laboratory of ARB can generate emission measurements that compare very well relative to the same measurements by the PMP participating laboratories as shown in Figure 48.

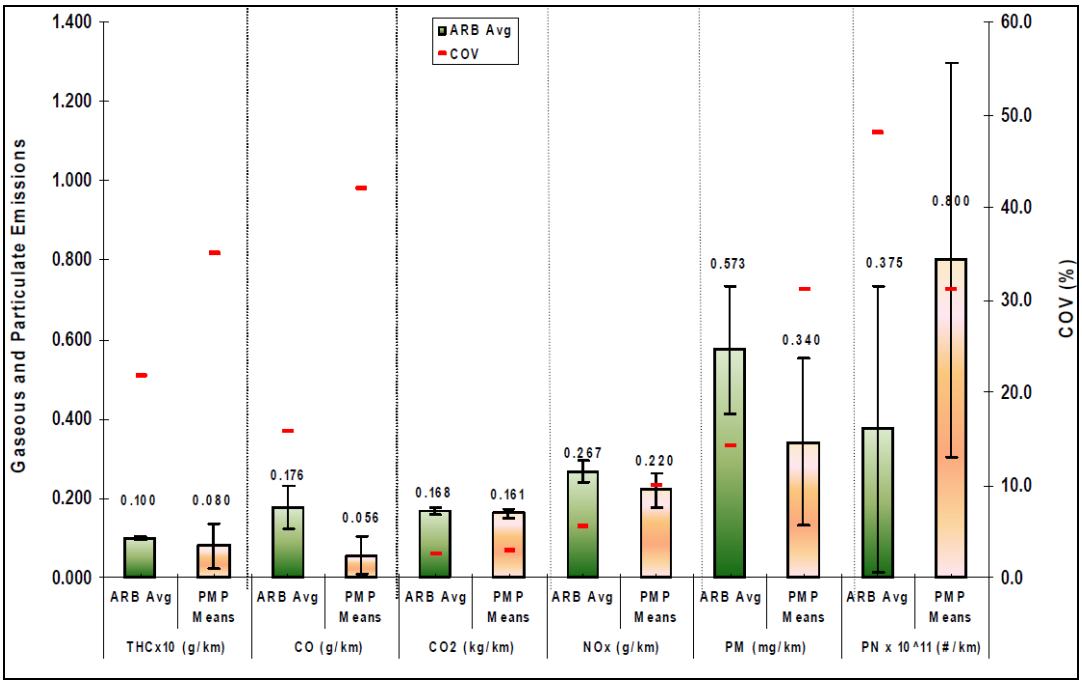


Figure 48. Comparison of average emissions and their standard deviations for gaseous and PM emissions from the PMP golden vehicle for ARB test laboratory and the PMP participating laboratories.
Source: Ayala et al., 2008.

During the course of regulation development and from interaction with industry, academia, the U.S. EPA, and others, it became apparent to ARB that there are still important questions concerning what the PMP test method does and does not do and that additional time is needed for further investigation. At this point, the agency will not be recommending an optional SPN standard. Instead, ARB is making a commitment to continue PM test development work to try to answer the specific data gaps related to the PMP test method as well as to explore other promising options

beyond PMP and PM mass. All this will be done in an effort to advance the general understanding of PM emissions from future vehicles as well as to explore areas for improvement and efficiency gains in the laboratory practices that can yield a superior test procedure with the needed sensitivity for accurately measuring PM at the 1 mg/mi level.

ARB has conducted a number of investigations on the PMP method for heavy-duty diesel engines in partnership with researchers from a number of academic research groups (Ayala et al., 2007; Durbin et al., 2008; Herner et al., 2007, 2009; Robertson et al., 2007; Zhang et al., 2008; Zheng et al., 2011). The major focus has been to determine if there are a significant number of sub-23 nm and semi-volatile particles and how can the PMP method be modified to measure those particles. The exhaust PN and PM mass distribution for a typical uncontrolled diesel engine is shown in Figure 49.

ARB has reported that one important question concerning the structure of the PMP measurement is the method's exclusion of particles in the sub-23 nm size range. The basis for this exclusion, according to PMP reports, is that these particles are semi-volatile in nature and, hence, are highly sensitive to sampling conditions and subject to variation. Second, the European method assumes that these particles are likely soluble and, hence, not as great a concern as solid particles because of the body's natural removal mechanism. In this work, ARB staff will not attempt to address the second point made above. That is left for discussion in section V, subsection F: Health Effects in the ISOR. However, previous research by ARB and others has already shown that the counting of sub-23 nm particles is both feasible with current instruments and necessary because depending on vehicle operation (i.e., duty cycle), most of the particle emissions can occur in this size range as shown in Figure 50. In this work, ARB investigators showed that a DPF-equipped engine can result in particle emissions, which depending on the duty cycle, can be mostly in the sub-23 nm size range.

Care must be taken when heating the sample train to remove semi-volatiles. The semi-volatile fraction of the PM can account for 10-30% of the PM mass and 70-90% of PN (Biswas et al., 2008). Increasing the thermodenuder temperature from 150 to 230°C, as shown in Figure 51a, can lead to can lead to a decrease in nucleation mode particle formation. This effect is especially important for diesel vehicles with advanced aftertreatment, as shown in Figures 51a and 51b.

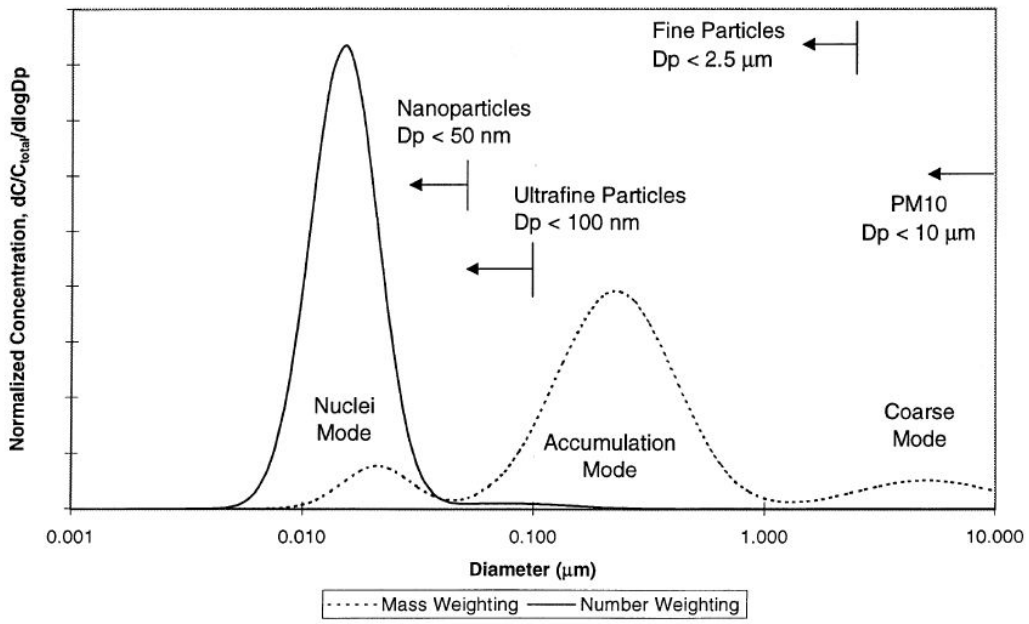


Figure 49. Typical engine exhaust size distribution for both PM mass and PN Source: Kittelson, 1998.

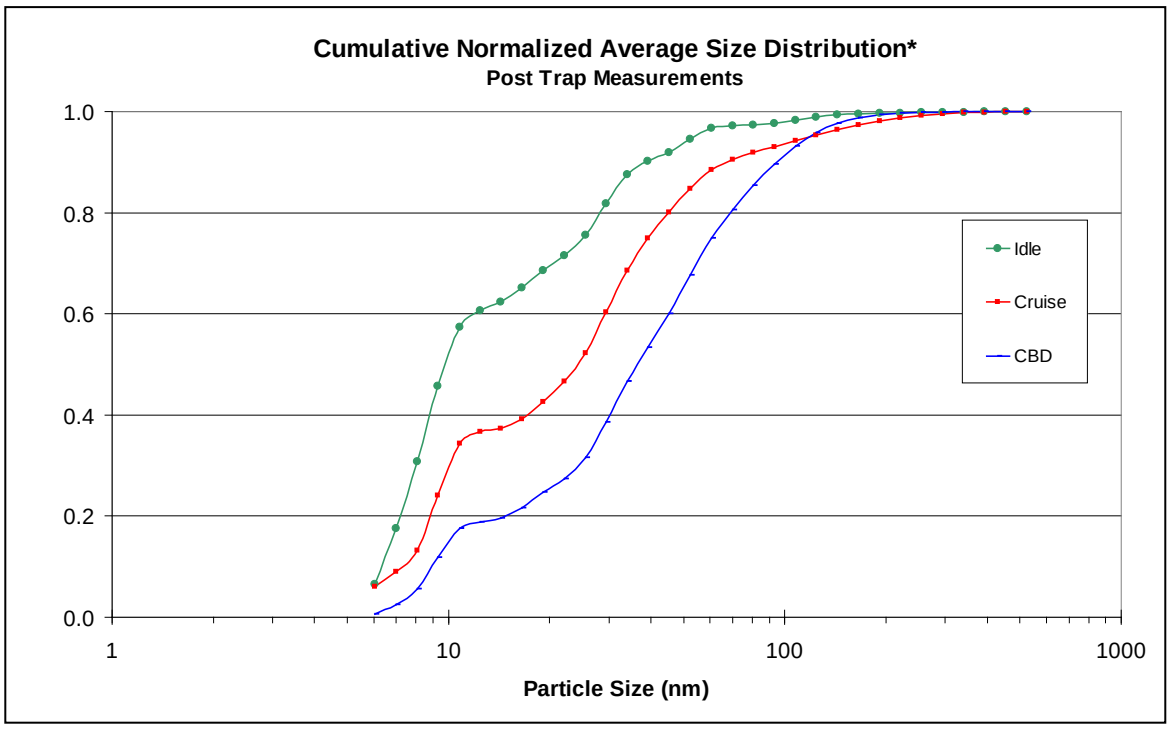


Figure 50. Cumulative normalized size distribution using the PMP test protocol. 25-75% of solid particles are smaller than 20 nm and are not counted by the PMP method. Source: Herner et al., 2007.

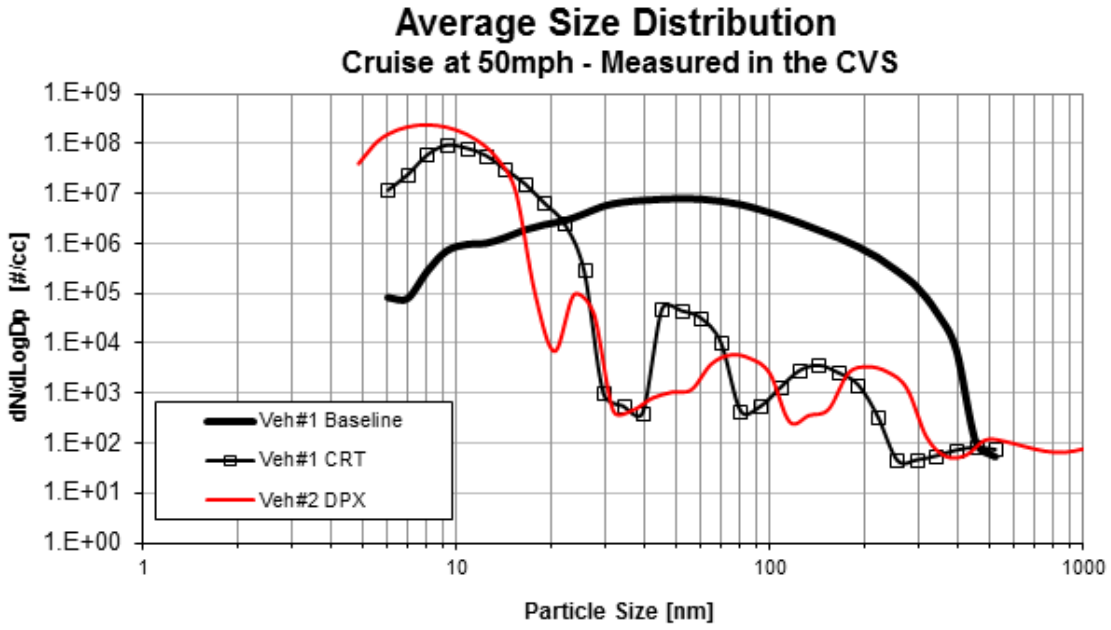


Figure 51a. Size distribution for HDDV without heating
Source: Herner et al., 2011.

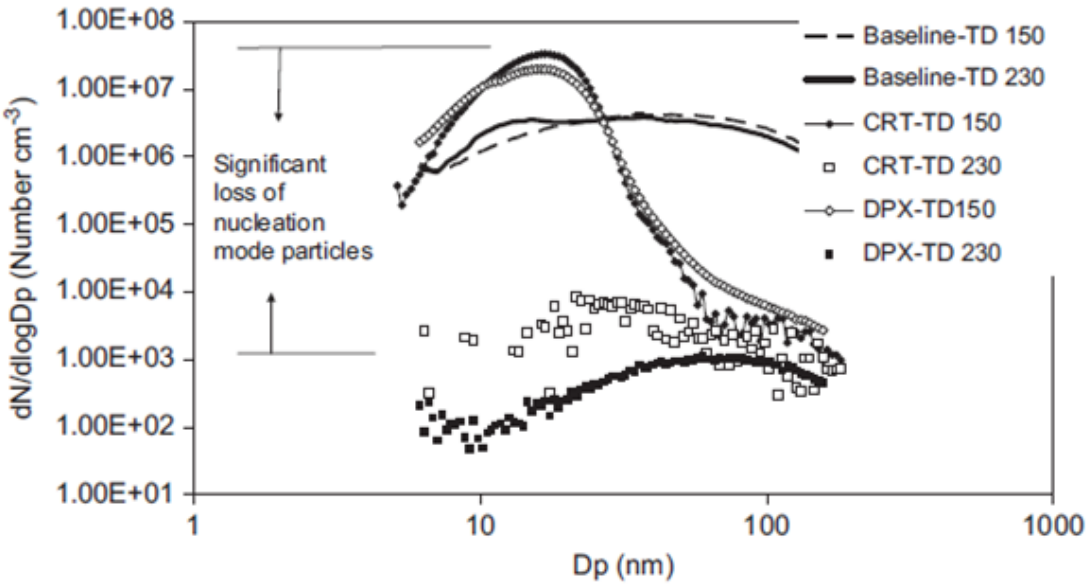


Figure 51b. Size distribution of diesel exhaust after heating between 150 and 230 degree C.
Source: Biswas et al., 2008.

In the same work, ARB investigators also showed that inclusion of these smaller particles in the sub-23 nm size range is feasible and does not automatically result in a measurement that is less precise than a measurement for particles larger than 23 nm. Figure 52 illustrates that currently available particle counters indeed compare favorably in terms of measurement precision against the counting instrument recommended for use in the PMP test procedure.

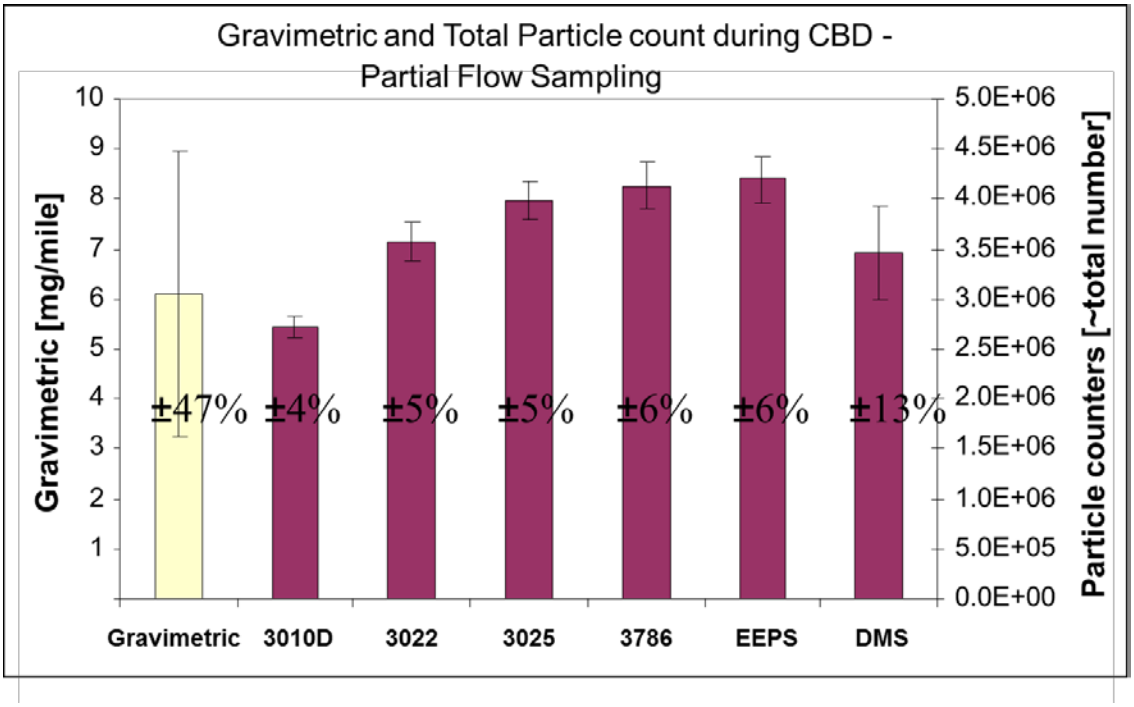


Figure 52. Gravimetric and post-DPF solid particle number measurements. The PMP particle counter is 3010D. The rest are commercially available particle counters and electrometers (EEPS and DMS) able to measure particles smaller than 23 nm in diameter. Source: Herner et al., 2007.

In a more recent study, during a follow-up evaluation of the European PMP methodology via on-road and chassis dynamometer testing for several DPF equipped heavy-duty diesel vehicles, Johnson and co-workers concluded and confirmed ARB's previous findings that "a significant fraction of sub-23 nm particles are not being counted by the PMP approach" (Johnson et al., 2009). The recommended PMP practice with a >23 nm cut point has the advantage of removing nucleation particles that can contribute to variability, but also removes the ability to characterize very small particles that survive heating in the volatile particle remover (VPR). The results of the evaluation are shown in Figure 53.

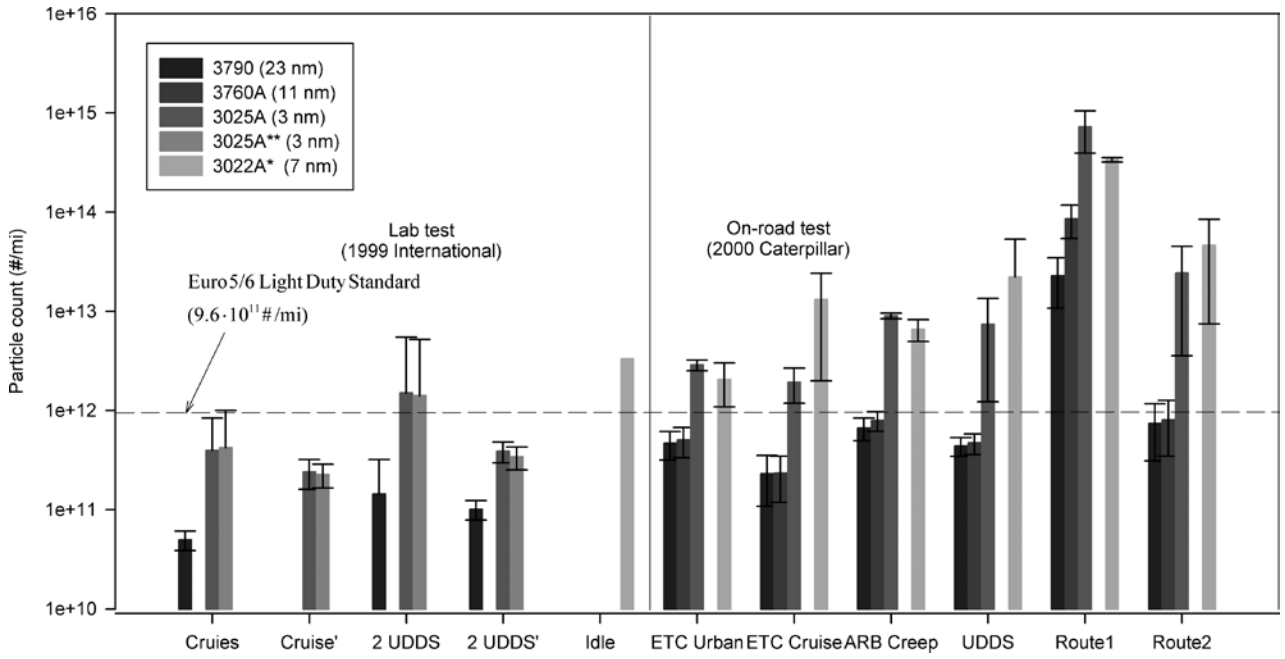


Figure 53. Particle number counts per mile for lab and on-road tests for HD trucks. Source: Johnson et al., 2009.

To support this rulemaking, ARB staff tested three GDI vehicles over the FTP (Appendices-Table 5, vehicles 7, 8, and 9) for SPN emissions using the PMP protocol. SPN emission rates are shown in Figure 54. A minimum of three repeat tests were run for vehicles 8 and 9 and two repeat tests were run for vehicle 7. As with PM mass emissions, the SPN emissions for all three vehicles were highest in the Phase I (cold start) portion of the FTP cycle with SPN emissions ranging from 6.8 $x10^{12}$ to 1.2$x10^{13}$ particles/mi. Average Phase I (cold start) SPN emissions measured were 9.4 $x10^{12}$ particles/mi. SPN emissions were an order of magnitude lower in Phases 2 and 3 of the FTP after engine warm up. Average SPN emission rates were 1.0 $x10^{12}$ and 1.2 $x10^{12}$ particles/mi in Phase II and Phase III, respectively. The average FTP weighted SPN emissions for the three GDI vehicles is 2.8 $x10^{12}$ particles/mi. The measured SPN emissions would be 25 to 30 percent higher if adjusted to reflect the amendments (E/ECE, 2009) to the PMP method where a particle number correction factor is used to account for particles lost in the sample train.

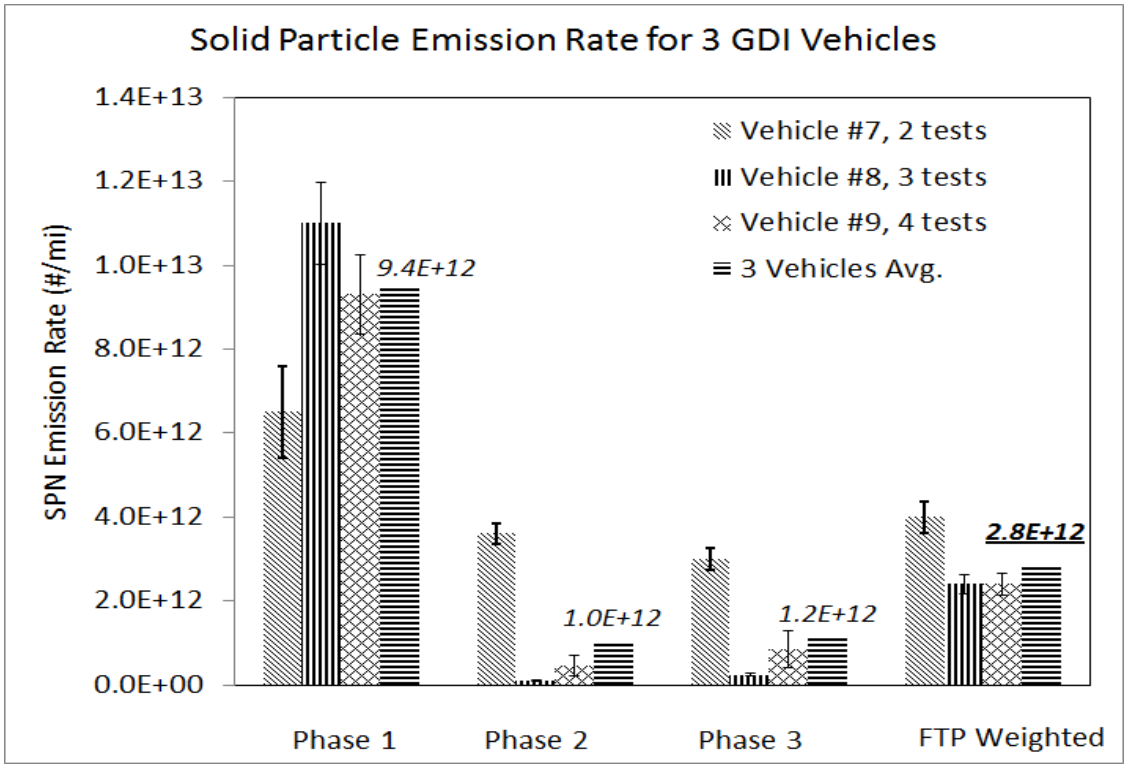


Figure 54. Solid Particle Number Emissions for 3 GDI Vehicles Using Phase 2 Certification Fuel

Figure 55 shows the results in terms of PM mass and SPN emissions for each phase of each test conducted on ARB's three GDI vehicles. The figure displays three clouds of decreasing data points for cold start, warm start and hot running emissions respectively. Figure 56 shows the FTP-weighted SPN and PM mass results for each FTP test. The bridge between SPN and PM mass is of fundamental importance because it opens the door for setting limits based on both mass and number as was done in Europe or based on an optional approach as ARB originally proposed based on SPN. The focus on this correlation dates back to the early stages of the PMP program as shown in Figure 57. PMP shows that the relationship between mass and SPN holds for both gasoline and diesel in the various emitting regimes governed by the use of PFI, GDI, and DPFs.

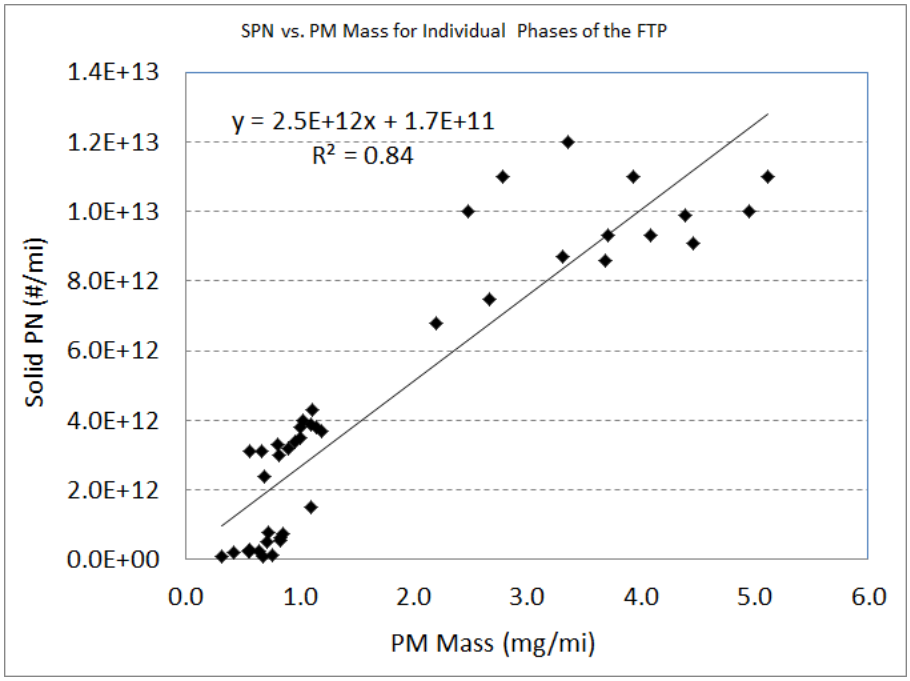


Figure 55. PM Mass and SPN emissions for three GDI vehicles over individual phases of the FTP.

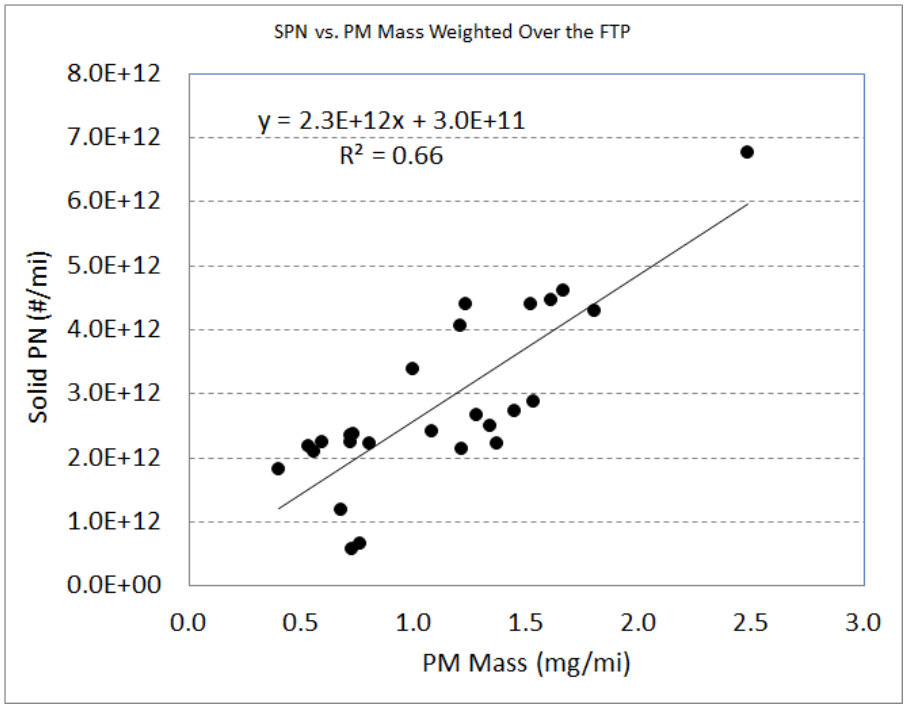


Figure 56. FTP-weighted PM mass and SPN emissions for three GDI vehicles.

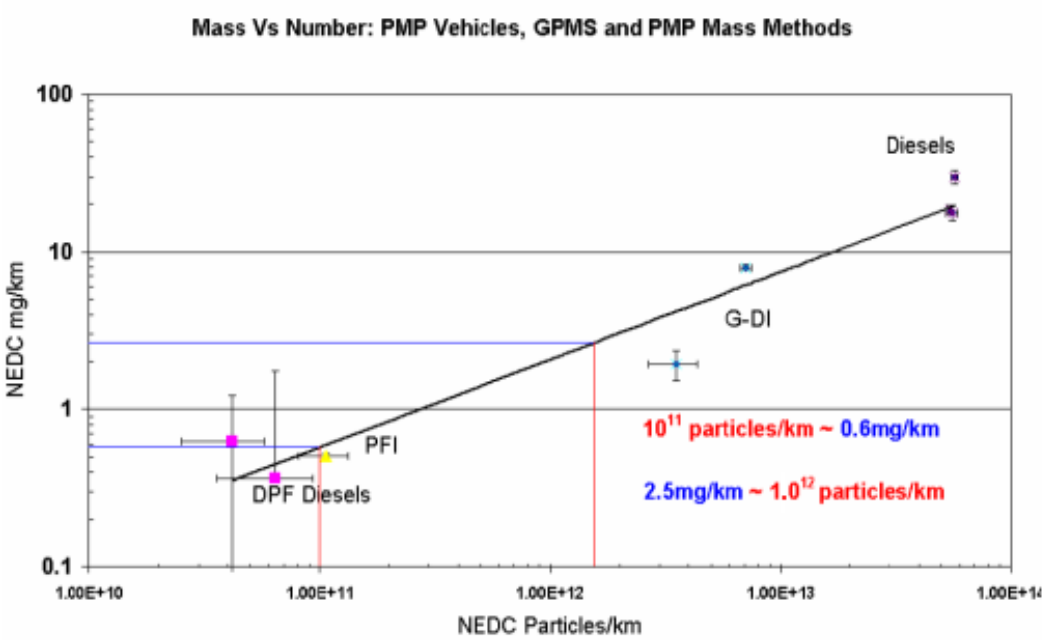


Figure 57. Correlation of PM mass and solid particle number showing directional relationship between both metrics for various types of vehicles. Source: Andersson and Dilara, 2005.

The regression line in both Figures 55 and 56 suggests that a total SPN limit of $7.5x10^{12}$ particles per mile corresponds to a PM mass limit of 3 mg/mi. The regression lines in both cases also show a fairly strong R^2 correlation. As expected, the regressions based upon the individual phases are dominated by the highest emissions points in Figure 55, which are the cold-start emissions. Figure 58 shows the expected scatter present for very low emission levels not associated with cold-start emissions. The hot-running and warm-start emissions are well below the proposed limit of 3 mg/mi, and their divergence from the regression line is not entirely surprising. When SPN concentrations are low, it is expected that the corresponding soot concentrations will be low as well. When the emissions consist primarily of carbonaceous particles (soot), there is a moderate correspondence between the number of solid particles and the total PM mass in the emissions. As the emissions become dominated by organic volatile species, lack of correspondence is expected from the variation in semi-volatiles caused by sampling conditions (e.g. temperature and concentration).

These results have important implications beyond the relationship between mass and number emissions. First, they demonstrate the ability of present-day testing practices and measurement approaches, both in terms of mass or particle counting, to determine vehicle emissions in the 1 mg/mi range and below. This is, then, critical evidence that suggests that the stated measurement challenges and desire to explore improvements to the current test methods is by no means an indication that measurements at the proposed 3 mg/mi and the future 1 mg/mi are not feasible. They are indeed feasible today. Second, these results also show conclusively that

car technology is indeed ready to achieve and meet the proposed new PM emission limits. The test vehicles included in ARB's investigations show that current technology GDI engines can not only meet an introductory 3 mg/mi standard, but they can also meet the future 1 mg/mi. Thus, the focus of the car manufacturer is expected to be on expanding and applying this technology over a wider range of operating conditions (i.e., over more aggressive driving as represented by the US06 cycle discussed previously), over more vehicle platforms, and on making sure that low emissions are maintained over the useful life of the vehicle. But given the emissions test results presented, ARB staff believes that the car industry has a great start. For its part, ARB will continue to evaluate alternative and complementary test methods to quantify PM emissions from different types of very low emitting vehicles. The work centered around PMP will continue to explore the same basic questions: (1) should the method measure particles <23 nm and (2) should the method measure all particles, not just solid particles. Elsewhere, these same questions are also now attracting some expert attention.

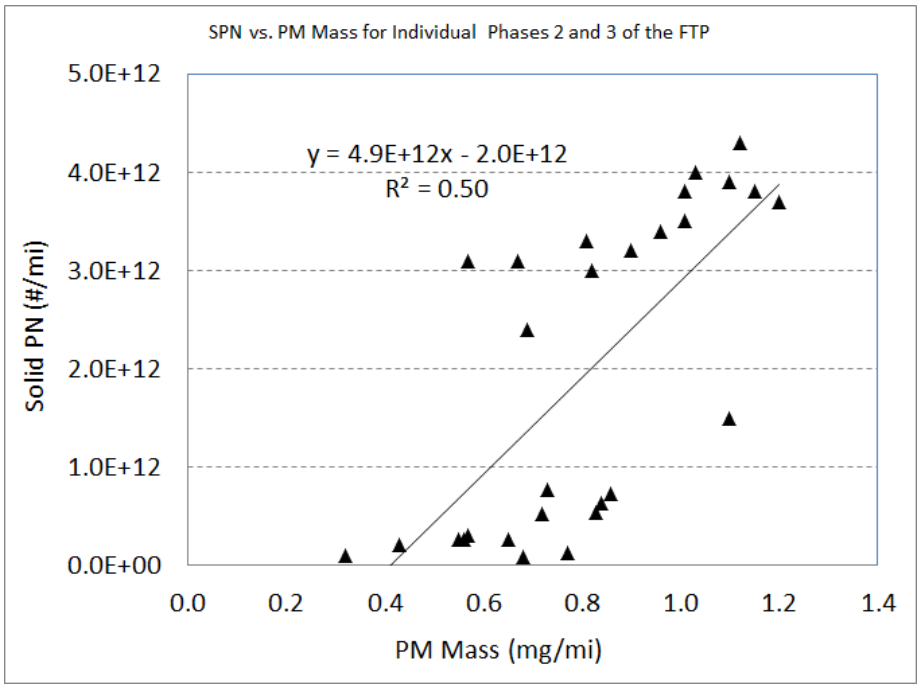


Figure 58. PM mass and SPN emissions for three GDI vehicles over the FTP. The regression is for all phases; the chart shows only data points for Phase II (hot running) and Phase III (warm start).

In 2008, an international group working to develop a PMP for heavy-duty engines agreed that counting particles smaller than 23 nm is important. PMP attributes the impetus for this work to findings by ARB (Durbin et al., 2008). It has been shown that metal-based additives in gasoline and lubricating oil generate solid particles in the sub-23 nm size range in vehicles without particle filters.

Vehicle exhaust contains semi-volatile particles including harmful organic compounds such as PAHs and inorganic compounds such as sulfates (Kado, 2005). Thus, this does raise the question of whether the PMP should be modified to include all particles, not just solid ones.

Figure 59 summarizes the PM mass and SPN emissions for all available test results that ARB collected during the LEV III rulemaking effort as well as data available from the published literature by others. In the PM emission range of 1-100 mg/mi, the SPN-PM data points collapse fairly well onto a single line. However, at low PM emission levels (<1 mg/mi) and high PM emissions levels (>100 mg/mi), the data points scatter on the same side of the line. Assuming the total particle number is larger than the SPN, this suggests that in these ranges, the PM mass increases faster than the increase of the SPN.

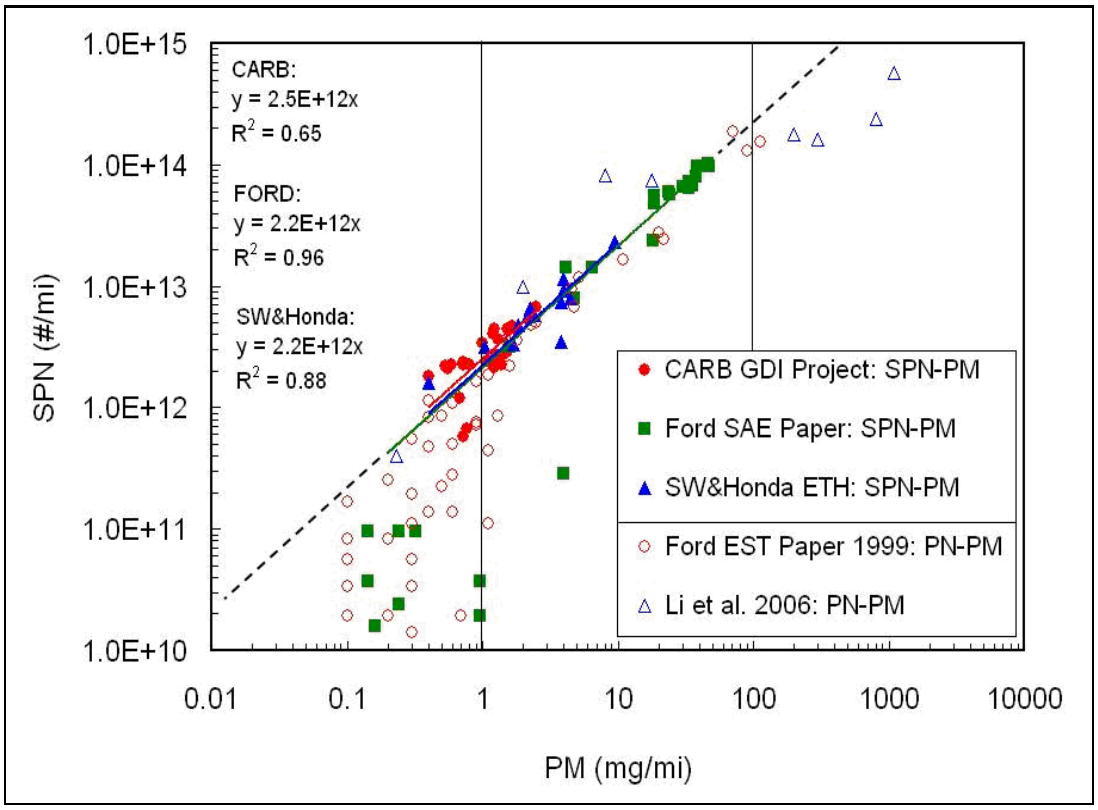


Figure 59. PM mass and SPN emissions for all available test results

The interest in understanding the nature of the particles from PMP measurements below 23 nm has generated additional research. In recent studies (Swanson and Kittelson, 2010; Khalek and Bougher, 2011; Zheng et al., 2011), researchers evaluated alternative ways to remove the semi-volatile fraction such as a catalytic stripper (CS) and compared this approach to the thermal method such as thermodenuder (TD) and VPR. A CS is a device which is composed of an oxidation catalyst and sulfur trap catalyst as an alternative approach to removing volatile particles. A thermal denuder is a device that is widely used for measuring volatility of particulate matter by passing the particles through a heating section to vaporize

volatile particles, and then the vapors are adsorbed onto an activated carbon adsorbent. A VPR consists of three components, a hot dilution section, an evaporation tube to evaporate semi-volatile material, and a cool dilution section to cool the aerosol and to reduce its concentration to less than 10,000 particles/cm^3. They found that the CS showed much less of a tendency to form artifact particles compared to the thermal method for volatile removal used by TD and VPR. These studies suggested that the thermal method for removing volatile particles may generate artifact sub-23 nm particles with the presence of sulfate and carbonaceous particle precursors, which are typical compounds of the diesel exhaust particles. Zheng et al. (2011) concluded that these particles are mainly present below 10 nm, suggesting that lowering a cut point to 10 nm is desirable and feasible. More research is needed to develop methods that do not promote the post-PMP re-nucleation of precursor material and the formation of particles.

Recently, researchers from Ford Motor Company published a study and provided their insight on PMP measurement (Maricq et al., 2011). The study concludes that particle counts from GDI vehicle emissions correlate with PM mass, just as for diesel LDV. Similar to other studies, the Ford study found that the correlation is due to the nature of the particle size distribution produced in combustion and that PM emission reduction methods impact the entire size distribution of solid particles, not just those >23 nm.

Global Harmonization of PM and Particle Number Test Procedures Under a New UN- ECE Effort

The UN-ECE is working to develop a Global Technical Regulation on passenger car and light-duty vehicle test procedures. The intent is to develop a universal test procedure that environmental agencies can adopt worldwide. A single test procedure will reduce the number of required certification tests for selling vehicles legally in a global market. The new PM test procedures will harmonize the best elements of 40 CFR Part 1065, UN-ECE Regulation 83, and Japan's Attachment 42 standards. Completion of the UN-ECE regulation is planned for the end of 2013.

ARB staff agreed to participate in these critical discussions given the related and on-going PM and PN work being conducted in California in support of the Advanced Clean Cars Program – LEV III PM standards. The UN-ECE group is made up of researchers, industry, and regulators. The UN-ECE group is working through many of the same technical issues that ARB is currently working through for LEV III. A snapshot of the issues that the UN-ECE group has identified and resolved are similar to PM measurement issues being faced by the ARB for the LEV III rulemaking. A complete list of the UN-ECE issues can be found in the Appendices (Table 6). The group has had to find solution to the same kinds of issues as discussed in this document. The UN-ECE group has been very effective at reconciling the variations among the test hardware, temperatures, and weigh room specifications. The more challenging issues have been those associated artifact

correction, filter handling, measuring DPF regeneration PM emission, and particle number counter calibration timing and procedure.

The group has asked ARB for input on very specific testing questions such as: how to best correct for background artifact, filter face velocity, filter handling, and filter blanks, number of filters, filter size, and sample train temperature (see Figure 60). The UNECE group has worked extensively on how to deal with PM mass artifact correction.

In North America, the U.S. EPA and ARB allow a dilution air correction but not a tunnel correction because it could incentivise the use of a dirty dilution tunnel. The UN-ECE allowed the use of a minimal correction factor with a hard cap, which compels the use of a clean dilution tunnel. Data collected by the UN-ECE group showed that the PN dilution tunnel background emissions are very low as shown in Figure 61. The draft regulatory language currently contains a background correction limit of $6x10^9$ #/km or 1 mg/km on the NEDC. Most other specifications are similar to those included in 40 CFR Part 1065, including filter temperature and flow rate, number of filters, weighing chamber requirements, and sample train physical specifications.

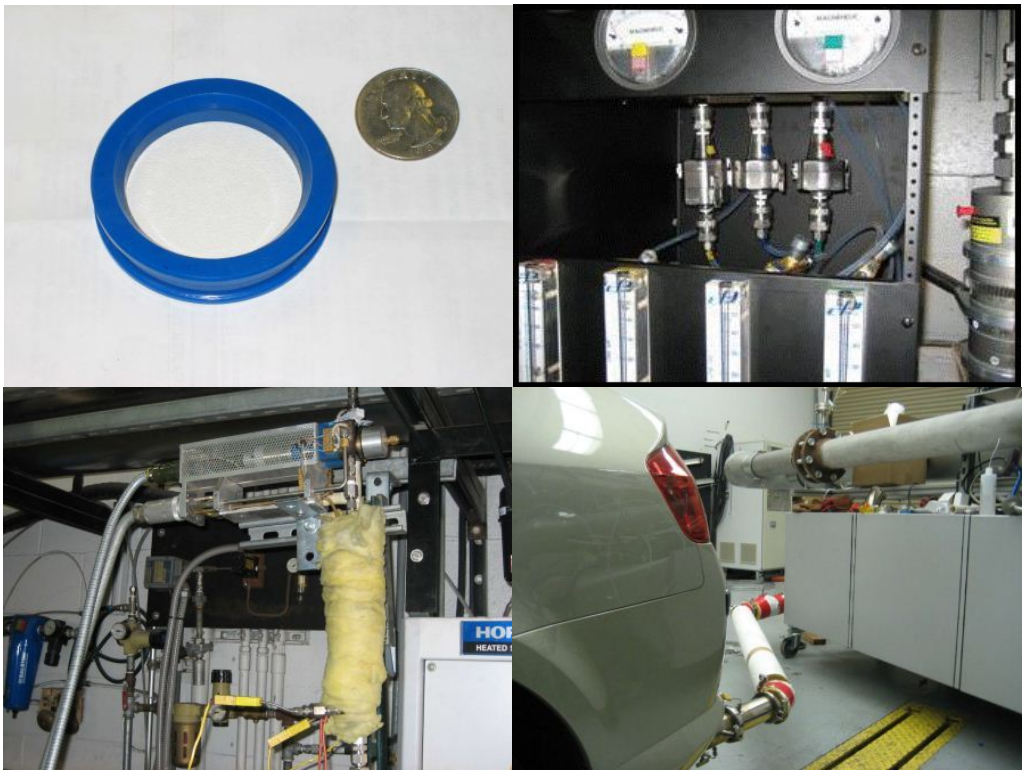


Figure 60. UNECE issues include filter size, filter temperature, and insulated sample train

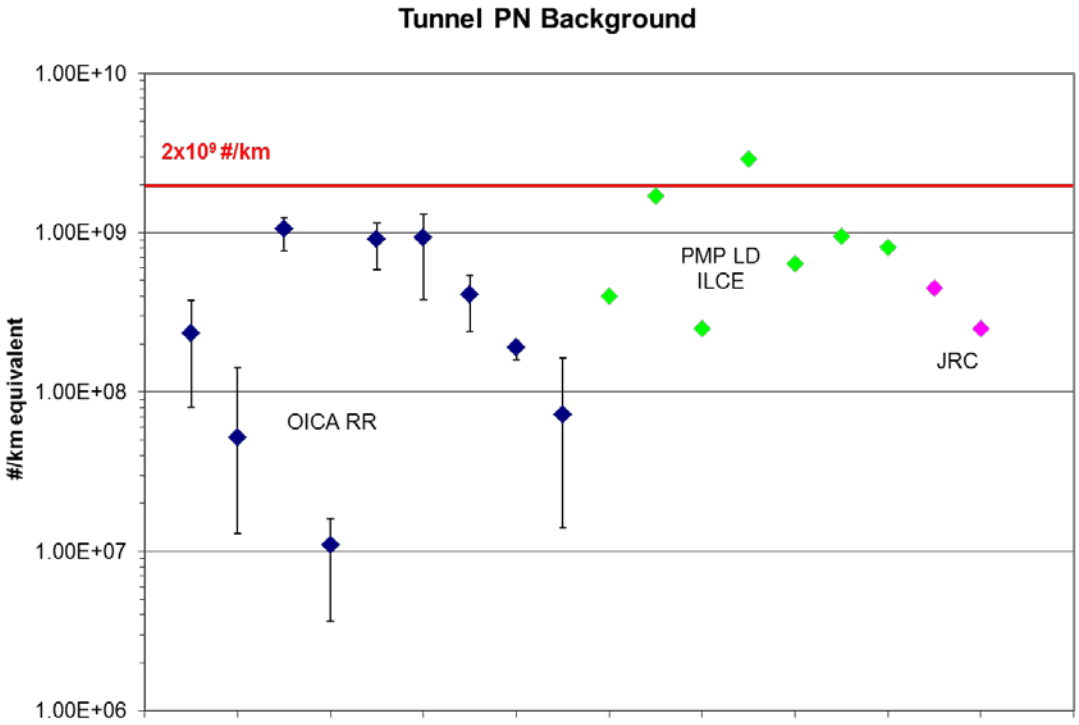


Figure 61. Tunnel SPN background test results. Working data from WLTP-DTP-PM/PN Subgroup, 2011.

Integrated Particle Size Distribution

There are other promising areas of measurement work that may offer a better alternative to either PMP or the gravimetric measurement. One of these is the integrated particle size distribution (IPSD) method argued by Liu and co-workers (Liu et al., 2009). This method relies on inferring mass emissions from the measured particle size distribution in the emissions with knowledge about the density and geometry of the particles in the PM emissions. In this method, the particle size distribution (PSD) is determined using an Engine Exhaust Particle Sizer (EEPS) spectrometer, a Scanning Mobility Particle Sizer (SMPS), or the differential mobility spectrometer (DMS). Figure 62 shows a particle size distribution using EEPS during a cold start test. Figure 63 shows a comparison of particle size distributions for an EEPS and SMPS for a John Deere diesel engine. The PSD is then multiplied by the density distribution of the particles and then integrated to obtain the total mass of the emissions. Figure 64 plots three effective density versus mobility diameter distributions. A detailed description of the EEPS is contained in Johnson et al. (2004). The EEPS can generate particle number distributions down to 5.6 nm. The advantage of this method is that there is no need to artificially set a limit to the size of the particles to be counted as with the PMP, which does not count particles <23 nm. This method considers all particles in the entire aerosol emission size range for determination of mass. The challenge, however and perhaps equally limiting as a specific particle size cut-point, is that knowledge about particle density and morphology is necessary. An experimental determination of these two factors

itself adds complexity to the measurement. A recent and widely noted comparative study (Liu et al., 2009) showed that the results from using IPSD to calculate PM mass emissions were within 20 percent of the PM mass measured gravimetrically. Figure 65 shows a comparison of total mass emissions from IPSD and gravimetric methods. This area of work shows promise and ARB intends to continue to follow these developments and to pursue its application to future vehicle testing efforts.

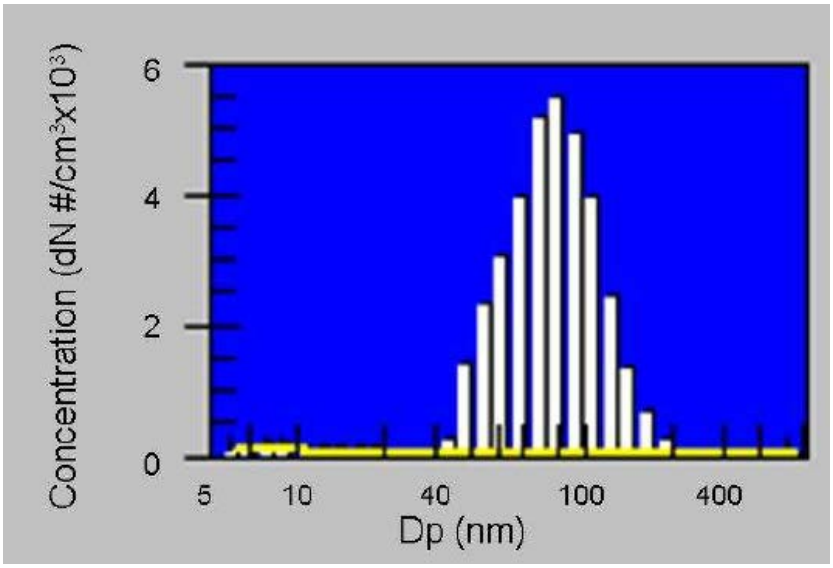


Figure 62. EEPS particle size distribution during cold start
Source: Ayala et al., 2008.

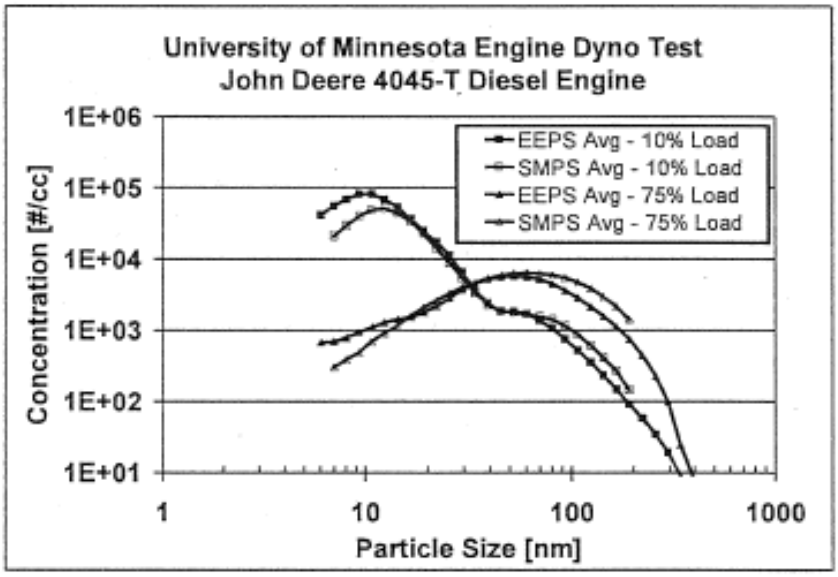


Figure 63. Comparison of EEPS vs. SMPS particle size distributions
Source: Johnson et al., 2004.

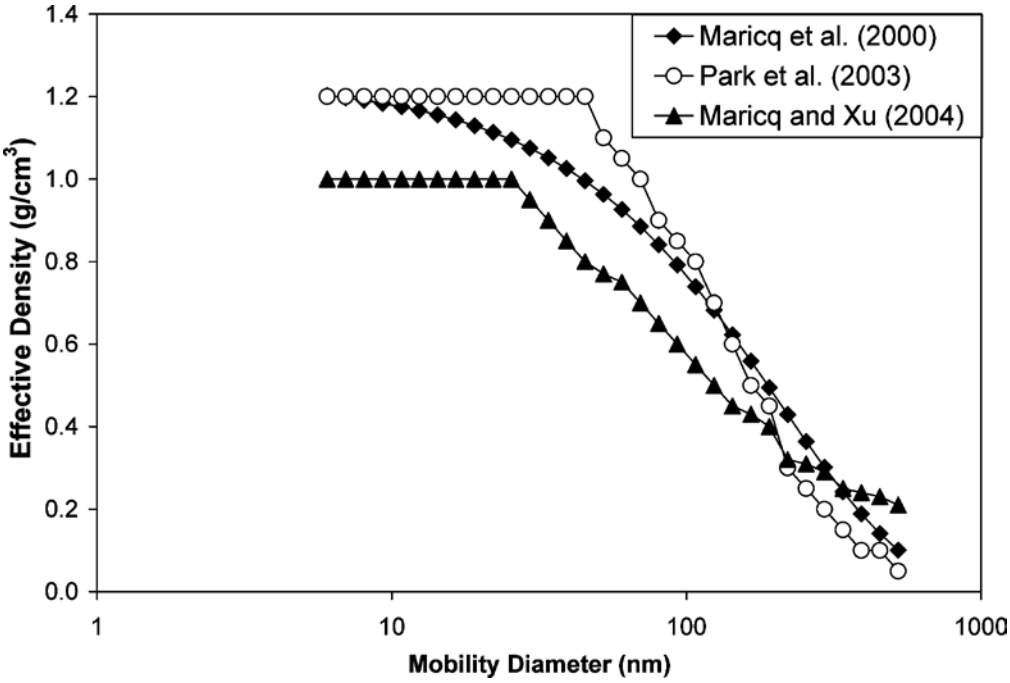


Figure 64. Effective density versus electrical mobility
Source: Liu et al., 2009.

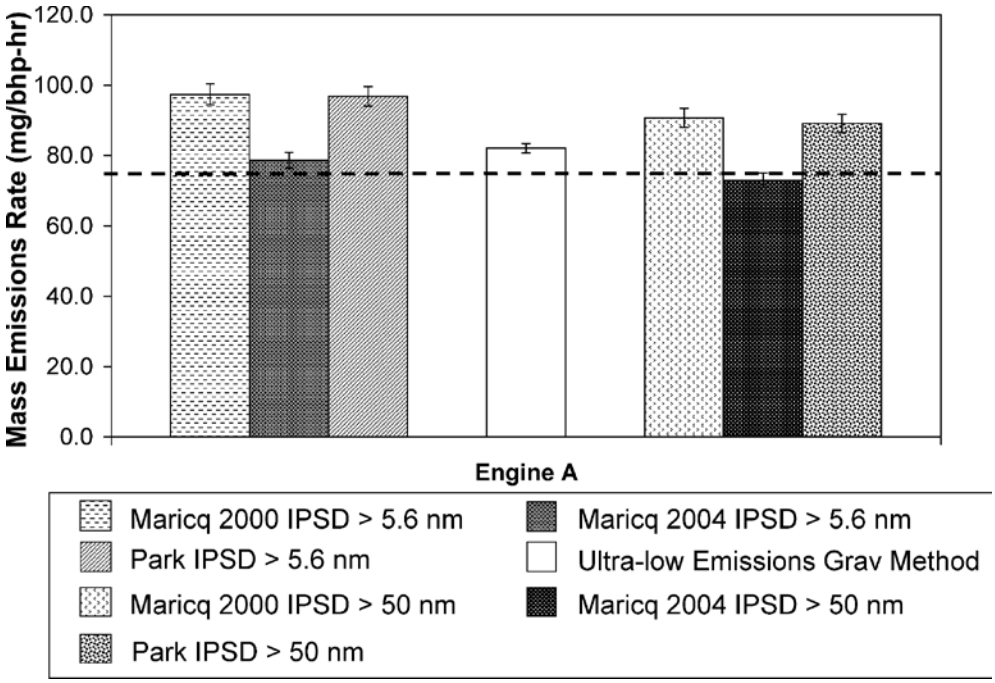


Figure 65. Comparison of total mass emissions from IPSD and gravimetric methods. Source: Liu et al., 2009.

Chemically Reconstructed Mass Measurement Method

Considering the physical characteristics of particles as described above is not the only alternative to PMP. One can also consider the chemical characteristics of the mass emissions, and from knowledge of those chemical constituents, determine PM mass emissions. In this sense, the basic idea of chemical mass reconstruction (CMR) involves determining the principal chemical components in the emissions, presumably through measurement methods that individually are superior to the CVS sampling and gravimetric method, and adding the mass of the chemical components. Some knowledge of the chemical make-up of the emissions is necessary. In general, the main families of constituents of interest are EC, OC, inorganic ions, and trace metals. A description of the technique can be found in "Comparison of Strategies for Measurement of Mass Emissions from Diesel Engines Emitting Ultra-Low Levels of Particulate Matter" (Liu et al., 2009). However, sample collection on filter media is still required. Quartz and Teflon filter media are used to collect samples of PM, which are then analyzed in the laboratory by various analytical methods. These analytical methods are well established. For example, a thermal-optical method for analysis of the quartz filter yields mass concentrations for OC and EC. This method is described later and in relation to the efforts under this rulemaking on black carbon emissions. A similar and specialized analysis of Teflon filters is necessary for results for trace metals, semi-metals, and inorganic ions. In practice, this technique is used as a complementary check of gravimetric mass measurement. Liu's 2009 study showed that CMR mass emissions are generally within ±20 percent of the gravimetric mass. There remains measurement artifacts (either negative or positive artifact) associated with the collection of OC, which is yet to be well handled.

Figure 66 compares chemical reconstruction, IPSD, and gravimetric techniques for measuring PM mass emissions. Chemical reconstruction offers the benefit of maximum selectivity to other methods (Birch and Cary, 1996). EC can be determined without interference between carbonized material, which is an important measurement of the vehicle exhaust. Also, another benefit of chemical reconstruction is that EC results from the thermo-optical method are not statistically different (Birch and Cary, 1996). This is another area of measurement science that ARB is supporting through its research program in the hope that the promise of the method can yield a practical improvement to the current test protocol for PM mass determination.

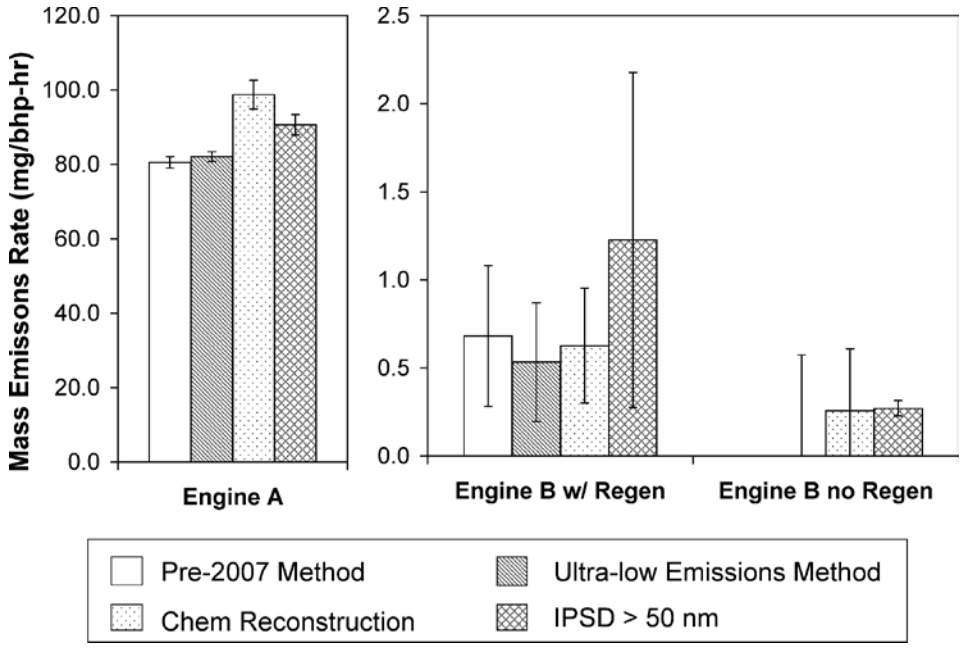


Figure 66. Total PM mass emissions during FTP cycles for Engines A, B with regeneration, and B without regeneration, as measured through the pre-2007 method, the ultra-low emissions method, chemical reconstruction and integrated particle size distribution.
Source: Liu et al., 2009.

C. Conclusion

Sections A and B described the rationale and need for setting lower PM standards and discussed technology and measurement issues, feasibility, benefits and impacts, and potential alternatives for quantification of PM control. The stringency of the proposed PM standards will ensure that LDV and MDV PM emissions do not increase as manufacturers incorporate new low- GHG technology.

The test results support the feasibility of the proposed new PM standards for LDVs and MDVs. There are four major engine technologies that are expected to be used to control GHG emissions; they are PFI, wall-guided GDI, spray-guided GDI, and clean diesel. Test data shows that there is readily available technology in use today that can meet the proposed MY 2017 standards. Test data and trends suggest that existing technology will evolve to easily meet the standards proposed for MY 2025. Compliance with the proposed 3 mg/mi PM 3 standard does not impose a cost increase to vehicles.

ARB's evaluation of measurement issues confirms that slight modifications to 40 CFR Part 1065 and improved laboratory and filter handling procedures allow accurate measurement of PM emissions at the 3 mg/mi level. Additional modifications to increase filter mass, such as reducing the dilution ratio and decreasing the number of filters from three to two or even one, shows promise of improving measurement sensitivity at or below the 1 mg/mi level.

Modifications to the PMP, such as counting sub-23 nm particles and developing ways to reduce artifact formation, may establish a low-cost method for quantification of PM control that has the required sensitivity for measurement of ultra-low PM emissions. IPSD and Chemical Reconstruction are also two techniques that have good potential for measuring ultra-low PM levels.

Further research is needed to improve all alternative measurement techniques before being considered as potential options for quantification of PM control from ultra-low emitting vehicles.

III. REVIEW OF FUEL EFFECTS ON PM EMISSIONS

The emissions rate of airborne toxic compounds and PM have steadily decreased over the years due to stringent regulatory standards (ARB, 2008, Ogawa et al., 1994). Various fuel properties have a direct and/or indirect impact on these emissions (Chen et al., 2010). For example, the reduction of sulfur in fuel composition has significantly reduced secondary PM formation in the atmosphere (Fujimoto et al., 1994). Although diesel engines are known major contributors to PM emissions, recent studies show that gasoline engines also play a key role (Iizuka et al., 2007).

Honda Research and Development (Honda) proposed that PM emissions can be predicted by fuel properties. Honda reported a linear correlation (R^2 ranges from 0.9488 to 0.9979) between PM emissions rates (in both mass and particle number) and the "PM Index (PMI)", a mathematical model (Jetter, 2010). With different oxygenate content in proposed new Phase 3 E10 fuel (from approximately 6 to 10 ethanol percentage of volume), the industry predicted that fuel would have a significant impact on PM emissions from all vehicles.

In order to determine the impact of gasoline fuels with different oxygenate content on PM emissions, three gasoline fuels with different ethanol content were evaluated in a test program. These included a California Phase 2 certification fuel, a California commercial Phase 3 E6 summer fuel, and a California commercial Phase 3 E10 summer fuel. The test fuel specifications are shown in Table 5 below and emission test results are tabulated in the Appendices (Table 5). A detailed comparisons of fuel effects on PM mass and SPN are discussed in section III.A. ARB staff also calculated PMI values of fuels, used these test data to assess the PMI concept and its applicability to California fuels, and evaluated the sensitivity of the PMI to specific fuel components, as discussed in section III.B.

Table 5. Test Fuel Specifications

Fuel Property	Phase 2 Cert. Fuel	Phase 3 E6 Summer Fuel	Phase 3 E10 Summer Fuel	Test Method
Oxygenate (vol %)	11.20 MTBE	5.65 Ethanol	9.49 Ethanol	ASTM 4815, GC/FID
Total Oxygen (mass%)	2.06	2.09	3.49	ASTM 4815, GC/FID
Benzene (vol %)	0.89	0.57	0.39	ASTM D5580, GC/FID
Total Aromatices (vol %)	23.85	23.72	14.03	ASTM D5580, GC/FID
RVP, psi	6.89	6.73	6.67	ASTM D5191
Distillation (^oF)				
T10	142	136	138	ASTM D86
T50	208	212	217	ASTM D86
T90	297	312	328	ASTM D86
Sulfur (ppm by wt)	28.0	8.1	10	ASTM 5453, ANTEK
Olefins (vol %)	4.8	5.2	6.9	ASTM 6550, SFC

A. Fuel Impact on PM Mass and Solid Particle Number Emissions

1. Fuel Effects on PM Mass Emissions

As discussed previously, four vehicles were tested by ARB using the FTP cycle and test procedure 40CFR1065 on California Phase 3 E6 summer fuel and Phase 2 certification fuel. Fuel effects on PM emissions was one area of investigation. One test vehicle was a wall-guided GDI vehicle (vehicle 7), two were spray-guided GDI vehicles (vehicles 8 and 9) and one was a PFI vehicle (vehicle 10). Four repeat tests were run on vehicle 7 with E6 fuel and two repeats tests with Phase 2 certification fuel. For vehicles 8, 9 and 10, a minimum of three repeat tests were run on each fuel. As shown in Figure 67, Phase I (cold start) PM mass emissions measured significantly lower when tested on Phase 2 certification fuel for all four vehicles. When comparing Phase 2 certification fuel with Phase 3 E6 summer fuel the weighted FTP PM mass emissions for the three GDI vehicles decreased from 2.2 mg/mi to 1.2 mg/mi, and from 1.0 mg/mi to 0.6 mg/mi for the PFI vehicle.

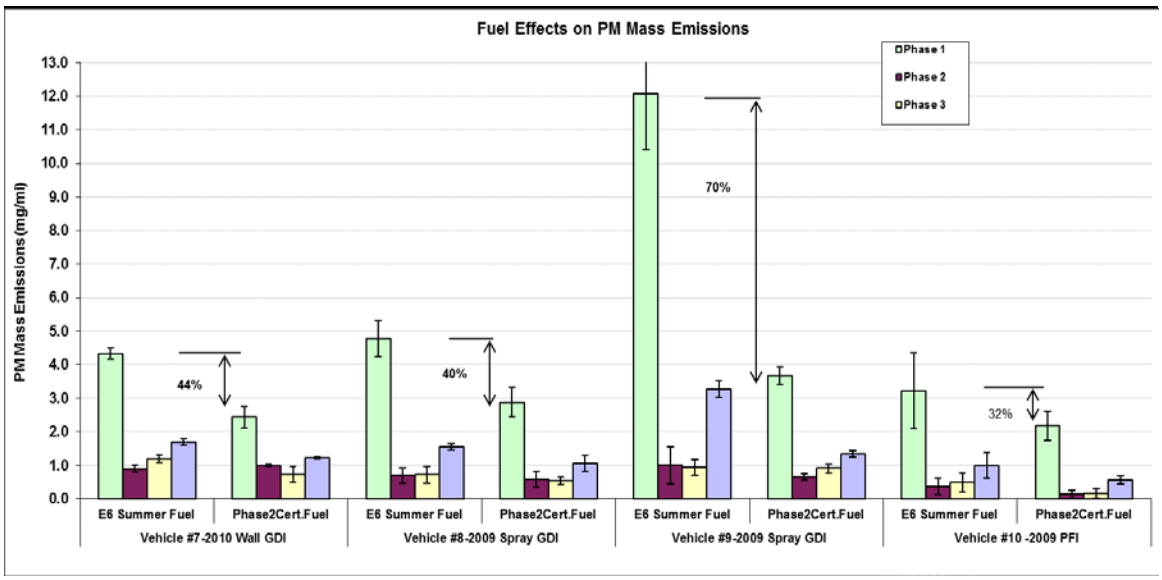


Figure 67. Fuel effects on PM mass emissions

One wall-guided GDI (vehicle 7) and one PFI vehicle (vehicle 11) were tested with both California commercial Phase 3 E6 and E10 summer fuels. For vehicle 7, three repeat tests were run on E6 fuel and two repeat tests were run on E10 fuel. Four repeat tests were run for vehicle 11 on both fuels. PM mass emission rates are plotted in Figure 68. As shown there, during FTP cycle Phase I (cold start) the GDI vehicle showed a moderate increase of 15 percent in PM mass emissions on E10 fuel, with PM mass emissions decreasing by 24 percent in Phase II (hot running) and 10 percent in Phase III (warm start). The weighted FTP PM mass emissions of 1.7 mg/mi remained the same on both fuels. For the PFI vehicle, FTP cycle Phase I (cold start) PM mass emissions were 16 percent lower on E10 fuel, with significantly larger decreases in emissions for Phase II (hot running) (75 percent) and Phase III

(warm start) (45 percent). Measured FTP weighted PM mass emissions were 40 percent lower on the E10 fuel.

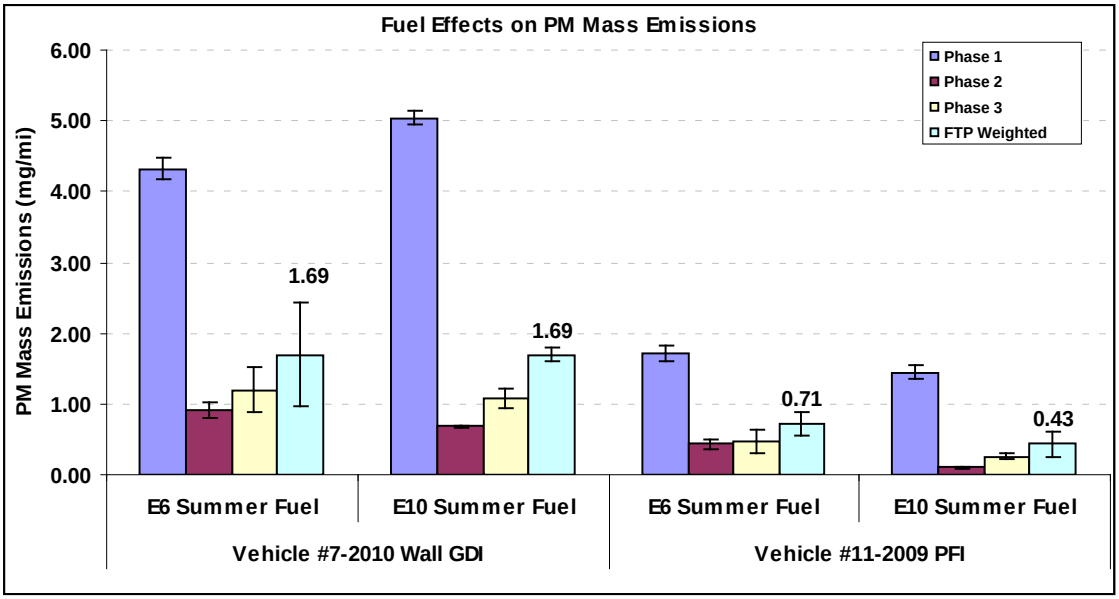


Figure 68. Comparison of PM mass emissions using Phase 3 E6 and E10 summer fuel

2. Fuel Effects on Solid Particle Number Emissions

Similar to the investigation on fuel effects on PM mass emissions, SPN emissions were measured for one wall-guided GDI vehicle (vehicle 7) and one PFI vehicle (vehicle 10) with a minimum of three repeat tests on Phase 3 E6 summer fuel and Phase 2 certification fuel. The SPN measurements carried out by ARB adhere to the test protocols described in the PMP as discussed previously. The SPN emissions for the two vehicles are plotted in Figure 69. As shown there, FTP cycle Phase I (cold start) SPN emissions of the GDI vehicle were 30 percent lower on Phase 2 certification fuel, but remained basically unchanged for the PFI vehicle. However, for Phase II (hot running) and Phase III (warm start), SPN emissions are reduced significantly for the PFI vehicle, 80 percent for Phase II (hot running) and 59 percent for Phase III (warm start), similar to the trend observed for PM mass emissions. For the GDI vehicle, minor changes in SPN emissions were measured in FTP Phases 2 (hot running) and 3 (warm start). The FTP weighted SPN emissions for both vehicles were 14 percent lower on Phase 2 certification fuel.

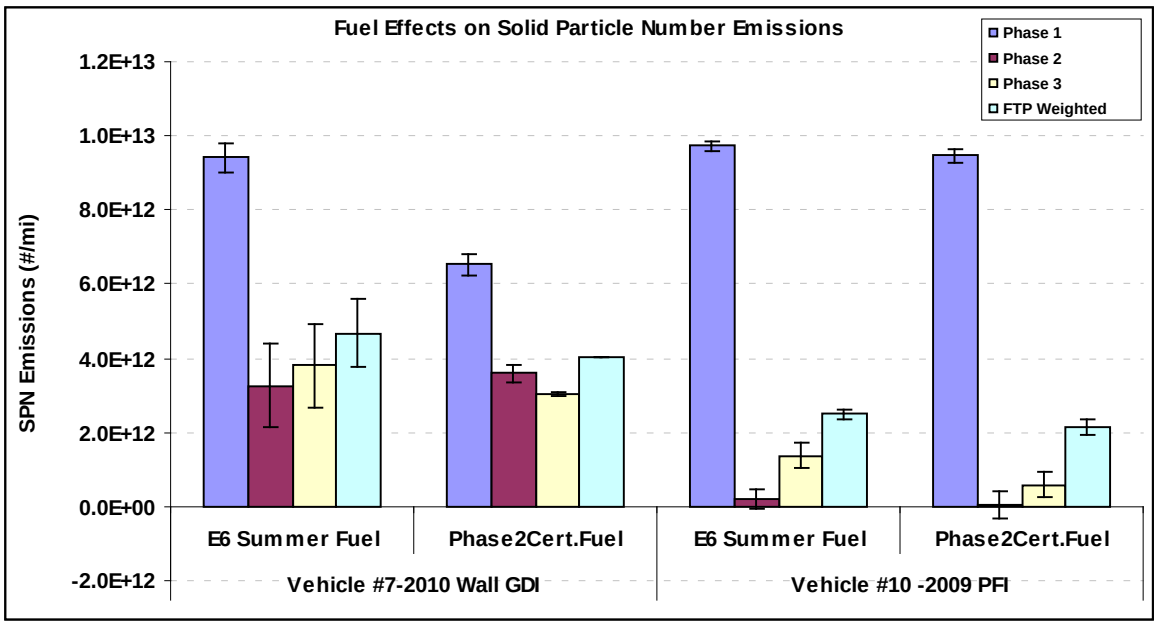


Figure 69. Fuel effects on solid particle number emissions

Vehicle 7 (wall-guided GDI) and vehicle 11(PFI) were tested for fuel effects on SPN emissions with both California commercial Phase 3 E6 and E10 summer fuels. For vehicle 7, three repeat tests were run on E6 fuel and two repeat tests were run on E10 fuel. Four repeat tests were run for vehicle 11 on both fuels. PM SPN emission rates are plotted in Figure 70.

As shown in Figure 70 and as expected given the correlation between PM mass and SPN emissions, changes observed for the GDI vehicle SPN emission rate were similar to those observed for PM mass emissions. On E10 fuel, SPN emissions increased by 12 percent in FTP cycle Phase I (cold start), followed by a 15 percent decrease in Phase II (hot running) and a 10 percent increase in Phase III (warm start). The FTP weighted SPN emissions remained unchanged between E6 and E10 fuels. SPN emissions of the PFI vehicle were 10 percent higher on E10 fuel for Phases 1 (cold start) and 3 (warm start) and 33 percent lower for Phase II (hot running). The weighted FTP SPN emissions were essentially the same on both fuels. In general, SPN emission rate remains un-changed, regardless of the fuel used.

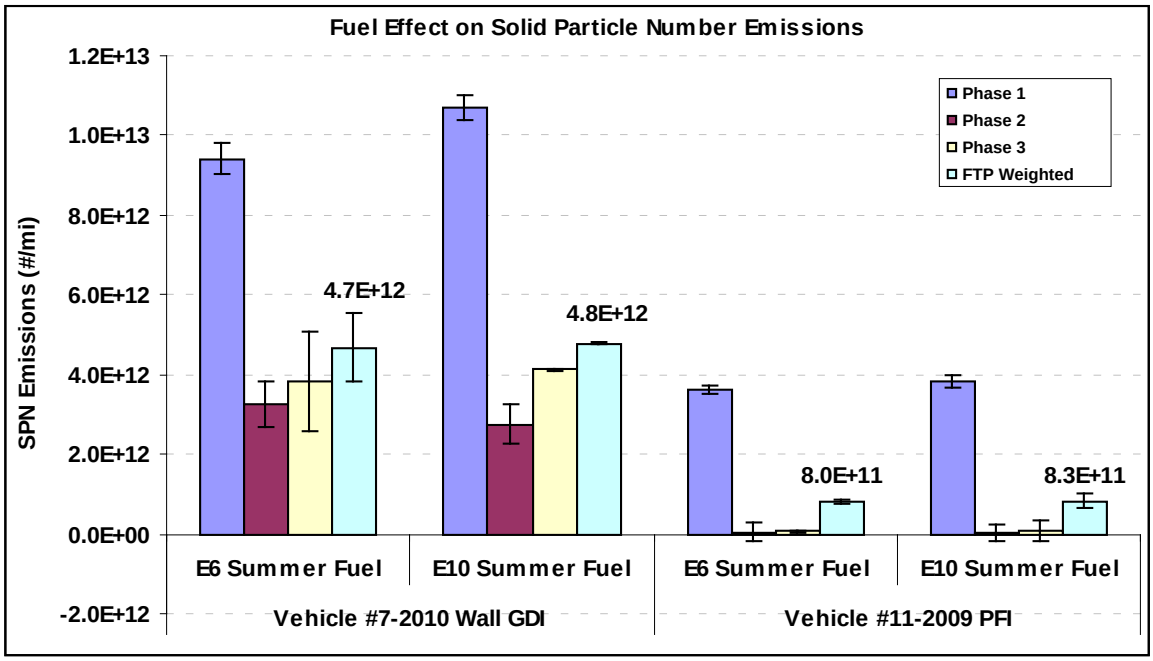


Figure 70. Comparison of SPN emissions using Phase 3 E6 and E10 summer fuel

B. Assessment of a PM Index

Honda had suggested that PM emissions could accurately be predicted by knowledge of the fuel properties. This hypothesis was based on the results of their testing (Aikawa et al., 2010; Khalek et al., 2010). Honda collected over 1400 gasoline samples worldwide and quantified each sample using ASTM Method D6729 (Detailed Hydrocarbon Analysis, DHA). The PM index (PMI) calculated from these samples ranged from 0.67 to 3.86. Honda reported linear R^2 correlations between PM Index and PM emissions rates for PM mass and particle number that ranged from 0.9488 to 0.9979 based on their PMI, a mathematical model (Aikawa et al., 2010). The correlation was based on combined tests on different engines, test cycles and fuels. The equation for PM Index is defined as:

$$PM\ Index = \sum_{i=1}^{n}\left(\frac{DBE_i + 1}{V.P(443K)_i} \times Wt_i\right)$$

DBE_i is the double bond equivalent of component "i" and is based on the total number of hydrogen, carbon, nitrogen, and oxygen atoms in gasoline. $V.P\ (443K)_i$ is the vapor pressure of component (i),at 443 K. Wt_i is the weight percentage of the component "i". The PMI is therefore a collective property of the PM emission contributions of each individual constituent of a gasoline sample.

To assess the validity of the PMI concept and its applicability to California fuels, ARB investigators calculated the PM Indices of fuels used in the LEV III Advanced Clean

Car testing program. Measured PM emission data were correlated with the calculated PM Indices for a number of vehicles. Staff also evaluated the sensitivity of the PM Index to specific fuel components.

1. Methods

Five gasoline samples were sent to Southwest Research Institute (SwRI) for DHA analysis; SwRI had analyzed all of Honda's fuel samples. These five gasoline samples were also analyzed by ARB for crosscheck purposes, using alternative methods for specific classes of compounds. The first three fuels were used in ARB's LEV III Clean Car testing program (as listed in Table 5: California Phase 2 certification fuel, commercial Phase 3 E6 summer fuel, and commercial Phase 3 E10 summer fuel). The last two test fuels were market summer fuels from different sources (E10 Underground and E10 Market).

The PMI of these five fuels were calculated according to Honda's equation. These PM Indices were then correlated to PM emissions data obtained from extensive chassis dynamometer emission tests. Lastly, the concept of PMI was further evaluated by calculating PM Indices of every chemical and carbon group for each sample (Table 6 and Table 7).

2. Results and Discussion

The chemical properties of each fuel are shown in Table 6 along with the ASTM designation for the test method used.

Table 6. Fuel Properties Based on California Fuel Enforcement Test Method (percent wt.)

	Paraffins-D6839	**Aromatics D5580**	**Naphthenes D6839**	**Olefins D6550**	**Oxygenates D4815**
Phase 2 Cert	*	28.17	*	5.64	11.33
E6 Summer	50.22	27.94	8.26	6.12	6.02
E10 Summer	39.27	16.43	20.64	8.01	10.05
E10 Underground	47.15	27.05	7.98	5.68	10.13
E10 Market	41.60	23.06	14.96	7.06	10.39

* Not analyzed due to MTBE

PM Index Calculations

PM Indices of the five gasoline samples are shown in Table 7. A relatively small range (1.435-1.581) in PMI values was observed for the three sample fuels used in ARB's LEV III testing program (shown in bold). In addition, three E10 samples were

also evaluated to assess PMI variability of California 2010 market fuels from different sources. These E10 fuel samples had an average PMI value of 1.5844 with one standard deviation value of 0.0282.

Table 7. PM Index of Five California Gasoline Samples

Sample ID	PMI
Phase 2 Cert	**1.4353**
E6 Summer	**1.4535**
E10 Summer	**1.5808**
E10 Underground	1.5582
E10 Market	1.6143

PM Index Based on Chemical Groups

The PM Indices for each chemical group are calculated and summarized in Table 8. To compare the PM emissions potential of each chemical group, the group PMI was plotted against each chemical group. Plots of all five samples are shown in Figure 71.

Table 8. PMI Break Down for Different Fuels Based on Chemical Groups

Groups	**Phase 2 Cert**		**E6 Summer**		**E 10 Summer**		**E10 Underground**		**E10 Market**	
	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)
Paraffins	50.49	0.09	51.68	0.10	44.74	0.12	48.85	0.10	42.61	0.11
Mono-Aromatics	30.94	0.94	30.19	1.03	18.04	0.79	28.36	1.02	22.94	0.92
Naphthalenes	0.55	0.30	0.24	0.10	0.62	0.29	0.37	0.17	0.51	0.25
Naphthe/Olef-Benz	0.14	0.02	0.33	0.05	0.30	0.04	0.31	0.04	0.23	0.03
Indenes	0.43	0.06	0.87	0.13	1.44	0.24	1.11	0.18	1.19	0.22
Naphthenes	2.10	0.01	7.67	0.03	15.15	0.07	7.23	0.03	11.97	0.06
Olefins	3.99	0.01	5.10	0.01	7.37	0.03	4.91	0.01	8.58	0.03
Oxygenates	10.83	0.01	3.23	0.00	7.57	0.01	7.58	0.01	7.06	0.01

%WT: Weight percentage
PMI(G): PM Index value based on chemical groups

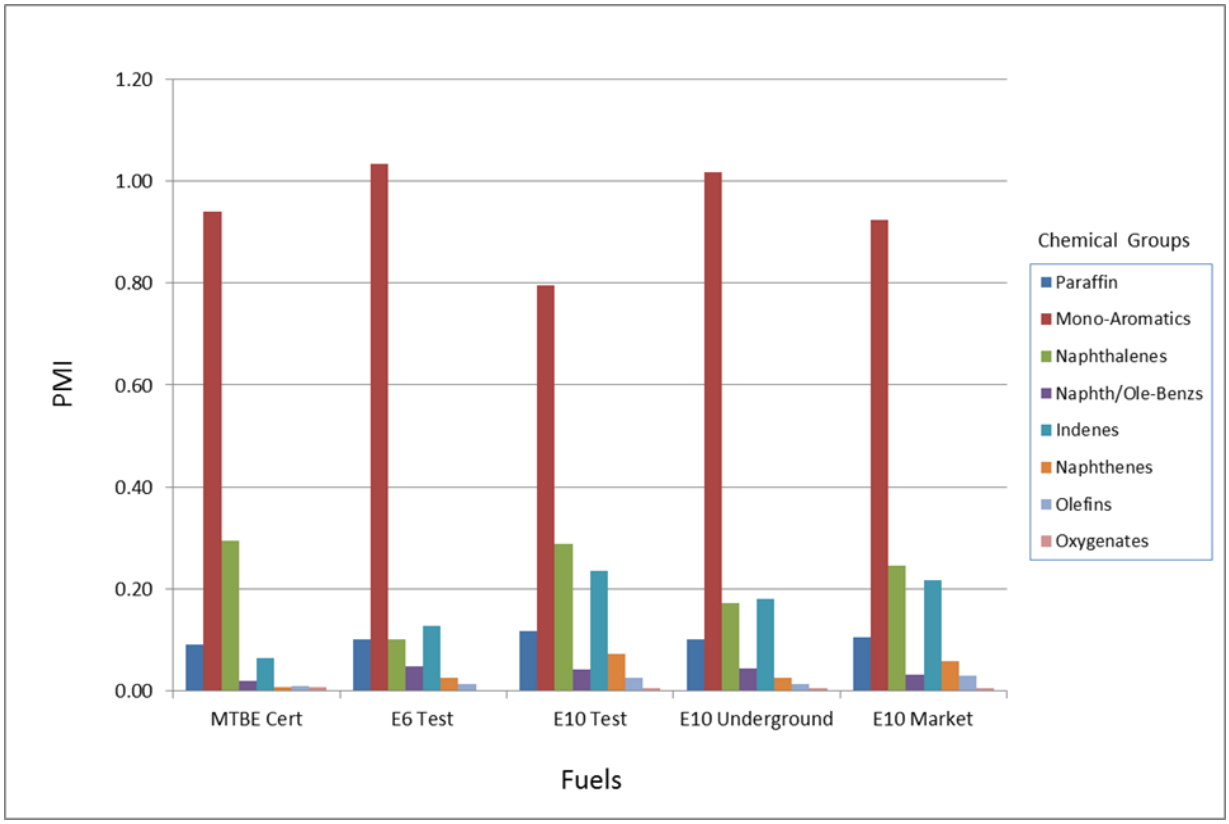


Figure 71. PMI Distribution Based on Chemical Group

The five major chemical groups are: paraffins, total aromatics, naphthenes, olefins and oxygenates. Paraffins, the most abundant chemical group, made up 47.7 percent of total weight but only contributed 6.7 percent to total PMI. Since the total aromatics group was a significant contributor to the total PMI, sub-groups were broken down and further analyzed. These four sub-groups in total aromatics are: mono aromatics, naphthalenes, naphtheno/olefino-benzenes and indenes. Total aromatics represented ~27.8 percent of the total weight but contributed ~ 89.4 percent to the total PMI. PMI values of total aromatics did not have a significant difference between the three test fuels nor between the three E10 market fuels (1.22-1.25). Significantly, naphthalenes, which are high in carbon content and DBE but low in V.P. (443K), contributed the most. An average gasoline sample had only 0.5 percent of naphthalenes, yet this chemical group contributed ~14.4 percent to the total PMI of each sample.

PM Index Based on Carbon Numbers

Table 9 lists the calculated PM Indices by carbon number group. These PM Indices are then plotted against each carbon number group as shown in Figure 72. Groups C_7 to C_{12} accounted for 97.8 percent of the total PMI. The PMI of C_9 to C_{12} groups made up of ~18.9 percent of the total mass, yet contributed ~ 73.5 percent of the total PMI. The PM Index value (C_9 to C_{12}) was the highest for E10 summer fuel and the lowest for Phase 2 Cert fuel and is relatively constant for the three E10 fuels.

The C_8 group (the most abundant hydrocarbon group) composes 24.6 percent of the total mass, but accounts for an average PMI of only 17.3 percent.

Table 9. PMI Breakdown for Different Fuels Based on Carbon Number Group

Carbon #	Phase 2 Cert		E6 Summer		E10 Summer		E10 Underground		E10 Market	
	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)	%WT	PMI (G)
2			3.13	0.00	7.46	0.01	7.50	0.01	6.98	0.00
3	0.09	0.00	0.10	0.00	0.12	0.00	0.09	0.00	0.08	0.00
4	1.37	0.00	0.75	0.00	0.87	0.00	0.68	0.00	0.56	0.00
5	21.44	0.01	11.08	0.01	10.20	0.01	11.10	0.01	11.52	0.01
6	9.88	0.02	16.97	0.02	12.59	0.02	16.40	0.02	14.83	0.02
7	21.81	0.13	22.45	0.12	20.26	0.08	21.07	0.11	18.85	0.09
8	30.75	0.32	26.25	0.30	22.64	0.20	22.22	0.26	21.07	0.23
9	8.92	0.30	11.96	0.42	10.23	0.30	12.28	0.42	11.68	0.33
10	4.00	0.29	5.26	0.35	7.78	0.42	5.59	0.38	6.64	0.38
11	0.87	0.24	0.89	0.17	2.14	0.42	1.16	0.26	1.76	0.38
12	0.33	0.12	0.46	0.06	0.91	0.14	0.62	0.10	1.03	0.16
13			0.01	0.00	0.04	0.00	0.02	0.00	0.07	0.00
14					0.01	0.00	0.01	0.00	0.01	0.00
15							0.00	0.00		

%WT: Weight percentage
PMI(C#): PM Index value based on carbon number group

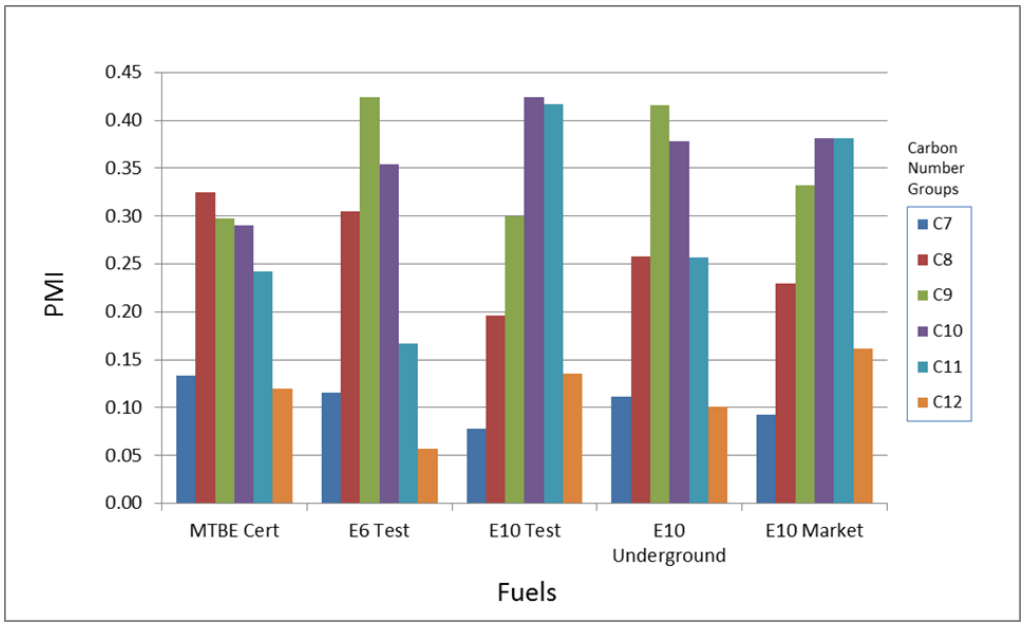


Figure 72. PMI for Each Carbon Number Groups

The Correlation between PM Index and Emissions Data

As described previously, chassis dynamometer emission tests were conducted using Phase 2 Cert fuel, E6 summer and E10 summer fuels. Table 10 shows all tests and average emissions data; Vehicle 7 was the only car tested using all three of these test fuels. All the data used here were obtained using the FTP cycle. Figure 73a compares the emissions data with PM Indices for all vehicles tested in the program and Figure 73b compares PM mass emissions to Vehicle 7.

Table 10. PM Emissions Data for Tested Fuels

Vehicle #	Fuel Inject	Fuel	# of test	PM Ave mg/mi	EC Ave mg/mi	SPN Ave
Vehicle 8	GDI	Phase 2 Cert	9	0.87	0.52	2.44E+12
Vehicle 9	GDI	Phase 2 Cert	5	1.57	0.71	2.40E+12
Vehicle 10	PFI	Phase 2 Cert	5	0.56	0.45	2.15E+12
Vehicle 7*	GDI	Phase 2 Cert	2	1.21	N/A	4.23E+12
Vehicle 8	GDI	E 6	5	1.62	1.21	N/A
Vehicle 9	GDI	E 6	10	2.98	2.33	N/A
Vehicle 10	PFI	E 6	4	0.97	1.19	2.72E+12
Vehicle 11	PFI	E 6	5	0.62	0.36	7.94E+11
Vehicle 7*	GDI	E 6	8	1.77	1.44	5.06E+12
Vehicle 5	GDI	E 6	2	4.65	1.80	N/A
Vehicle 11	PFI	E 10	5	0.37	0.37	N/A
Vehicle 7*	GDI	E 10	4	1.29	1.44	N/A

*Vehicle 7 was tested in chassis dynamometer with Phase 2 Cert fuel, E6 Summer fuel, and E10 Summer fuel.

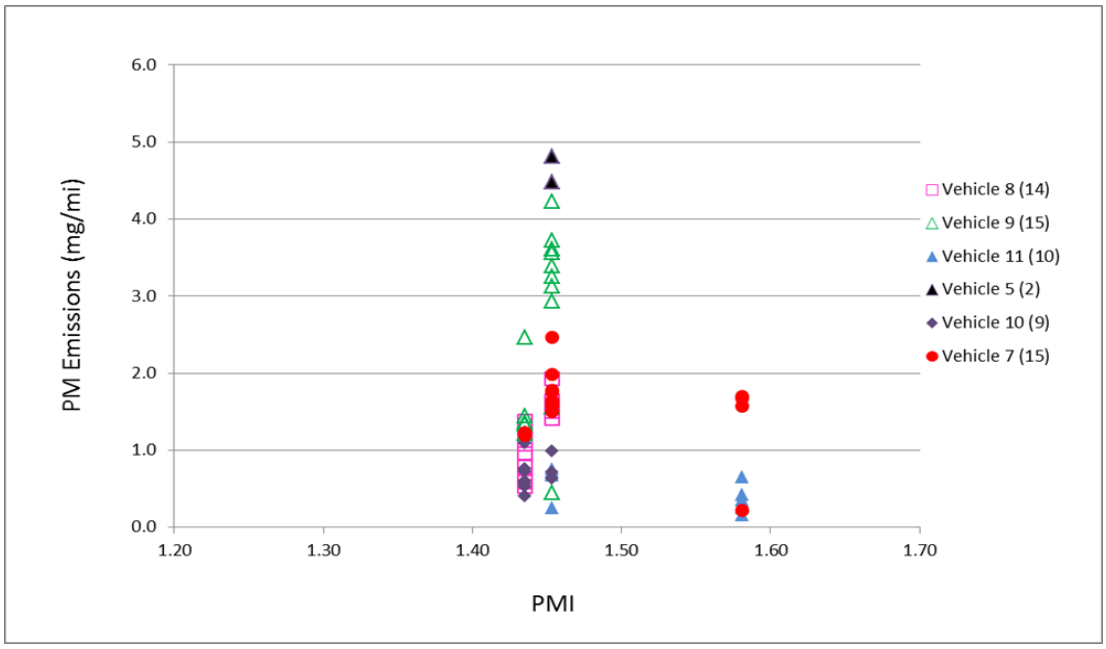


Figure 73a. PM Mass Emissions vs. PMI for All Tested Vehicles

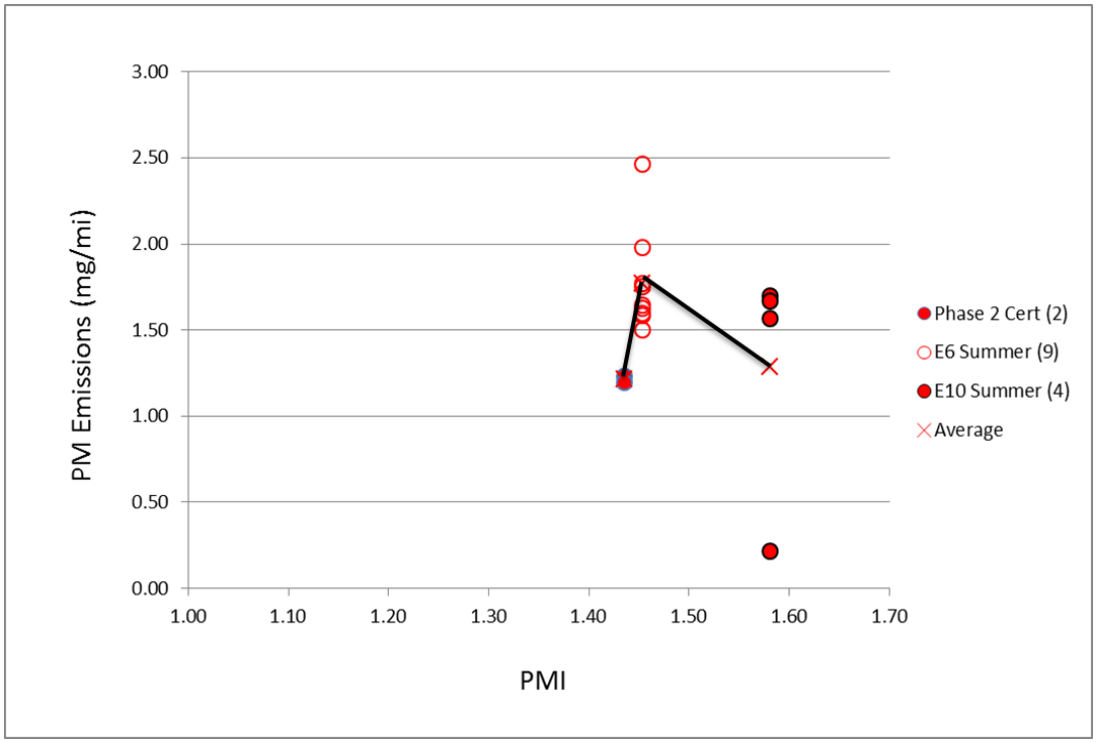


Figure 73b. PM Mass Emissions vs. PMI for Vehicle 7

Table 11 lists the average emissions data in PM mass, EC and SPN of the fuels used. Figure 73b does not demonstrate a correlation between PM emissions and PMI. It is likely that test-to-test variability overwhelms the fuel effect.

Table 11. Emissions Data for Vehicle 7

Fuel Type	PM Index	Ave PM Mass (mg/mi)	# of tests	SDx1	Ave EC (mg/mi)	SDx1	# of tests	Ave SPN	SDx1	# of tests
Phase 2 Cert	1.435	1.213	2	N/A	N/A			4.23 E+12	2.48 E+11	2
E6 Summer	1.454	1.770	7	0.30	1.443	0.21	5	5.06 E+12	1.14 E+12	4
E10 Summer	1.581	1.287	3	0.72	1.438	N/A	N/A	N/A		

* SD only for n≥3

A t-test was calculated to determine how the average data from different fuels were related. This is an inferential test that determines if there is a significant difference between the two sets of data. A calculated p-value expresses statistical significance; when the p-value is under the significance level of 0.05, the result is considered statistically significant. The calculated p-values suggested a significant difference between the Phase 2 Cert fuel and the E6 summer fuel. The t-test could not find significant differences between the emissions data of the E6 summer and E10 summer fuels or between the Phase 2 Certification fuel and the E10 summer fuel. The t-test results are listed in Table 12.

Table 12. T-test Results for Vehicle 7 PM Emissions Data

Fuel Types	t-test (p-value)
Phase 2 Cert/E6 Summer	0.0005
Phase 2 Cert/E10 Summer	0.8507
E6 Summer/E10 Summer	0.2738

Elemental carbon data and solid particle number were also plotted against PM Index, as seen in Figures 74a and 74b. It is inconclusive since the data is limited.

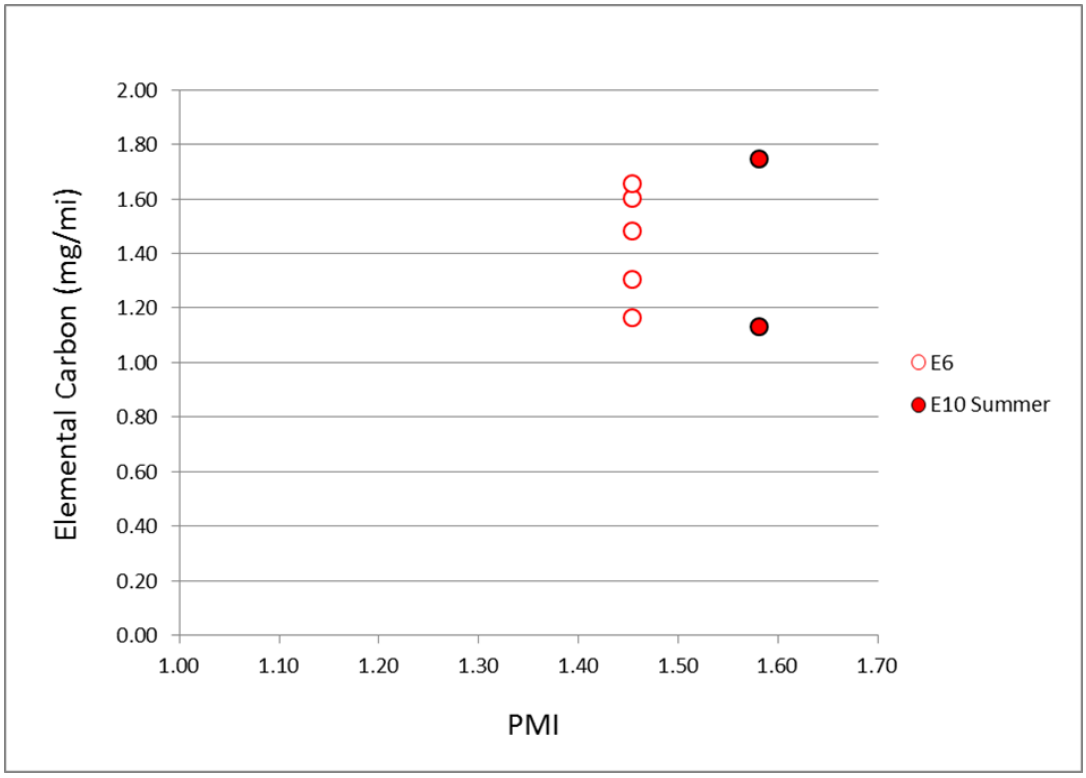


Figure 74a. Elemental Carbon Emissions vs. PM Index

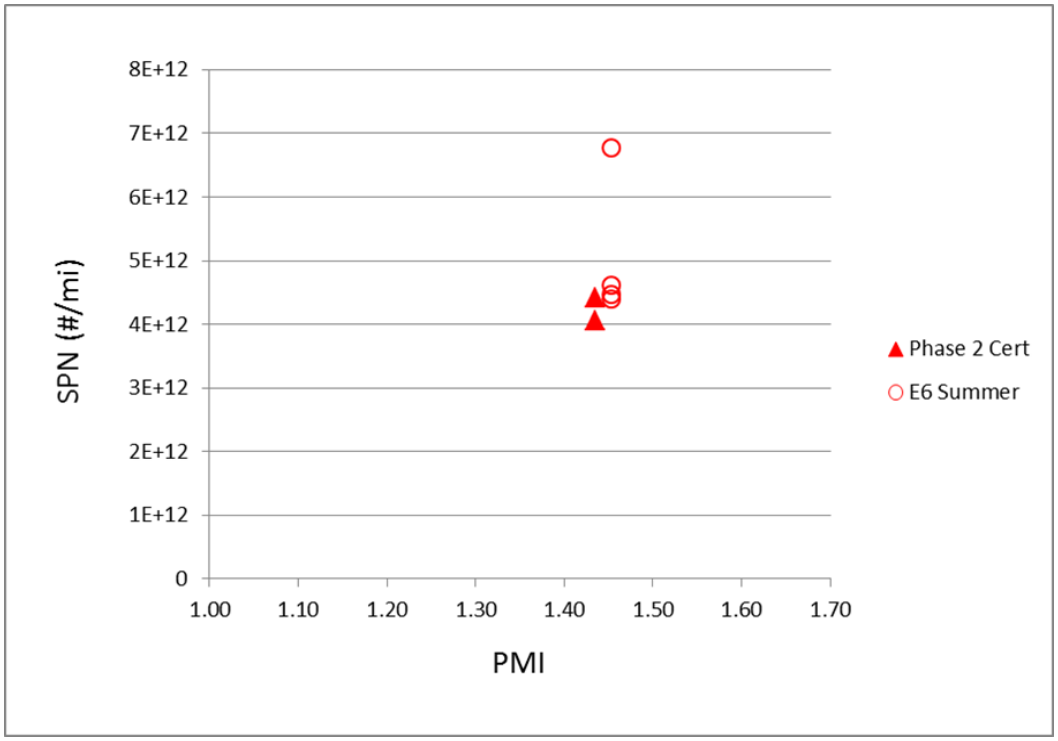


Fig 74b. Solid Particle Number Emissions (using PMP-23 nm) vs. PM Index

C. Conclusion

As part of the LEV III test program ARB evaluated the impact of gasoline fuels with different oxygenate content on PM mass and SPN emissions. No clear relationship between PM mass and fuel composition was found. SPN emission rate remains unchanged, regardless of the fuel composition.

ARB also assessed the applicability of using Honda's PMI mathematical model to predict PM emission rates with California fuels. California fuels displayed a PMI that covers only a narrow range (1.44 to 1.58), which makes an assessment difficult. Given the large test-to-test and even larger vehicle-to-vehicle variability in PM emissions, a correlation between PMI and PM emissions could not be ascertained for the fuels tested. Overall, ARB determined that the PMI model was not useful in predicting PM mass emission rates for vehicles using California fuels.

IV. MEASUREMENT OF BLACK CARBON EMISSIONS FROM LIGHT-DUTY GASOLINE VEHICLES

Black carbon, the light-absorbing carbonaceous fraction of PM, is a positive radiative forcing agent and has an established impact on climate change (Menon et al., 2002; Ramanathan and Carmichael, 2008). There is also evidence that BC may be responsible for some of the negative health effects associated with the respiration of particulate matter (Gauderman et al., 2004; Mordukhovich et al., 2009). Therefore, co-reductions in BC emissions, as a result of reductions in PM emissions, could lead to substantial climate and health co-benefits, both locally and globally.

Black carbon emissions are gaining significant attention in the general discussion of climate change and a low carbon future. The United Nations Environment Program (UNEP) recently released a report (UNEP, 2011) which summarizes findings and conclusions of an assessment of black carbon and tropospheric ozone. The assessment looks into all aspects of anthropogenic emissions of black carbon and tropospheric ozone precursors, such as methane. It examines a large number of potential measures to reduce harmful emissions, identifying a small set of specific measures that would likely produce the greatest benefits, and which could be implemented with currently available technology. In May 2011, a task force, convened by the Arctic Council, produced a comprehensive technical document on assessment of emissions and mitigation options for black carbon. The task force compiled and compared national and global BC emissions inventories, examined emission trends and projections, synthesized existing policies and programs, and identified additional emission mitigation opportunities for BC (ARCTIC, 2011).

To that end, the EPA recently submitted a draft document to congress entitled "Report to Congress on Black Carbon" (U.S. EPA, 2011), which included a summary of the present knowledge about the current and future impacts of BC, and the effectiveness of BC mitigation strategies. Based upon the information gathered, the EPA developed the following seven conclusions: 1. "BC and other light-absorbing particles exert a powerful influence on the earth's climate, especially at the regional scale;" 2. "BC is different from long-lived GHGs, like CO_2, both in the variety of mechanisms by which it affects climate and in its short atmospheric lifetime;" 3. "Mitigating BC can make a difference, in the short term, for climate; at least in sensitive regions;" 4. "BC mitigation strategies are likely to provide substantial public health and environmental benefits;" 5. "Careful targeting of mitigation programs is essential for both public health and climate purposes;" 6. "The sequence of policies is important for ensuring maximum benefits;" and 7. "There is a strong need for additional quantitative analysis examining the climate, public health, and environmental impacts of specific control strategies."

The analysis also included discussion of several high priority research needs. These included the necessity for improved measurement methods for light absorbing PM and expanded observations of BC. Furthermore, the EPA indicated that it would be beneficial to harmonize the BC measurement and BC reference methods; and that more source measurements are needed to improve emission

inventories and minimize modeling uncertainties. For more information on the relevant science and an extensive discussion on the recent developments regarding BC, see the LEV III staff report (ISOR, section III.A.1).

One objective of ARB's technical development in support of this rulemaking was to advance the measurement science and understanding of best practices and experimental approaches for determining BC emissions from LDVs. At the present time there is no widely-accepted standard method for measuring BC in exhaust emissions. However, a variety of promising methods have emerged. The accurate determination of exhaust BC is necessary for future assessments of vehicle contributions to atmospheric BC. In 2010, the ARB conducted a series of dynamometer tests at the Haagen-Smit Laboratory in El Monte to assess the BC mass emissions levels of recent model-year LDVs. Several different commercially-available instruments were used, including those based on photoacoustic, thermal/optical and light attenuation principles. Measurements made by collocated BC instruments provided an opportunity to conduct a pilot assessment of their agreement and performance. The evaluation of the results was predominantly focused on determining the agreement between EC by the IMPROVE_A method and BC by the most common, commercially available methods. While we discuss these comparisons, we do not attempt to delve into the impact of the physicochemical properties of BC on the measurements, nor do we assess the direct relevancy of the BC methods to the prediction of climate forcing potential. Section IV.A leads with a discussion of BC and the various terms used to refer to it. This is followed by a brief discussion of the most common BC measurement methods, their underlying principles and mechanisms, operational details, and some historical perspectives. The next section, IV.B presents the results of emissions tests conducted by ARB staff in 2010. Data analyses were used to derive estimates of method limits of detection (LOD) and measurement repeatability for several instruments. Correlation between the results obtained by the various BC measurement instruments is also examined. In section C, the observed relationships between BC and two other important PM related metrics, SPN and PM mass, are discussed.

A. Review of Current Black Carbon Measurement Methods

1. Relationships between Black Carbon, Soot, and Elemental Carbon

The mostly carbonaceous fraction of PM has been described by various terms, depending on context. The most common terms are "soot," elemental carbon, and black carbon. None of these terms describe a single chemical compound, but rather a complex group of materials. Figure 75 illustrates the relationships between the soot, BC, and EC terms; which are explained in more detail in the text that follows. These relationships are based, in part, on the review article by Andreae and Gelencsér (Andreae and Gelencsér, 2006).

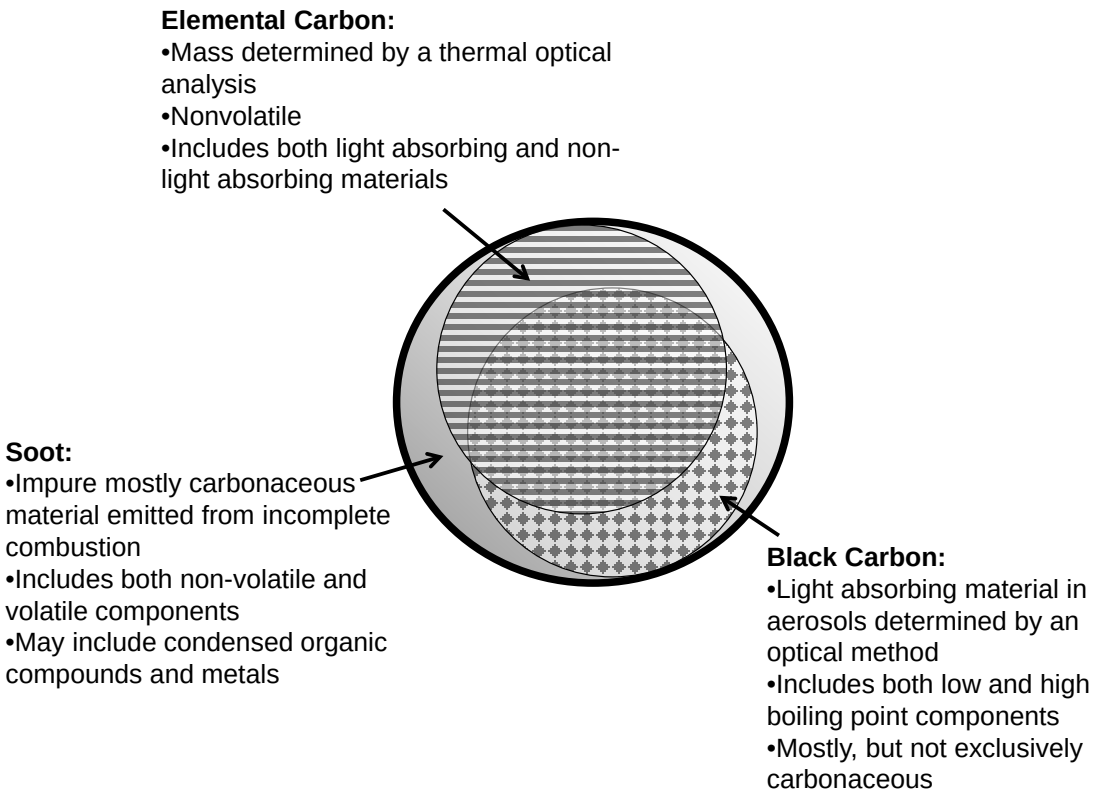


Figure 75. Relationships between Elemental Carbon, Soot, and Black Carbon in Motor Vehicle Exhaust

The term “soot” commonly refers to the mixture consisting mostly of organic carbon (OC) and BC, and trace levels of ash (metals/elements) (Wang et al., 2003) resulting from incomplete combustion. BC is defined as the “carbonaceous component of PM that absorbs all wavelengths of solar radiation”, and EC is suggested as “an indicator of light absorbing carbon (or soot)” (U.S. EPA, 2011). The amount of BC determined in a PM sample depends upon the wavelength of light used to probe the sample and the absorption efficiency of the sample (b_{abs}); applying a constant mass extinction efficiency may not be adequate because of the variable composition, sizes, and shapes of PM in alternate types of samples and their ultimate impact on radiative forcing. For example, BC may include organic compounds (Andreae and Gelencsér, 2006; Jacobson et al., 1999; Sun et al., 2007) which absorb at measurement wavelengths, typically in the visible or near infrared region, i.e., brown carbon (BrC), but would not be quantified as EC in a thermal/optical analysis. Jacobson compiled a list of BrC compounds in the atmospheric aerosols which included nitrates, benzaldehydes, PAHs and other species (Jacobson, 1999), and Chen has observed strongly absorbing BrC generated by smoldering biomass (Chen et al., 2010).

Another term commonly used to identify the mostly carbonaceous fraction of PM is EC. Here we define EC as the fraction of PM that is quantified in the later stages of a thermal/optical OC/EC analysis. This fraction typically has a low volatility and is resistant to evaporation from a filter at high temperatures. Most EC does absorb visible light due to the fact that its carbon content is mostly graphitic; however, it

may include materials that do not substantially absorb light at wavelengths typically used by BC instruments. EC is generally accepted as the largest contributor to visible light absorption in vehicle PM emissions (Horvath, 1993). Consequently, the terms are often used interchangeably.

2. Descriptions of BC Measurement Methods

The most common methods for measuring BC include thermal/optical-based methods, photoacoustic methods, and light attenuation-based methods. In the following discussion the underlying mechanisms and operational details are presented as well as advantages and disadvantages of applying each of these BC measurement methods to the analysis of BC in vehicle exhaust. Two newer methods, aerosol mass spectroscopy and laser induced incandescence are also discussed.

Thermal/optical Based Methods

Thermal/optical carbon analysis methods determine the OC, EC, and total carbon (TC) of PM samples. They are based on the assumption that the organic fraction of the sample can be distinguished from the elemental fraction by its thermal properties. In a typical measurement, PM is collected from an air stream onto a quartz fiber filter. A fraction of the filter is removed and inserted into a thermal/optical carbon analysis instrument. The filter is then heated in stages; each stage corresponding to a period of time at a preselected temperature. During each stage, certain fractions of the filter sample are removed either by volatilization or oxidation. The removed carbon fractions are then oxidized to CO_2, reduced to CH_4, and then quantified by a flame-ionization detector. The OC fractions of the PM sample are quantified in a non-oxidizing atmosphere (helium) in the early, lower temperature stages; whereas the solid carbonaceous EC fractions are removed from the filter at the higher temperature stages with the presence of an oxidizing environment (98 percent helium and 2 percent oxygen). OC and EC materials are quantified as different sub-fractions based upon the stage in which they are removed from the filter. These sub-fractions may be combined to give total EC and OC masses. EC and OC may also be combined to give total carbon (TC) mass.

Complicating the thermal approach to separating the elemental and organic fractions of PM is the fact that a fraction of the OC can be charred to produce EC during the analysis. This leads to delayed volatilization and quantification of the pyrolyzed OC from the filter and a potential mis-quantification of a substantial amount of OC as EC. However, a correction procedure is used to account for this effect. Throughout the analysis, the light reflectance off the sample, and/or light transmittance through the sample, is monitored using a laser. As charring takes place in the non-oxidizing atmosphere, there is an increase in light absorption, resulting in a decrease in reflectance or transmittance of the laser beam; the light reflectance/transmittance decreases as the atmosphere in the instrument becomes oxidizing and the temperature ramps up. Based upon the change in the reflectance/transmittance of the laser light, an adjustment is made in the cutoff point which divides the mass quantified as OC and the mass which is quantified as EC.

There are several different protocols that can be used to carry out a thermal/optical carbon analysis. Two of the more popular protocols are the (1) Interagency Monitoring of Protected Visual Environments protocol, IMPROVE_A (Chow et al., 1993, 2007) and (2) the National Institute of Occupational Safety and Health protocol, NIOSH-5040 (NIOSH 1996, NIOSH 1999, Peterson and Richards, 2002). The protocols differ mainly in the temperature set points used for division of the OC and EC components. A second difference is in the method used to correct for OC charring. The IMPROVE_A protocol uses reflectance, while the NIOSH-5040 uses transmittance; IMPROVE_A was used in this study. NIOSH-5040 and IMPROVE_A may or may not give similar results for identical PM samples (Klouda et al., 2005). The degree of agreement depends upon the nature of the sample, and hence the sample source. Samples containing more water soluble OC or humus will generally experience more charring in a thermal/optical carbon analysis; and it appears that the manner in which this charring is accounted for may be the biggest cause of the disparity between the two methods (Cavalli et al., 2010).

One of the important benefits of using a thermal/optical carbon analysis is the availability of a widely-accepted, extensively used, calibration method (Fung, 1990; Chow, et al., 1993; Birch and Cary, 1996; NIOSH, 2003). Four calibration standards are used in this calibration procedure: potassium hydrogen phthalate (KHP), sucrose, CO_2, and CH_4. Methane is used for calibrating the flame ionization detector response and CO_2 is used to verify the effectiveness of the methanator. KHP and sucrose are used as calibration surrogates for OC and EC. The FID response to a known carbon mass can be accurately determined by loading various amounts of sucrose and KHP onto the filter. This carbon mass-based calibration methodology is widely accepted for the thermal/optical carbon analysis regardless of which thermal ramping protocol is used.

Light Attenuation-Based Methods

Light attenuation-based methods have been used to measure BC for several decades (Rosen and Hansen, 1985; Quincey et al., 2009). Light attenuation instruments quantify BC based on a measured reduction of light intensity when a light passes through BC particles. The measured quantity is referred to as BC, rather than EC, because the amount of substance determined is directly proportional to the ability of the sample under consideration to absorb light at the measurement wavelength.

Many state-of-the-art light attenuation based instruments are capable of measuring BC in real-time, while others have time resolutions on the order of minutes. Most methods involve the capture of BC on a substrate, such as a Teflon filter or quartz fiber filter tape, by directing a sample airstream through the substrate. A light beam is directed at the substrate, containing the PM particles, and the attenuation of light is measured using a light detector (Hansen et al., 1984; Petzold and Schönlinner, 2004). Real-time analysis is made possible by advancing the tape when the BC deposit approaches optical saturation (Hansen et al., 1984). The attenuation is typically due primarily to absorption and some scattering. The BC mass is then

determined using a calibration coefficient, typically empirically derived by the manufacturer.

Photoacoustic-Based Methods

Photoacoustic methods have been applied to the real-time analysis of BC since the late 1970s (Truex, 1979). In a photoacoustic measurement of BC, sample is drawn into a resonance chamber and excited repeatedly via a modulated laser beam. The laser beam typically has a wavelength in the visible or near-infrared region. Rapid excitation and thermal relaxation leads to a periodic transfer of heat from the BC particles to the surrounding gas molecules, expansion and contraction, and a sound wave at the frequency of the modulation. Since the modulation frequency is typically near the resonant frequency of the chamber, the sound wave persists and is picked up by a microphone in the chamber. The microphone signal output is proportional to the mass concentration of the BC in the chamber.

As with light attenuation methods, the quantity measured using photoacoustic spectroscopy is BC rather than EC because the amount measured is related to the light absorption properties of the substance. Photoacoustic methods are fairly sensitive; capable of acquiring BC mass data in real-time at concentrations below a microgram per cubic meter.

Photoacoustic instruments tend to be fairly easy to maintain, have a wide operating range, and do not suffer from the filter effects which affect light attenuation methods. Furthermore, when the excitation wavelength is chosen correctly the technique is not influenced substantially by interferences (Mörsch, 2001).

Interferences and Discrepancies between Instruments

When measuring BC using a thermal/optical instrument, a light attenuation instrument, or a photoacoustic spectrometer, matrix effects, calibration differences, filter effects, and measurement wavelength settings can lead to results that would have been different if an alternative instrument was used. For instance, certain aromatic compounds, volatilized in the OC stages of a thermal/optical carbon analysis, can absorb radiation at the visible or near-infrared wavelengths commonly used by light attenuation or photoacoustic instruments. Therefore, if one of those light attenuation or photoacoustic units had been used instead, those organic compounds may have been quantified as BC (Mayol-Bracero et al., 2002). In other cases, the presence of metal oxides, such as iron oxides, may reduce the oxidation temperatures of EC and lead to the quantification of EC as OC (Wang et al., 2010).

When using light attenuation methods or photoacoustic methods to measure BC, one must consider the applicability of the factory derived conversion factors used to correlate measured signals to BC mass concentrations. These calibration factors may be inappropriate for quantification of BC in a given PM sample, because that PM sample is dissimilar to the calibrating PM; and PM samples obtained from different sources may not have identical absorption properties. For instance, Lawless and coworkers found overlapping but very different light absorption

patterns for environmental tobacco smoke PM and urban air PM (presumed to be mostly of vehicular origin), using a real-time light attenuation instrument (Lawless et al., 2004).

Findings quite relevant to vehicle exhaust BC measurement were obtained by Schnaiter and coworkers (Schnaiter et al., 2006) who investigated the aerosol particles produced by propane soot generators. These particles are designed to be similar to vehicle exhaust PM in terms of size and carbon content and have been proposed as a calibration aid for quantifying BC (OICA, 2003) and have also been used as a surrogate for urban aerosol BC in surface chemical reactivity experiments (Monge et al., 2009). Schnaiter et al. measured the extinction and cross-section of particles emitted by a propane soot generator. They found a strong dependence of these quantities on the carbon/oxygen ratio in the diffusion flame and the resultant particle diameters (Schnaiter et al., 2006). The results suggest that the light absorption features of PM particles, in vehicle exhaust, can also change based upon the air/fuel ratio and the particle diameters. These quantities may, in turn, depend upon fuel content (i.e. additives), driving conditions (i.e. driving cycle), altitude, etc. (Maricq et al., 1999; Al-Hasan, 2003; Bishop et al., 2001; Benvenutti et al., 2003; Hsieh et al., 2002). Therefore a single calibration factor, no matter how carefully derived, may not be appropriate for measuring vehicle exhaust BC when multiple fuels, vehicles, or test conditions are involved.

Matrix effects and scattering due to filter-BC and BC-BC interactions may also lead to incorrect determinations of BC mass using light attenuation-based/photoacoustic-based methods (Cappa et al., 2008; Moosmüller et al., 2009). Moosmüller and coworkers, for example, concluded that the quantification of BC using optical techniques employing filters is “strongly influenced by filter type and specific filter characteristics which determine potential absorption enhancement due to multiple scattering in/on the filter medium and deposited particles, location of the particles on the filter medium, angular distribution of scattered light, and particle morphology changes upon deposition.”

Photoacoustic spectrometer determination of BC is further influenced by particle size. The technique is not very effective at measuring particles with diameters of >2.5 μm because of signal loss due to slow thermal relaxation (Arnott et al., 2003). The importance of this effect is ameliorated; however, by the fact that most gasoline powered vehicles emit PM particle sizes with diameters < 300 nm (Kleeman et al., 2000; Maricq et al., 1999; Robert et al., 2007). A more serious issue may be that the OC coating of PM particles (externally mixed) will influence the light absorption of the BC soot particles via lensing and scattering effects. The lensing effect tends to lead to an “absorption enhancement” whereas the scattering effect leads to a decrease in absorption. The importance of these effects appears to depend upon the chemical composition of the OC and the film’s thickness (Cross et al., 2010; Slowik et al., 2007).

Other Black Carbon Measurement Methods

Very few methods are currently commercially available for the measurement of BC that cannot be categorized as thermal/optical, light attenuation, or photoacoustic in nature. Two promising methods are laser-induced incandescence (LII) and aerosol mass spectrometry (AMS). Both are sophisticated methods that have not yet attained widespread usage.

LII is a real-time BC measurement technique which involves the use of a high energy laser to bombard BC containing aerosol particles. This bombardment heats the particles to a very high temperature (2000K), which causes the particle then to incandesce. In this temperature range, refractory BC remains in the particle and all the volatile components are evaporated and do not participate in incandescence. The incandescent emission is measured and the signal may be used to determine the mass of the BC in the sample stream. LII is capable of a fast response, on the order of 20 Hz, and has a detection limits on the order of 2 $\mu g/m^3$. Data from a fairly recent study showed that these instruments are capable of measuring BC without being affected by the presence of OC coatings (Slowik et al., 2007), which may impact measurements made using photoacoustic or light attenuation methods.

The ARB participated in a series of studies to evaluate the LII (Huai et al., 2006). These studies compared LII measured BC to same-test PM mass and EC diesel exhaust. Overall, LII BC was well correlated with both PM and EC, yet returned BC values that were higher than total PM. The erroneously higher values of BC, determined by LII, were determined to have been due to inadequate calibration. As is the case for the light attenuation and photoacoustic based methods, there is not currently a widely accepted standardized method for the calibration of laser-induced incandescence instruments.

The measurement of BC using conventional AMS instruments can only be performed by indirect means. AMS targets the OC component of soot aerosols for analysis. In the AMS, aerosol particles are sampled and then passed through an aerodynamic lens which focuses them into a narrow beam. The beam is then accelerated in a vacuum to supersonic velocities and separated by time of flight mass spectrometery. The separated particles then strike a heated surface where the volatile and semi-volatile components (i.e. OC) are vaporized and then ionized by electron impact and detected by a quadrupole MS. Therefore, it is possible to determine BC by combining AMS with a PM measurement, such as via scanning mobility particle sizer, through subtraction (Slowik et al., 2007). Recently the technologies of LII and AMS have been combined into one instrument that is suggested to be capable of vaporizing both OC and BC and measuring both materials using mass spectroscopy (Sun et al., 2011).

B. ARB Studies on Black Carbon Measurement

1. Introduction

In 2010, a series of dynamometer tests were carried out by ARB staff at the Haagen-Smit Laboratory in El Monte, CA. The main purpose of these experiments was to define the typical levels of BC and other pollutants emitted from recent model-year LDV. During many of these tests, BC was measured by multiple devices running simultaneously; including photoacoustic spectrometers, a thermal/optical-based instrument, and light attenuation-based instruments. The same-test multiple instruments results provided the opportunity for data analyses to assess the agreement between the different instruments and their relative performance. In this section we discuss the results of those analyses. General experimental details of the dynamometer tests are presented in Subsection 2. These include information on the vehicles tested, the fuels used to power them, the driving cycles employed, the exhaust collection methods, and the BC measurement methods. Subsections 3 and 4 report the details and results of analyses to determine estimates of the method LOD and repeatability for several of the BC instruments when applied to the measurement BC from automobile exhaust using a CVS tunnel. In Subsection 5, a direct comparison is made between the results obtained by photoacoustic and light attenuation methods and those obtained by a thermal-optical method running the IMPROVE_A protocol. In Subsection 6, a thermal/optical method is suggested as the potential reference method for the measurement of BC in LDV and MDV exhaust emissions and the reasons for that selection are discussed. Finally, in Subsection 7 the criteria for selecting a reference method for BC in LDV and MDV exhaust emissions are listed.

2. Experimental Details

Six LDV underwent dynamometer testing at the Haagen-Smit Laboratory Test Cell Seven. The LDV examined included two center-guided gasoline direct injection (CGDI) vehicles, two wall-guided gasoline direction injection vehicles (WGDI) vehicles, and two PFIs. While port-fuel injection is currently the dominant fuel injection technology in LDV, gasoline direct injection is expected to become the most prevalent injection technology in new LDV within 5-10 years. Preliminary data, collected at the ARB, indicated that the BC emissions, associated with these two fuel injection technologies, differ substantially, thus necessitating the testing of both PFI and GDI vehicles. CGDI and WGDI are variants of the gasoline direct injection technology. In WGDI systems the fuel is sprayed onto the piston floor and a cloud of fuel and air forms above it which travels towards the spark plug. In CGDI systems, a hollow cone of fuel is generated at the spray nozzle which remains stable until it is ignited.

Three different batches of fuel were used in the tests: “E6,” a 2009 Phase 3 Commercial Grade Summer Fuel containing 6 percent ethanol; “E10,” a 2010 Phase 3 Commercial Grade Fuel containing 10 percent ethanol; and “P2 Cert,” a Phase 2 Certification Fuel containing MTBE.

Two “regular” test cycles were used in the investigation; the Federal Test Procedure-75 driving cycle and the California Unified driving cycle. The vast majority of the data presented is from the FTP-75 cycle. The FTP-75 phase-integrated BC emission masses were converted to mg/mi using standard FTP-75 weighting factors. Un-weighted phase averaging was used to determine mg/mi values for UC tests. For the determination of method LOD, an alternative driving cycle, ALT, was used. This cycle will be explained in more detail in Subsection 3. The number of tests performed and analyzed for each vehicle, test cycle, and fuel are indicated in Table 13.

Testing was carried out using constant volume sampling according to 40 CFR Part 1065. A very small portion of the diluted exhaust stream was then subsampled from the CVS tunnel to the BC measurement instruments and filters via lines that were connected to the tunnel. The CVS tunnel temperatures were dependent upon vehicle and test cycle; however, the test-average CVS tunnel temperatures never exceeded 57℃ in any test. The CVS flow rates were held constant during all the four tests. Test-to-test variability in the CVS flow rate, between the four tests, was <0.4 percent, ranging from 18,200 L/min to 18,400 L/min.

Table 13. Test Matrix Indicating the Number of Tests Performed and Analyzed for Each Vehicle Fuel and Test Type

Vehicle ID	FTP			UC	ALT
	P2 Cert	E6	E10	P2 Cert	P2 Cert
Vehicle #8	10	5	0	0	0
Vehicle #9	7	11	0	0	0
Vehicle #5	0	5	0	0	0
Vehicle #7	2	8	4	0	4
Vehicle #11	5	5	0	4	0
Vehicle #10	5	4	0	0	0

The BC measurement instruments whose data were used in the analyses are indicated in Table 14. Some instruments were available for a short period of time and therefore some of our assessments in the following discussion are based on limited data. Note the ID column indicates abbreviations that will be used for the instruments in the forthcoming figures and text. With regard to the Thermal/Optical instrument, the method followed was the ARB Monitoring and Laboratory Division’s method number 139 (MLD, 2006). With regard to the other BC measurement instruments, we worked cooperatively with the instrument manufacturers in the deployment of their instruments to ensure that instrument setup, use, and data acquisition were in accordance with their standard operating procedures and specifications.

Table 14. Instruments used in ARB Studies on Black Carbon Measurement

Instrument	Analyte	Operating Principle	λ	Time Resolution	Intake Flow Rate	ID
ECOC/IMPROVE_A	EC	Thermal/Optical	633 nm	Time Integrated	60 L/min	EC
Light Attenuation Based Instrument	BC	Light Attenuation	880 nm	Time Integrated	60 L/min	OT
Photoacoustic Instrument	BC	Photoacoustic	808 nm	1 sec	1.9 L/min	PA1
Photoacoustic Instrument	BC	Photoacoustic	781 nm	1 sec	1.0 L/min	PA2
Light Attenuation Based Instrument	BC	Light Attenuation	880 nm	5 sec	2.0 L/min	AE1
Light Attenuation Based Instrument	BC	Light Attenuation	880 nm	1 sec	0.10 L/min	AE2

3. Method Limits of Detection Study

Method LODs for four of the instruments, when applied to the measurement of LDV exhaust BC using a CVS tunnel, were determined. The instruments examined in this study were EC, OT, PA1, and AE2. A 2009 light-duty gasoline vehicle was employed as the test vehicle. The test cycle used, ALT, was not a standard driving cycle. ALT is a constant speed driving cycle designed to assure the vehicle emits near-zero mass concentrations of BC, while still emitting somewhat normal levels of the matrix components typically found in exhaust.

Prior to each dynamometer test, the vehicle was inspected and prepped. The test involved the following steps: (1) starting the vehicle, (2) increasing the speed to 20 mph, (3) driving the vehicle at 20 mph for five minutes, (4) initiating filter sampling and real-time BC measurement instrument data logging, (5) continuing driving at 20 mph and simultaneously sampling and measuring for 20 minutes, (6) ending sampling and measuring, (7) and then decelerating and turning off the vehicle.

Five replicate tests were conducted on different days. PM samples, collected on quartz filters, were analyzed by the EC and OT instruments for BC. The mass per test values were then converted to mass/mi values. These data are indicated in columns 2 and 3 of Table 15. Soot mass concentration versus time plots, from the two real-time instruments, were also obtained. These concentration data were combined with the real-time CVS flow rates and driving mileages to determine BC mg/mi values for each of the tests. These values are indicated in columns four and five of Table 15.

Table 15. Test Results, Descriptive Statistics, and Method Limits of Detection for Four Instruments

	Time Integrated		Real-Time	
Test ID	**EC (mg/mi)**	**OT (mg/mi)**	**PA1 (mg/mi)**	**AE2 (mg/mi)**
705620	0.0354	0.2188	0.1608	0.1147
1028822	0.0068	-0.1264	0.0629	0.0160
1028841	0.1307	0.0000	0.0938	0.0232
1028885	0.1997	0.0968	0.1501	0.0900
1028899	0.0424	0.0328	No Data	0.0452
μ	0.0830	0.0444	0.1169	0.0578
σ	0.0800	0.1269	0.0465	0.0429
df	4	4	3	4
$t_{0.95}$	2.78	2.78	3.18	2.78
LOD	*0.22 mg/mi*	*0.35 mg/mi*	*0.15 mg/mi*	*0.12 mg/mi*

In a method LOD experiment, blank or "near zero" concentration samples are analyzed repeatedly. The standard deviation of the measured results is multiplied by the Student's t-score to give an estimate of the LOD of the method. In this study, the vehicle exhaust emitted during of each of the five tests, constituted a blank. Actual vehicle exhaust, rather than zero air or helium, was used so that matrix effects would be accounted for. For example, exhaust NO_x and OC can interfere with light attenuation or photoacoustic measurements.

A standard deviation (σ) for each instrument in mg/mi,σ, was calculated based upon the replicate test results. Detection limits were then derived using the following equation

$$\text{LOD (mass/mi)} = [\sigma(\text{g/mi}) * t\ (0.05, df)]$$

where t is the t-score obtained from the one-sided Student's t distribution, *df* is the number of degrees of freedom (N – 1), and 0.05 is the significance. For the EC, OT, AE1, and AE2 instruments, *df* was four since there were five replicate measurements. For the PA1 the *df* was three because the data failed to log during one test.

The LOD values determined for each method/instrument, and presented in the last row of Table 15, were similar and quite low compared to the LEV II and LEV III PM standards. The real-time instruments performed remarkably well, in this respect, considering that their intake flow rates are only a fraction of the flow rate used for

the filter sampling which precedes the EC and OT analyses. The method LOD of OT and EC were 0.35 mg/mi and 0.22 mg/mi respectively. These were somewhat higher than those observed for the real-time instruments; 0.15 mg/mi for PA1 and 0.12 mg/mi for AE2. The higher LOD for the time-integrated instruments may have been due to inherent problems with filter sampling. These may include unequal spatial deposition of PM during sampling, filter contamination and prepping issues.

Based on the results of this method LOD investigation, staff concluded that commercially available methods, including thermal/optical carbon analysis, are capable of quantifying BC at low levels, using the current CVS-based sampling methodology. Data presented later in this report show that BC accounts for more than half of PM emissions from future model year vehicles. These methods will be able to determine the BC mass emissions of vehicles whose PM emissions are near or above the 3 mg/mi PM mass standard set for MY 2017.

4. Repeatability Analysis

A repeatability analysis was performed to estimate how consistent BC mg/mi results were between repeated dynamometer tests, and if consistency depends upon the BC measurement instrument used. BC measurement repeatability values were determined based upon “repeated tests;” and here we define repeated tests as dynamometer tests involving the same vehicle, fuel type, and driving cycle.

In this analysis, data from 65 FTP-75 tests and four UC tests were used. These dynamometer tests involved all six LDV and all three fuels indicated earlier in Table 13. Thirteen different combinations of vehicle/driving cycle/fuel were analyzed.

These combinations are listed in the first column of Table 16, which also indicates the repeatability data for the EC and OT instruments. Mean, SD, RSD, and N, represent the mean, standard deviation, relative standard deviation, and number of tests, for each test combination and instrument respectively. There are more test repeats for certain measurement types than others because not all instruments were used in every test. The RSD values and number of tests, for each test combination, were used to a derive pooled-RSD statistic for each instrument. Each pooled RSD statistic represents a point estimate of the repeatability for an instrument/method. Based on six vehicle/driving/cycle/fuel combinations, the repeatability of the EC method, using the thermal/optical method and the IMPROVE_A protocol, is approximately 25 percent. EC performed better than the light attenuation, filter-based OT method; which returned a repeatability statistic of 35 percent for 9 test combinations.

Table 17 presents repeatability data for the real-time photoacoustic instruments and the real-time light attenuation instruments. BC data from the photoacoustic instruments PA1 and PA2 generated repeatability statistics of 25 percent and 23 percent, respectively. The real-time light attenuation instruments AE1 and AE2 gave repeatability values of 20 percent and 26 percent.

The data indicates that the repeatability for the time-integrated thermal/optical instrument using the IMPROVE_A protocol is similar to that of the photoacoustic and real-time light attenuation instruments, at approximately 25 percent of the average value. The similarity of the BC measurement repeatability values, across the different instruments, suggests that test-to-test results differences are mostly likely due to test-to-test variation in the actual BC emissions.

Table 16. Repeatability Data for the Time-Integrated BC Mass Measurement and the Thermal/Optical IMPROVE_A Carbon Analysis for EC.

		EC				**OT**			
#	Combination	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N
1	Vehicle #8/FTP/P2 Cert	0.60	0.09	15.6	2	0.43	0.00	1.00	3
2	Vehicle #8/FTP/E6								
3	Vehicle #9/FTP/P2 Cert	0.71	0.14	19.2	2				
4	Vehicle #9/FTP/E6	2.33	0.75	32.3	4	1.45	0.84	57.5	3
5	Vehicle #11/FTP/E6					0.54	0.07	13.6	3
6	Vehicle #11/FTP/E10					1.16	0.12	10.7	2
7	Vehicle #5/FTP/E6					2.88	0.51	17.7	2
8	Vehicle #10/FTP/P2 Cert					0.41	0.18	42.8	4
9	Vehicle #10/FTP/E6								
10	Vehicle #7/FTP/P2 Cert								
11	Vehicle #7/FTP/E6	1.44	0.21	14.2	5	1.94	0.25	13.1	2
12	Vehicle #7/FTP/E10	1.44	0.43	30.2	2	1.64	0.45	27.3	2
13	Vehicle #11/UC/P2 Cert	2.10	1.44	68.6	2	0.28	0.13	45.2	4
	Pooled RSD		**25%**				**35%**		

Table 17. Repeatability Data for the Real-Time Photoacoustic and Light Attenuation-Based Instruments

		PA1				PA2				AE1				AE2			
#	Combination	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N	Mean (mg/mi)	SD (mg/mi)	RSD (%)	N
1	Vehicle #8/FTP/P2 Cert	0.59	0.20	33.4	9					0.81	0.06	7.8	3	0.64	0.03	4.1	3
2	Vehicle #8/FTP/E6																
3	Vehicle #9/FTP/P2 Cert	0.85	0.50	58.5	4												
4	Vehicle #9/FTP/E6	2.19	0.25	11.3	6												
5	Vehicle #11/FTP/E6	0.27	0.07	27.6	5	0.20	0.07	33.7	5	0.38	0.13	34.3	5	0.29	0.08	28.6	4
6	Vehicle #11/FTP/E10	0.27	0.06	20.8	4												
7	Vehicle #5/FTP/E6	2.74	0.22	8.2	2												
8	Vehicle #10/FTP/P2 Cert	0.37	0.06	15.8	4	0.27	0.05	17.1	4	0.54	0.06	10.3	3	0.39	0.06	15.6	3
9	Vehicle #10/FTP/E6	0.60	0.21	34.1	4												
10	Vehicle #7/FTP/P2 Cert	1.02	0.12	11.9	2												
11	Vehicle #7/FTP/E6	1.50	0.31	20.5	6												
12	Vehicle #7/FTP/E10																
13	Vehicle #11/UC/P2 Cert	1.11	0.09	8.5	3	1.07	0.14	13.4	3	2.06	0.25	12.3	3	1.22	0.62	50.7	3
Pooled RSD		**25%**				**23%**				**20%**				**26%**			

5. Relationship between EC and BC in LDV Exhaust Emissions

Emissions data, obtained from tests involving the six vehicles, driving under the FTP-75 cycle were analyzed to characterize the relationships between BC, measured by the light based methods, and EC measured by the thermal/optical method. BC data from PA1, PA2, AE1, AE2, and OT were analyzed. Note, in the previous sections on the LOD and Repeatability Analyses, the OT data that were reported were from samples collected on Teflon filters. In this section OT data are reported for samples collected on Teflon filters (OT_T) and quartz filters (in this section denoted as OT_Q).

BC mg/mi values, from the photoacoustic and light attenuation instruments, are plotted against the same test EC mg/mi values in Figure 76. Best-fit lines were used to model the relationships. Each series represents data for a different photoacoustic or light attenuation instrument. The thick dashed black line represents a 1:1 correspondence. The other lines represent linear fits to the series data. Note, these are individual dynamometer test results, and thus, no error bars are included.

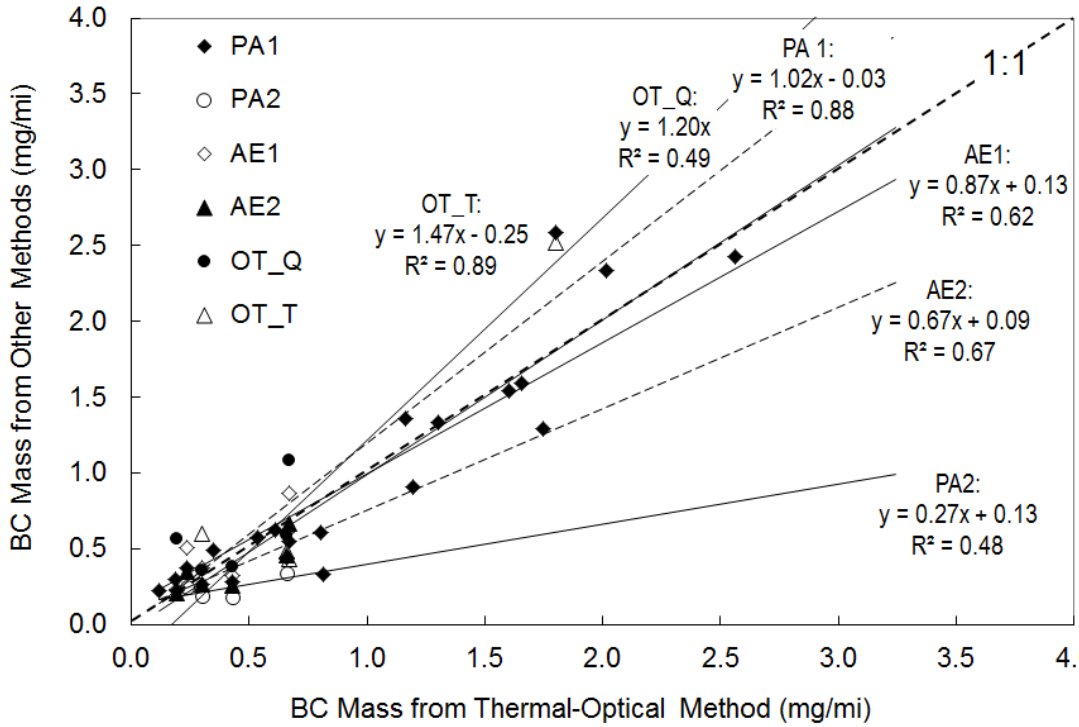


Figure 76. Same Test BC and EC Data from LDV Undergoing FTP-75 Testing

There was a wide disparity in the correlation of BC with EC for the different instruments. Data from the photoacoustic instrument PA1 exhibited the highest degree of correlation with EC (R^2 = 0.88). The PA2 instrument exhibited the lowest degree of correlation with EC (R^2 =0.48). Data from the real-time light attenuation instruments were in similar agreement with EC, with R^2 = 0.62 for AE1 and R^2 = 0.67 for AE2. The degree of correlation with EC, for data obtained from OT

analyses of BC on Teflon filters, R^2 = 0.89, was far superior to that obtained from the OT analyses of BC on quartz filters, R^2 = 0.49.

BC versus EC slopes were quite variable. Focusing on slope, the best agreement with EC was again observed for PA1, with m = 1.02. OT_Q and AE I BC plots against EC also returned slopes that were also near unity, at m = 1.20 and 0.87 respectively. The slope generated by AE2 vs. EC was 0.67. The linear model for PA2 versus EC had the smallest slope, which was m = 0.27.

Several instruments in this study were only available for tests with an extremely narrow and low emissions range and this could be a factor in the discrepancy between measurements. However, the measured BC and EC mass/mi values were almost all well above the LOD values determined in the Method LOD Analysis of Subsection 3.

The methods used for calibrating various BC measurement instruments in this study differ substantially. That should at least partially explain the differences in the calculated slope values. For example, PA2 is calibrated in a different manner than PA1 (via carbon black versus a soot generator). As discussed earlier in this appendix, calibration differences can lead to the lack of unity in slope when comparing paired data from two different instruments. Since the correlation between the PA2 and EC data was poor, interpretation of the slope is difficult. Nevertheless, it should be restated that there is no agreed upon calibration method for photoacoustic or light attenuation BC measurement instruments and that can lead to difficulties when comparing or merging the BC data from multiple instruments.

These ARB results may be compared to those reported in the review article by Watson and coworkers in 2005, who summarized the relevant results of 42 publications comparing various BC measurement methods when applied to the analysis of ambient and source samples (Watson et al., 2005). For instance, the results of studies that compared paired data from a photoacoustic instrument and one or more thermal/optical instrument (Adams et al., 1990; Moosmüller et al.,1998; Moosmüller, 2001) were recapped. The results of these studies indicated good correlation between the two method types, with R >0.9 for paired data in all of the studies. These results are consistent with the high degree of correlation observed between PA1 and EC, in this study; but are in contrast with the poor agreement observed between PA2 and EC. However, one of the reviewed references reported poor agreement, between the two methods, when EC levels were low (Moosmüller et al.1998). As stated above, the measured BC/EC mass emissions were fairly low in tests where both the PA2 and EC analyses were performed.

Publications comparing various light attenuation based methods with thermal/optical methods were also recapped. Their results indicated that BC obtained, via most light-based instruments, is generally well-correlated with thermal/optical EC (Hitzenberger et al., 1999; Allen et al., 1999; Babich et al., 2000; Moosmüller et al., 2001) but the slopes often deviate from unity (Babich et al., 2000;, Moosmüller et al., 2001; Sharma et al., 2002). That is consistent with the results plotted above for

OT_Q and AE2 which indicated substantial deviation from unity. There were also studies which indicated inconsistent values of $b_{abs,}$ depending on the sample source. For instance Babich and coworkers determined b_{abs}, using simultaneous measurements of EC and BC, and found a strong dependence upon the site in which the ambient measurements were made (Babich et al., 2000); and this indicates differences in the absorption properties of various types of BC as discussed in section IV.A.2.

6. Preliminary Selection of the Thermal/Optical Method with IMPROVE_A as the Reference Method for Measurement of BC in LDV and MDV Exhaust Emissions

Based on the results from the ARB studies on BC measurement methods, information gathered during a literature review, and the staff's experiences with the instruments, the staff tentatively proposes:

1) The thermal/optical method with IMPROVE_A be adopted as the reference BC test method

2) The total EC fraction, in an IMPROVE_A analysis, be used as the equivalent of BC

3) The BC emissions from LDV and MDV should be made based upon direct measurement and not estimated from total PM

The reasons for the preliminary selection of the thermal/optical method with IMPROVE_A, as the reference method, for BC measurement are indicated below.

1) A standard, well-agreed-upon calibration method is available for this method.

The choices of calibration standards are well accepted for the thermal/optical carbon analysis, regardless of thermal ramping protocol (Cachier et al., 1989; Fung, 1990; Chow et al., 1993; Birch and Cary, 1996; NIOSH, 2003). Elemental carbon, defined as the difference between total carbon and organic carbon, has been used as a baseline in many other BC measurement comparison studies.

2) OC/EC methods have been used in both ambient monitoring and source measurement of BC for many years

The IMPROVE_A thermal/optical carbon analysis is the designated carbon analysis method for the US IMPROVE air quality monitoring network (for Class I National Parks), designed to meet the visibility standard set by the US Regional Haze Rule. The IMPROVE_A protocol has also been used for the EPA Speciation Trends Network (STN) at urban sites, since 2007 (NAREL, 2008). The adoption of the IMPROVE_A thermal/optical carbon analysis will synchronize the OC/EC database of source emissions and ambient monitoring network (SLAM and NLAM).

3) The IMPROVE_A thermal/optical carbon analysis is the only mass-based BC measurement.

The light-based BC measurement instruments use a fixed wavelength to directly or indirectly probe BC. The absorption signal is converted to a BC mass via a factory derived conversion factor. However, the absorption spectra of BC may vary significantly between various engine technologies and vehicles. There is also evidence that light absorption by BC, as occurs in photoacoustic and light attenuation based measurements, may be heavily influenced by coatings on particles (Cross et al., 2010; Slowik et al., 2007). The mass-based measurement of EC is much less affected by these two matrix effect as it is independent of the optical properties of the analyte.

4) EC correlate with BC emissions in motor vehicle exhaust

In the ARB 2010 LEV III study, EC masses measured by IMPROVE_A protocol correlate with BC measured from various light-based instruments. The correlation is particularly strong in for vehicles which use the GDI technology. These GDI vehicles are expected to comprise a very large fraction, perhaps the majority, of the US fleet in the next decade. Correspondence of EC and BC is essential because IPCC has identified BC as a global warming agent.

5) Method Repeatability and Method LOD Differences are not Large between Methods

As also described earlier in this appendix, the method repeatability and method LOD of the IMPROVE_A thermal/optical carbon analysis are similar to those of the other measurement methods. The results indicate that the variation between tests is likely due to the variations in the actual emissions. The similarity in the calculated method LOD indicates that, perhaps, the sampling methodology plays more of a role in determining the method LOD than does the individual instrument LOD.

Despite the strong advantages of thermal-optical carbon analysis listed above, staff recognizes that the IMPROVE_A thermal/optical carbon analysis has a few inherent disadvantages.

1) Potential Mis-Classification of BC/EC

The EC fraction is comprised of the vast majority of BC in a PM sample from a vehicle emission. A certain percentage of the OC emitted, in the early stages of the thermal/optical carbon analysis, absorbs actinic radiation and could be mis-classified as BC. However, the data in Figure 2 indicates fairly good correlation between BC and EC in vehicle exhaust. This indicates that, for the most part, EC and BC in vehicle emissions represent the same chemical components.

2) Early Decomposition Due to Catalytic Effect

It has been shown that the presence of certain elements and salts (Na, K, Pb, Mn, V, Cu, Ni, Co, and Cr, SO_4^{2-}) catalyze the removal of EC at lower temperatures (Lin and Friedlander, 1988; Yu et al., 2002). This effect occurs most often in the analysis of ambient PM samples and source samples containing biomass burning. The amounts of these elements/complexes in vehicle exhaust emissions, however, are expected to be relatively small; and for IMPROVE_A, the reflectance correction for charring compensates for the evolution of EC at lower temperatures (Chen et al., 2004; Chow et al., 2004).

3) Relative Poor Time Resolution

Finally, the IMPROVE_A thermal/optical carbon analysis is a method which provides test-phase integrated data but does not provide any real-time BC emissions data in the vehicle testing. The real-time BC measurement may provide a means to assess how BC emissions are influenced by the variables of the driving cycle (vehicle speed, acceleration etc.), which could support future development of BC emission control strategies and improved combustion technologies.

7. Moving Forward

ARB will assess the vehicle exhaust BC measurement methods using a decision matrix. The decision matrix used can be similar to, but more developed than, the one depicted in Table 18. Scores for each of the categories indicated in the first row (and possibly other categories), can be determined for each method. The scores can then be weighted by category importance and summed across each row, to generate total scores for each method. The method with the highest total score can then be chosen as the reference method.

Table 18. Tentative Decision Matrix for Reference BC Measurement Method

Method	Standard Calibration Available	Ambient Data Available	Relevancy to Climate Change	LOD	Interferences	Repeatability	Time Resolution	Price	Ease of Operation
Time-Integrated Thermal/Optical	+	+	•	•	+	•	–	•	–
Time-Integrated Light Attenuation	–	–	+	–	–	–	–	+	•
Real-Time Light Attenuation	–	•	+	+	–	•	+	+	+
Real-Time Photoacoustic	–	•	+	+	–	•	+	–	+

C. Relationships between Black Carbon and other PM Related Quantities in LDV Exhaust Emissions

1. Introduction

The focus of this section is on the relationships between EC and two other PM related metrics; solid particle number and PM mass. In addition to measuring BC, PM mass and SPN were measured during several of the dynamometer tests of the ARB 2010 study at the Haagen-Smit Laboratory. In this section the observed relationships between BC and SPN are described (BC and SPN are measured using the PMP Protocol, as detailed in section II.B.4).

The European 5b and 6 standards include limits on both SPN and PM mass for compression ignition diesel passenger cars. For these vehicles, SPN must fall below 6 $x10^{11}$ particles/km, in addition meeting the 5 mg/mi PM mass standard, under the NEDC. In the US, there are only PM mass standards and BC is controlled indirectly by these standards. However, solid particle number has been suggested as a superior measurement and more sensitive alternative method which could be used in combination with the PM mass method in the future. Descriptions of the PM and SPN measurement instruments used in these studies are indicated in Table 19.

Table 19. PM and SPN Measurement Instrument Descriptions

Instrument	Analyte/ ID	Operating Principle	Time Resolution	Intake Flow Rate	Unit
Microbalance	PM	Weighing	Time Integrated	60 L/min	0.1 µg
PMP	SPN	Thermal Denuding/Condensation Particle Counting	1 sec	5.0 L/min	particles/ cm^3

2. Relationship between EC and PM: EC to PM Fraction

Data from 26 FTP-75 dynamometer tests were analyzed to determine the range of EC/PM ratios in LDV exhaust emissions, and the results are shown in Figure 77. The tests included six vehicles (two injection technologies), and three different fuels (E6, E10, and Phase 2 Cert). In general, PFI vehicles emitted much lower EC mass than GDI vehicles. EC/PM fractions of 0.70$\pm$0.12 mg/mi and 0.83$\pm$0.27 mg/mi were determined for the GDI and PFI vehicles, respectively. The EC/PM varies from 0.57 to 1.10 at the 95 percent confidence level for PFI and is 0.58 to 0.82 for the GDI vehicles. The overlap of the confidence intervals indicates that the EC/PM fractions for the PFI vehicles and GDI vehicles were not statistically different from one another.

The overall slope, 0.70$\pm$0.10 mg/mile which was most influenced by the high emissions levels and numbers of the GDI vehicle vehicles. The positive slopes indicate a positive association between EC and PM in LDV exhaust emissions. The fact that the R^2 values were not that close to unity, however, indicates that the EC/PM fraction does not hold constant at all PM emission levels nor for all vehicle models.

The results of this analysis indicate that EC accounts for approximately 70 percent of the PM mass emissions from gasoline-powered LDV. This result is in stark contrast to lower EC/PM ratios reported by others (U.S. EPA, 2008; Li et al., 2006; Bosteels et al., 2006). The rising EC/PM ratio observed in the newer vehicles tested in this study indicates that the reduction in EC emissions may not follow PM mass reductions. More testing is needed to determine the typical ratios of EC/PM in LDV exhaust, as these ratios seem to be changing over time. These data can then be used, in combination with other vehicle fleet information, to more accurately estimate the atmospheric contribution of BC by LDV in climate models.

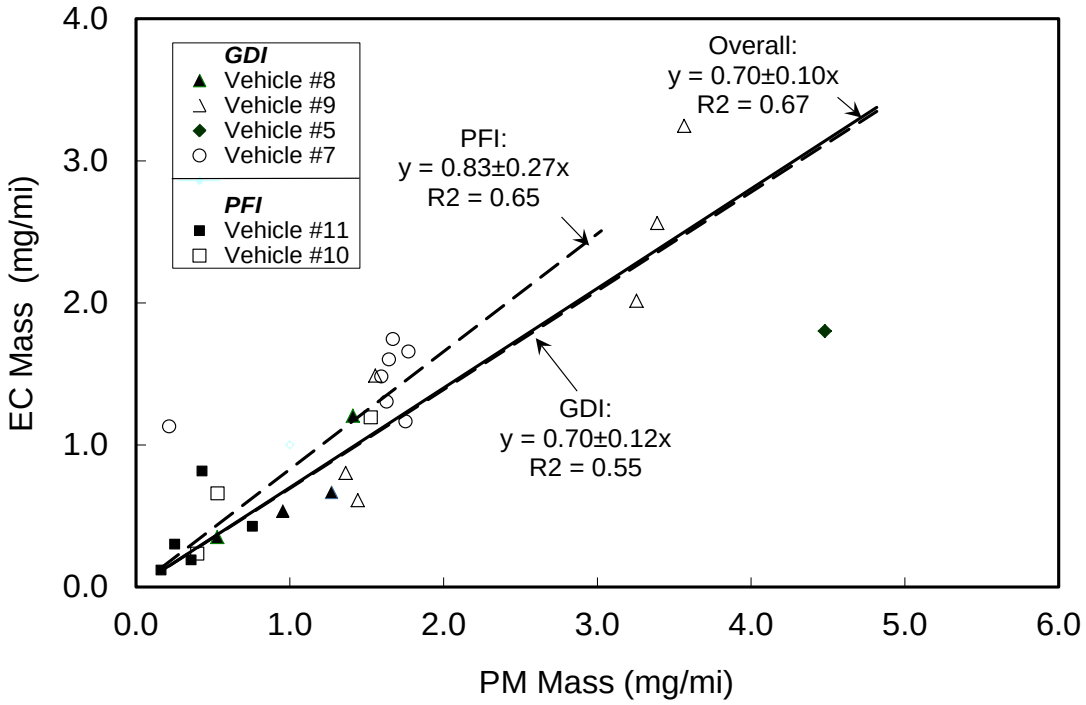


Figure 77. EC Versus PM for Several Vehicles Undergoing FTP-75 Dynamometer Testing

3. Relationship between EC and SPN

ARB had considered including SPN measurement, via PMP, as an alternative to the PM mass measurement in the proposed LEV III regulations. For the reasons outlined earlier in this appendix, the ARB decided not to pursue the SPN alternative in the initial LEV III regulations package. However, the ARB is still maintaining the importance of the particle counting alternative and is pursuing an active study program on particle number measurement as an alternative to the filter-based method.

PMP based SPN measurement and thermal/optical analysis determined EC measure approximately the same black carbonaceous material in diesel exhaust. ARB, therefore, assessed the correlations between SPN and EC for LDV emissions and the results are plotted in Figure 78. In Figure 78, each data point represents the results of one test. The inner solid line represents the best-fit linear approximation for the data. A 90 percent confidence interval represents the range within which we are 90 percent certain that the mean value of SPN is, for a given value of EC value. A 90 percent prediction interval indicates, for any given EC value, the range in which 90 percent of the individual test SPN emission results are expected to lie.

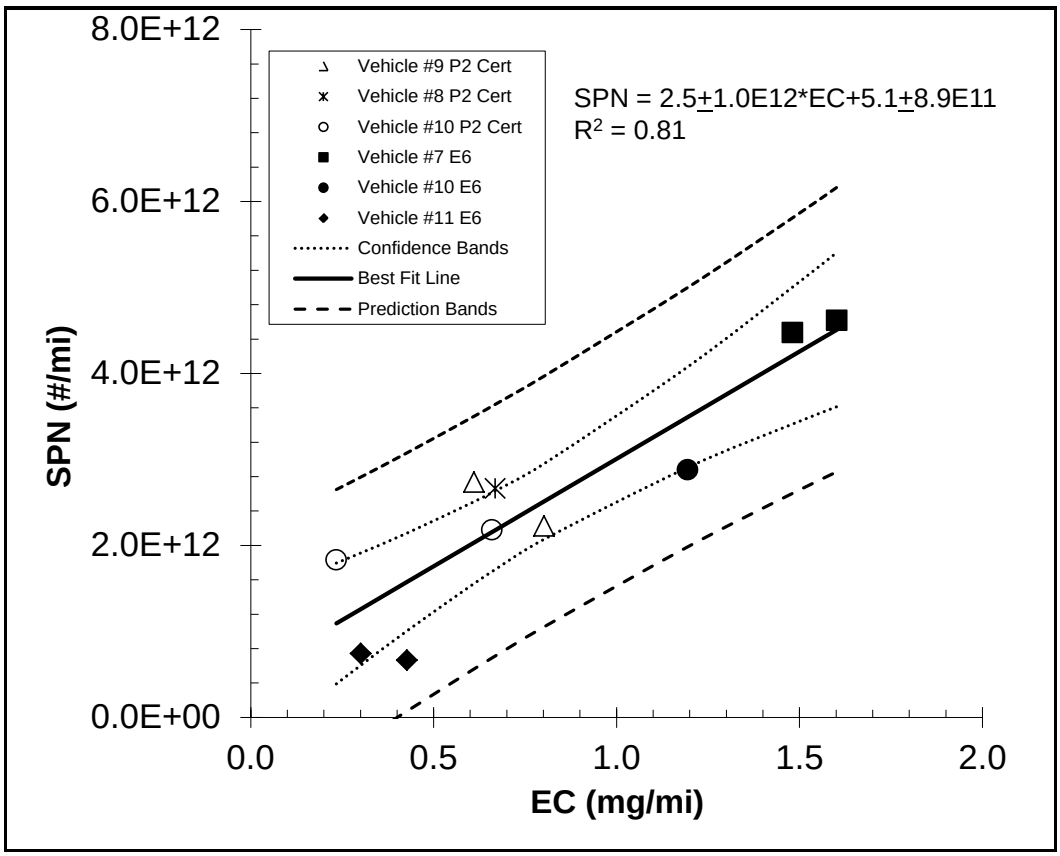


Figure 78. SPN Versus EC for Several Vehicles Undergoing FTP-75 Dynamometer Testing

Overall, the relationship was linear with an $R^2 = 0.81$. This indicates that vehicle-to-vehicle differences in SPN/EC are not large and that SPN/EC ratios do not strongly depend upon the magnitude of the EC mass emissions. The slope was $2.5 \pm 1.0 \times 10^{12}$, where 1.0×10^{12} is the 95 percent confidence interval for the slope. This indicates that an emission of 2.5×10^{12} solid particles corresponds to an emission of roughly 1 mg of EC. This result is close agreement with the corresponding relation of 2.2×10^{12} particle per mg of mass emitted reported by Ford Motor Company (Kirchner et al., 2010), who compared exhaust SPN to PM, for a GDI vehicle undergoing NEDC cycle dynamometer testing.

Honda and SwRI also performed a study in which they measured SPN and soot from a single GDI vehicle, using their Solid Particle Sampling System, undergoing FTP testing; and found the slope to be 3.2×10^{12} (the intercept was fixed to zero) (Khalek et al., 2009). A regression analysis of the same ARB data, from Figure 78, with the intercept fixed to zero returns a slope of $3.0 \pm 0.5 \times 10^{12}$, in fairly good agreement with Honda/SwRI.

The size of the prediction intervals indicates a fairly large spread in the SPN emission values for vehicles at identical EC emission levels. For example, the 90 percent prediction interval for SPN for cars emitting 1.0 mg/mi of EC is 1.5×10^{12}-4.5×10^{12} mg/mi; representing a 300 percent difference between the highest and

lowest SPN emitters at this EC level. Nevertheless, based upon the SPN-EC correlation observed in this study, it is likely that the inclusion of a strict SPN standard would lead to reductions in EC (i.e. BC) emissions.

D. Conclusion

In this section, a literature review on, and data from an evaluation study of, BC measurement methods were presented in support of the proposed LEV III regulations. The evaluation study involved dynamometer testing of several LDV's at the ARB's Haagen-Smit Laboratory in El Monte CA. Six different commercially available BC measurement instruments were examined and these fell into three different categories: thermal/optical, light attenuation, and photoacoustic.

Method LODs were determined for several of the instruments and these ranged from 0.12 mg/mi to 0.35 mg/mi. The data indicated that the real-time instruments had slightly lower method LOD's than the time-integrated instrument, despite the fact that the real-time instruments required much lower sample flow rates.

Test-to-test repeatability estimates were made based upon data from repeat tests (same vehicle/driving cycle/fuel) for several of the BC measurement instruments. The data indicated that repeatability did not heavily depend upon the BC measurement method, with values ranging from 20 percent to 35 percent, suggesting that most of that variability is due to real differences between tests in exhaust BC emissions.

Agreement between same-test BC data, acquired using photoacoustic and light attenuation-based measurement methods, and BC data, acquired using the IMPROVE_A thermal/optical carbon analysis were examined. Agreement with EC varied between the different instruments, as the calculated R^2 and slopes ranged from 0.89 to 0.48 and 1.47 to 0.27 respectively.

The relationship between EC and PM, and EC and SPN, in LDV exhaust were explored using EC data from the IMPROVE_A protocol, PM mass following 40CFR Part 1065 and SPN data from a PMP compliant solid particle analyzer. The correlation between BC and PM was moderate, $R^2 = 0.67$, and the EC/PM fraction was fairly high, at 0.70, when both PFI and GDI vehicles were used in the linear analysis. Correlation between SPN and EC was even greater with an R^2 of 0.81, indicating that SPN emissions vary linearly with EC emissions and that SPN/EC ratios tend to be fairly consistent.

V. CONCLUSION

This document has established the technical rationale and need for lowering the existing LEV II PM standards by 90% for LDVs in a phased-in approach. Technology for reducing and controlling PM emissions to allow for compliance with the proposed 3 mg/mi and 1 mg/mi standards is known and available today. The stringency of the proposed PM standards will ensure that LDV and MDV PM emissions do not increase as manufacturers incorporate new technology to reduce GHG emissions.

There are several major fossil fuel-based ICE technologies that are expected to gain market share for controlling GHG emissions; they are PFI, GDI, clean diesel, alternative fuels and hybrid variants of these. Test data shown in this report suggests that there is readily available technology in use today that can meet the proposed 2017 standards. Test data and trends suggest that existing technology is on track to meet the standards proposed for 2025. Importantly, compliance with the proposed PM standards does not impose a cost increase to vehicles.

ARB's evaluation of the PM measurement based on current best practices confirms that modifications to 40 CFR Part 1065 and improved laboratory and filter handling procedures will allow for the necessary accuracy and repeatability in the measurement of emissions at the 3 mg/mi level. Additional modifications to increase filter mass loadings, such as reducing dilution and decreasing the number of filter media used for a test, can greatly improve measurement sensitivity at or below the 1 mg/mi level.

While the gravimetric determination of PM mass will stand, promising alternative approaches are emerging as potentially useful technical supplements. ARB is committed to exploring these options. The first of these areas is improvements to the PMP method, such as inclusion of sub-23 nm particles and developing ways to reduce artifact formation. If successful, an improved method may establish the basis for a viable, low-cost and more streamline approach for quantification of PM control that has the required sensitivity for measurement of ultra-low PM emissions. Characterization of emission profile in terms of its physical or chemical components is also a viable area for additional work. The integration of the particle size distribution in the PM emissions or determination of PM mass based on the chemical reconstruction of the emission profile are two leading techniques that have shown, based on the published literature, potential for measuring ultra-low PM levels. Further research is needed to improve these alternative measurement techniques and ARB is committed to this research activity.

As part of the LEV III test program ARB evaluated the impact of gasoline fuels with different oxygenate content on PM mass and SPN emissions. For the narrow range of fuel types tested, no clear relationship between PM mass and fuel composition was found. SPN emission rate remains unchanged, regardless of the fuel composition.

ARB also assessed the applicability of Honda's proposed PM Index and its mathematical construct to predict PM emission rates with California fuels. California fuels displayed a PMI that covers only a narrow range (1.44 to 1.58), which makes an assessment difficult. Given the large test-to-test and even larger vehicle-to-vehicle variability in PM emissions, a correlation between PMI and PM emissions could not be ascertained for the narrow PMI range of the fuels tested. Thus, for California fuels, the PMI is not advantageous.

The extensive investigation of BC measurement was successful and revealed a number of important findings to advance the general understanding of BC and vehicle PM emissions. The study involved dynamometer testing of several LDV's at the ARB's Haagen-Smit Laboratory in El Monte, CA. Six commercially available BC measurement instruments were examined. Method LODs for the instruments ranged from 0.12 mg/mi to 0.35 mg/mi. The data indicated that the real-time instruments had slightly lower method LOD's than the time-integrated instrument, despite the fact that the real-time instruments required much lower sample flow rates. This is a promising development. Test-to-test repeatability data for several BC instruments indicated that repeatability did not heavily depend upon the BC measurement method. The repeatability values ranging between 20 and 35 percent, suggesting that most of that variability is due to real differences between tests in exhaust BC emissions. Agreement between same-test BC data, acquired using photoacoustic and light attenuation-based measurement methods, and BC data, acquired using the IMPROVE_A thermal/optical carbon analysis were examined. Agreement with EC varied between the different instruments, as the calculated R^2 and slopes ranged from 0.89 to 0.48 and 1.47 to 0.27 respectively.

The relationship between EC and PM, and EC and SPN, in LDV exhaust were explored using EC data from the IMPROVE_A protocol, PM mass following 40CFR Part 1065 and SPN data from a PMP compliant solid particle analyzer. The correlation between BC and PM was moderate, $R^2 = 0.67$, and the EC/PM fraction was fairly high, at 0.70, when both PFI and GDI vehicles were used in the linear analysis. Correlation between SPN and EC was even greater with an R^2 of 0.81, indicating that SPN emissions vary linearly with EC emissions and that SPN/EC ratios tend to be fairly consistent.

VI. REFERENCES

Adams, K.M., Davis, L.I., Japar, S.M., Finley, D.R., Cary, R.A. (1990). Measurement of Atmospheric Elemental Carbon: Real-Time Data for Los Angeles During Summer 1987. *Atmospheric Environment 24A(3): 597-604.*
(CD: adams1990)

Aikawa, K., Sakurai, T., Jetter, J.J. (2010). Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions. *SAE Technical Paper* 2010-01-2115. DOI: 10.4271/2010-01-2115.
(CD: sae2010012115)

Al-Hasan, M. (2003). Effect of Ethanol–Unleaded Gasoline Blends on Engine Performance and Exhaust Emission. *Energy Conversion and Management* 44: 1547-1561.
(CD: alhasan2003)

Allen, G.A., Lawrence, J., Koutrakis, P. (1999). Field Validation of a Semi-Continuous Method for Aerosol Carbon (Aethalometer) and Temporal Patterns of Summertime Hourly Black Carbon Measurements in Southwestern PA. *Atmospheric Environment (*33)5: 817-823.
(CD: allen1999)

Andersson J. and Dilara, P. (2005). Update and Report on First Results: Light-Duty Inter-Laboratory Correlation Exercise. 9th International ETH Conference on Combustion-generated Nanoparticles, August 15-17, 2005, Zurich, Switzerland.
(CD: andersson2005)

Andersson, J., Giechaskiel, B., G., Munoz-Bueno, R., Sandbach, E., Dilara, P. (2007). Particle Measurement Programme (PMP) Light-Duty Inter-Lightaboratory Correlation Exercise (ILCE_LD) Final Report. European Commission, Directorate General, Joint Research Center (JRC), Institute for Environment and Sustainability, 2007, EUR 22775 EN.
(CD: andersson2007)

Andersson, J., Keenan, M., and Akerman, K. (2009). GDI Particles – Legislation, Current Levels and Control. RD. 09/99801.1.
(CD: andersson2009)

Andreae, M.O. and Gelencsér, A. (2006). Black Carbon or Brown Carbon? The Nature of Light-Absorbing Carbonaceous Aerosols. *Atmospheric Chemistry and Physics* 6: 3131-3148.
(CD: andreae2006)

Araujo, J.A., Barajas, B., Kleinman, M., Wang, X., Bennett, B.J., Gong, K.W., Navab, M., Harkema, J., Sioutas, C., Lusis, A.J., Nel, A.E. (2008). Ambient Particulate Pollutants in the Ultrafine Range Promote Early Atherosclerosis and Systemic Oxidative Stress. *Circulation Research* 102(5): 589-596.
(CD: araujo2008)

ARB (2004). Initial Statement of Reasons for Proposed Rulemaking, Public Hearing to Consider Adoption of Regulations to Control Greenhouse Gas Emissions from Motor Vehicles. California Air Resources Board. Date of Release: August 6, 2004. http://www.arb.ca.gov/regact/grnhsgas/isor.pdf, accessed on 08/31/2011.
(CD: carb2004)

ARB (2007). Status Report on the California Air Resources Board's Zero Emission Vehicle Program. California Air Resources Board. Date of Release: April 20, 2007. http://www.arb.ca.gov/msprog/zevprog/zevreview/zev_review_staffreport.pdf, accessed on 08/31/2011.
(CD: carb2007)

ARB (2010). Preliminary Discussion Paper – Amendments To California's Low-Emission Vehicle Regulations for Criteria Pollutants – Lev III. Presented at March 2, 2010 LEV III Workshop.
http://www.arb.ca.gov/msprog/levprog/leviii/meetings/030210/lev_iii_discussion_paper_2-10.pdf, accessed on 08/31/2011
(CD: carb2010)

ARCTIC (2011). An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council. Technical Report of the Arctic Council Task Force on Short-Lived Climate Forcers. May 2011.
(CD: arctic2011)

Arnott, W.P., Moosmüller, H., Sheridan, P.J., Ogren, J.A., Raspet, R., Slaton, W.V., Hand, J.L., Kreidenweis, S.M., Collet Jr., J.L. (2003). Photoacoustic and Filter-Based Ambient Aerosol Light Absorption Measurements: Instrument Comparisons and the Role of Relative Humidity. *Journal of Geophysical Research* 108: 4034-4044.
(CD: arnott2003)

Ayala, A., Herner, J.D., Zhang, S., Robertson, B., Frodin, B., Huai, T., Haste, R., McMahan, W., and Lemieux, S. (2007). Experiences from the CARB PMP-Based Program. International Conference on Transport and Environment: A Global Challenge, Technical and Policy Solutions, March 19-21, 2007, Milan, Italy.
(CD: ayala2007)

Ayala, A., Zhang, S., Collins, J., Zhan, T., Dwyer, H., Huai, T., Herner, J., Chau, W. (2008). California's Informal Participation in the Particle Measurement Programme (PMP) Light Duty Inter-Laboratory Correlation Exercise (ILCE_LD), ARB Final

Research Report, October, 2008. http://www.arb.ca.gov/research/veh-emissions/pmp-ld/CARB_Golden_Vehicle_PMP_Report_Final-05JAN09.pdf
(CD: ayala2008)

Babich, P., Davey, M., Allen, G., Koutrakis, P. (2000). Method Comparisons for Particulate Nitrate, Elemental Carbon, and $PM_{2.5}$ Mass in Seven U.S. Cities. *Journal of the Air and Waste Management Association* 50: 1095-1105.
(CD: babich2000)

Benvenuti, L., Di Benedetto, M.D., Di Gennaro, S., Sangiovanni-Vincentelli, A. (2003). Individual Cylinder Characteristic Estimation for a Spark Injection Engine, *Automatica* 39: 1157-1169.
(CD: benvenuti2003)

Birch, M.E. and Cary, R.A. (1996). Elemental Carbon-Based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust. *Aerosol Science and Technology* 25(3): 221-241.
(CD: birch1996)

Bishop ,G.A., Morris, J.A., Stedman, D.H., Cohen, L.H., Countess, R.J., Countess, S.J., Maly, P., Scherer, S. (2001). The Effects of Altitude on Heavy-Duty Diesel Truck On-Road Emissions. *Environmental Science and Technology* 35: 1574-1578.
(CD: bishop2001)

Biswas, S., Hu, S., Verma, V., Herner, J.D., Robertson, W.H., Ayala, A., and Sioutas, C. (2008). Physical Properties of Particulate Matter (PM) from Late Model Heavy-Duty Diesel Vehicles Operating with Advanced PM and NO_x Emission Control Technologies. *Atmospheric Environment* 42**:** 5622–5634.
(CD: biswas2008)

Bosteels, D., May, J., Karlsson, H., de Serves, C. (2006). 'Regulated' and 'Non-regulated' Emissions from Modern European Passenger Cars. *SAE Technical Paper 2006-01-1516*. DOI: 10.4271/2006-01-1516.
(CD: bosteels2006)

Bougher, T., Khalek, I., Giannelli, R. (2010). Update on the PM Generator. September 1, 2010.
(CD: bougher2010)

Cachier, H., Bremond, M-P., Buat-Ménard, P. (1989). Determination of Atmospheric Soot Carbon with a Simple Thermal Method. *Tellus* 41B: 379-390.
(CD: cachier1989)

CAFCP (2011). California Fuel Cell Partnership. http://www.cafcp.org/faq/pwhat-fuel-cell. Accessed on 09/16/2011.
(CD: cafcp2011)

Cappa, C., Lack, D., Burkholder, J., Ravishankara, A. (2008). Bias in Filter-Based Aerosol Light Absorption Measurements Due to Organic Aerosol Loading: Evidence from Laboratory Measurements. *Aerosol Science and Technology* 42: 1022-1032.
(CD: cappa2008)

Cavalli, F., Viana, M., Yttri, K.E., Genberg, J., Putaud, J.-P. (2010). Toward a Standardised Thermal-Optical Protocol for Measuring Atmospheric Organic and Elemental Carbon: The EUSAAR Protocol. *Atmospheric Measurement Techniques* 3: 79-89.
(CD: cavalli2010)

Chase, R.E., Duszkiewicz, G.J., Richert, J.F.O., Lewis, D., Maricq, M.M., Xu, N. (2004). PM Measurement Artifact: Organic Vapor Deposition on Different Filter Media. *SAE Technical Paper* 2004-01-0967. DOI: 10.4271/2004-01-0967
(CD: sae2004010967)

Chen, L., Chow, J., Watson, J., Moosmuller, H., Arnott, W. (2004). Modeling Reflectance and Trasnmittance of Quartz-Fiber Fil;ter Samples Containing Elemental Carbon Particles: Implications for Thermal/Optical Analysis. *Journal of Aerosol Science* 35: 765-780.
(CD: chen2004)

Chen, L., Braisher, M., Crossley, A., Stone, R., Richardson, D. (2010). The Influence of Ethanol Blends on Particulate Matter Emissions from Gasoline Direct Injection Engines. *SAE Technical Paper* 2010-01-0793.
DOI: 10.4271/2010-01-0793.
(CD: sae2010010793)

Chien, S.-M., Huang, Y.-J., Chuang, S.-C., Yang, H.-H. (2009). Effects of Biodiesel Blending on Particulate and Polycyclic Aromatic Hydrocarbon Emissions in Nano/Ultrafine/Fine/Coarse Ranges from Diesel Engine. *Aerosol and Air Quality Research* 9(1): 18-31.
(CD: chien2009)

Chow, J.C., Watson, J.G., Pritchett, L.C., Pierson, W.R., Frazier, C.A., Purcell, R.G. (1993). The DRI Thermal/Optical Reflectance Carbon Analysis System: Description, Evaluation and Applications in U.S. Air Quality Studies. *Atmospheric Environment* 27A: 1185–1201.
(CD: chow1993)

Chow, J.C., Watson, J.G., Chen, L.W.A., Chang, M.-C.O., Robinson, N.F., Trimble, D., Kohl, S. (2007). The IMPROVE_A Temperature Protocol for Thermal/Optical Carbon Analysis: Maintaining Consistency with a Long-Term Database. *Journal of the Air and Waste Management Association* 57(9): 1014-1023.
(CD: chow2007)

Cross, E.S., Onasch, T.B., Ahern, A., Wrobel, W., Slowik, J.G., Olfert, J., Lack, D.A., Massoli, P., Cappa, C.D., Schwarz, J.P., Spackman, J.R., Fahey, D.W., Sedlacek, A., Trimborn, A., Jayne, J.T., Freedman A., Williams L.R., Ng, N.L., Mazzoleni, C., Dubey, M., Brem, B., Kok, G., Subramanian, R., Freitag, S., Clarke, A., Thornhill, D., Marr, L.C., Kolb, C.E., Worsnop, D.R., Davidovits, P. (2010). Soot Particle Studies Instrument Inter-Comparison-Project Overview, *Aerosol Science and Technology* 44: 592-611.
(CD: cross2010)

Durbin, T., Jung, H., Cocker, D.R., Johnson, K., Chaudhary, A. (2008). Evaluation of the Proposed New European Methodology for Determination of Particle Number Emissions and Its Potential in California for In-Use Screening. Final report submitted to ARB, August 2008.
(CD: durbin2008)

Durbin, T.D., Miller, J.W., Johnson, K., Hajbabaei, M. (2009). Biodiesel Characterization and NO_x Mitigation Study. Draft Final Memorandum by University of California Riverside, December 2009.
(CD: durbin2009)

Dwyer, H., Ayala, A., Zhang, S., Collins, J. Huai, T., Herner, J., Chau, W. (2010). A Study of Emissions from a Euro 4 Light Duty Diesel Vehicle with the European Particulate Measurement Programme. *Atmospheric Environment* 44(29): 3469-3476.
(CD: dwyer2010)

E/ECE (2009). Uniform Provisions Concerning the Approval of Vehicles with Regard to the Emission of Pollutants According to Engine Fuel Requirements. E/ECE/324, E/ECE/TRANS/ 505, Rev.1/Add.82/Rev.3/Amend.2, April 16, 2009. Addendum 82: Regulation No. 83, Revision 3-Amendment 2.
(CD: eece2009)

Fujimoto, Y., Tasukasaki, Y., Takei, Y., Ogawa, T., Nakada, M. (1994). Effects of Diesel Fuel Properties on Particulate Emissions from D.I. Diesel Engine. *JSAE Technical Paper* 9437278, 1994.
(CD: jsae9437278)

Fung, K. (1990). Particulate Carbon Speciation by MnO_2 Oxidation. *Aerosol Science and Technology* 12: 122-127.
(CD: fung1990)

Gauderman, W.J., Avol, E., Gilliland, F., Vora, H., Thomas, D., Berhane, K., McConnell, R., Kuenzli, N., Lurmann, F., Rappaport, E., Margolis, H., Bates, D., Peters, J. (2004). The Effect of Air pollution on Lung Development from 10 to 18 Years of Age. *New England Journal of Medicine* 351(11): 1057-1067.
(CD: gauderman2004)

Graboski, M.S., McCormick, R.L., Alleman, T.L., and Herring, A.M. (2003). The Effect of Biodiesel Composition on Engine Emissions from a DDC Series 60 Diesel Engine. Final Report: National Renewable Laboratory, NREL/SR-510-31461, February 2003.
(CD: graboski2003)

Hansen A.D.A., Rosen H., Novakov T. (1984). The Aethalometer - An Instrument for the Real-Time Measurement of Optical Absorption by Aerosol Particles. *The Science of the Total Environment* 36: 191-196.
(CD: hansen1984)

Herner, J.D., Robertson, W.H., Ayala, A. (2007). Investigation of Ultrafine Particle Number Measurements from a Clean Diesel Truck Using the European PMP Protocol. *SAE Technical Paper* 2007-01-1114. DOI: 10.4271/2007-01-1114.
(CD: sae2007011114)

Herner, J.D., Hu, S., Robertson, W.H., Huai, T., Collins, J.F., Dwyer, H., Ayala, A. (2009). Effect of Advanced Aftertreatment for PM and NO_x Control on Heavy-Duty Diesel Truck Emissions. *Environmental Science Technology* 43: 5928-5933.
(CD: herner2009)

Herner, J.D., Hu, S., Robertson, W.H., Huai, T., Chang, M.-C.O., Rieger, P., Ayala, A. (2011). Effect of Advanced Aftertreatment for PM and NOx Reduction on Heavy-Duty Diesel Engine Ultrafine Particle Emissions. *Environmental Science Technology* 45: 2413–2419.
(CD: herner2011)

Hitzenberger, R., Jennings, S.G., Larson, S.M., Dillner, A., Cachier, H., Galambos, Z., Rouc, A., Spain, T.G. (1999). Intercomparison of Measurement Methods for Black Carbon Aerosols. *Atmospheric Environment* 33: 2823-2833.
(CD: hitzen1999)

Horvath, H. (1993). Atmospheric Light Absorption - A Review. *Atmospheric Environment* 27A: 293-317.
(CD: horvath1993)

Hsieh, W.-D., Chen, R.-H., Wu, T.-L., Lin, T.-H. (2002). Engine Performance and Pollutant Emission of SI Engine Using Ethanol-Gasoline Blended Fuels. *Atmospheric Environment* 36: 403-410.
(CD: hsieh2002)

Huai, T., Smallwood, G.J., Ayala, A., Bachalo, W., Payne, G., Witze, P.O., Johnson, K., Durbin, T., Chernich, D.J., Maldonado, H. (2006). Comparison of Particulate Matter Emission Measurements by Laser-Induced Incandescence to the Gravimetric Procedure. *16th CRC On-Road Vehicle Emissions Workshop*, March 28-30, 2006, San Diego, California.
(CD: huai2006)

Iizuka, M., Kirii, A., Takeda, H., Watanabe, H. (2007). Effect of Fuel Properties on Particulate Matter Emissions from a Direct Injection Gasoline Vehicle. *JSAE Technical Paper* 20074414, 2007.
(CD: jsae20074414)

Jacobson, M. (1999.) Isolating Nitrated and Aromatice Aerosols and Nitrated Aromatic Gases as Sources of Ultraviolet Light Absorption. *Journal of Geophysical Research* 104: 3527-3542.
(CD: jacobson1999)

Jetter, J. (2010). Effect of Fuel Composition on PM Emissions, LEV III Workshop, May 18, 2010, El Monte, California.
http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/fuel_effect_on_pm-lev_iii_workshop-v4.
(CD: jetter2010)

Johnson, T., Caldow, R., Pöcher, A., Mirme, A., Kittelson, D. (2004). A New Electrical Mobility Particle Sizer Spectrometer for Engine Exhaust Particle Measurements. *SAE Technical Paper* 2004-01-1341.
DOI: 10.4271/2004-01-1341.
(CD: sae2004011341)

Johnson, K.C., Durbin, T.D., Jung, H., Chaudhary, A., Cocker III, D.R., Herner, J.D., Robertson, W.H., Huai, T., Ayala, A., and Kittelson, D. (2009). Evaluation of the European PMP Methodologies during On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy-Duty Diesel Vehicles. *Aerosol Science and Technology* 43(10): 962-969
(CD: johnson2009)

Jonker, M.T.O. and Koelmans, A.A. (2002). Extraction of Polycyclic Aromatic Hydrocarbons from Soot and Sediment: Solvent Evaluation and Implications for Sorption Mechanism. *Environmental Science and Technology* 36: 4107-4113.
(CD: jonker2002)

Kado, N.Y, Okamoto, R.A., Kuzmicky, P.A., Kobayashi, R., Ayala, A., Gebel, M.E., Rieger, P.L., Maddox, C., and Zafonte, L. (2005). Emissions of Toxic Pollutants from Compressed Natural Gas (CNG) and Low Sulfur Diesel-Fueled Heavy-Duty Transit Buses Tested Over Multiple Driving Cycles. *Environmental Science and Technology* 39: 7638-7649.
(CD: kado2005)

Khalek I.A., Bougher T., Jetter, J. (2010). Particle Emissions from a 2009 Gasoline Direct Injection Engine Using Different Commercially Available Fuels. *SAE Technical Paper* 2010-01-2117. DOI: 10.4271/2010-01-2117
(CD: sae2010012117)

Khalek, I.A. and Bougher,T. (2011). Development of a Solid Exhaust Particle Number Measurement System Using a Catalytic Stripper Technology. *SAE Technical Paper* 2011-01-0635. DOI: 10.4271/2011-07-0635.
(CD: sae2011010635)

Kirchner, U., Vogt, R., Maricq, M. (2010). Investigation of EURO-5/6 Level Particle Number Emissions of European Diesel Light Duty Vehicles. *SAE Technical Paper* 2010-01-0789. DOI: 10.4271/2010-01-0789
(CD: sae2010010789)

Kittelson, D.B. (1998). Engines and Nanoparticles: A review. *Journal of Aerosol Science 29*: 575–588.
(CD: kittelson1998)

Kittelson, D., Watts, W., and Johnson, J. (2002). Diesel Aerosol Sampling Methodology - CRC E-43. Final Report to Coordinating Research Council, 2002. http://www.crcao.org/reports/recentstudies00-02/E-43%20Final%20Report.pdf
(CD: kittelson2002)

Kittelson, D., Watts, W., Johnson, J., and Zarling, D. (2004). Gasoline Vehicle Exhaust Particle Sampling Study. Final report to the U.S. Department of Energy, Cooperative Agreement DE-FC04-01A166910. U.S. Department of Energy, National Renewable Energy Laboratory, 2004.
(CD: kittelson2004)

Kleeman M.J., Schauer J.J., Cass G.R. (2000). Size and Composition Distribution of Fine Particulate Matter Emitted from Motor Vehicles. *Environmental Science and Technology* 34(7): 1132-1142.
(CD: kleeman2000)

Klouda, G.A., Filliben, J.J., Parish, H.J., Chow, J.C., Watson, J.G., and Cary, R.A. (2005). Reference Material 8785: Air Particulate Matter on Filter Media. *Aerosol Science and Technology* 39: 173-183.
(CD: klouda2005)

Korashy H.M. and El-Kadi, A.O.S. (2006). The Role of Aryl Hydrocarbon Receptor in the Pathogenesis of Cardiovascular Diseases. *Drug Metabolism Reviews* 38: 411-450.
(CD: korashy2006)

Lawless, P.A., Rodes, C.E., Ensor, D.S. (2004). Multiwavelength Absorbance of Filter Deposits for Determination of Environmental Tobacco Smoke and Black Carbon. *Atmopheric Environment* 38: 3373-3383.
(CD: lawless2004)

Li, W., Collins, J.F., Norbeck, J.M., Cocker, D.R., Sawant, A. (2006). Assessment of Particulate Matter Emissions from a Sample of In-Use ULEV and SULEV Vehicles. *SAE Technical Paper* 2006-01-1076. DOI: 10.4271/2006-01-1076.
(CD: sae2006011076)

Lin, C. and Friedlander, S.K. (1988). Soot Oxidation in Fibrous Filters. 2. Effects of Temperature, Oxygen Partial Pressure, and Sodium Additives. *Langmuir* 4: 898-903.
(CD: lin1988)

Liu, Z.G., Vasys, V.N., Dettmann, M.E., Schauer, J.J., Kittelson, D.B., Swanson, J. (2009). Comparison of Strategies for the Measurement of Mass Emissions from Diesel Engines Emitting Ultra-Low Levels of Particulate Matter. *Aerosol Science and Technology* 43(11): 1142-1152.
(CD: liu2009)

Maricq, M.M., Podsiadlik, D.H., Chase, R.E. (1999). Gasoline Vehicle Particle Size Distributions: Comparison of Steady State, FTP, and US06 Measurements. *Environmental Science and Technology* 33: 2007-2015.
(CD: maricq1999)

Maricq, M., Chase, R.E., Podsiadlik, D.H., Vogt, R. (1999). Vehicle Exhaust Particle Size Distributions: A Comparison of Tailpipe and Dilution Tunnel Measurements. *SAE Technical Paper* 1999-01-1461.
DOI: 10.4271/1999-01-1461.
(CD: sae1999011461)

Maricq, M. (2009). How Are Emissions of Nuclei Mode Particles Affected by New PM Control Technologies and Fuels? HEI Annual Conference, 2009.
(CD: maricq2009)

Maricq, M.M, Szente, J., Loos, M., Vogt, R. (2011). Motor Vehicle PM Emissions Measurement at LEV III Levels. *SAE Technical Paper* 2011-01-0623.
DOI: 10.4271/2011-01-0623.
(CD: sae2011010623)

Mayer, A. (2006). Why Use Size, Substance and Number of Solid Particles Instead of PM-Mass to Characterize and Limit Particle Emissions of IC-Engines. SCAQMD/CARB, April 30 – May 2, 2006, Los Angeles, California.
(CD: mayer2006)

Mayol-Bracero, O.L., Guyon, P., Graham, B., Roberts, G., Andreae, M.O., Decesari, S., Facchini, M.C., Fuzzi, S., Artaxo, P. (2002). Water-Soluble Organic Compounds in Biomass Burning Aerosols Over Amazonia 2. Apportionment of the Chemical Composition and Importance of the Polyacidic Fraction. *Journal of Geophysical Research* 107, 8091. DOI: 10.1029/2001JD000522.
(CD: mayol2002)

Menon, S., Hansen, J., Nazarenko, L., Luo, Y. (2002). Climate Effects of Black Carbon Aerosols in China and India. *Science* 297: 2250-2253.
(CD: menon2002)

Mikulic, I., Koelman, H., Majkowski, S., Vosejpka, P. (2010). A Study about Particle Filter Application on a State-of-the-Art Homogeneous Turbocharged 2L DI Gasoline Engine. 19. Aachener Kolloquium, 2010, Aachen, Germany.
(CD: mikulic2010)

MLD (2006). Procedure for Organic Carbon and Elemental Carbon (OC/EC) Analysis of Vehicular Exhaust Particulate Matter (PM) on Quartz Filters. SOP No. MLD139, Version 1.0, May 2006.
http://www.arb.ca.gov/testmeth/slb/exhaust.htm, accessed 06/14/2011.
(CD: mld2006)

MLD (2011). Procedure for the Determination of Particulate Matter (PM) Mass Collected on Filters. SOP No. MLD145, Version 5.1, April 2011.
http://www.arb.ca.gov/testmeth/slb/exhaust.htm, accessed 06/14/2011.
(CD: mld2011)

Monge, M.E., D'Anna, B., Mazri, L., Giroir-Fendler, A., Ammann, M., Donaldson, D.J., George, C. (2009). Light Changes the Atmospheric Reactivity of Soot. *Proceedings of the National Academy of Sciences of the United States of America* 107(15): 6605-6609.
(CD: monge2009)

Moosmüller, H., Arnott, W.P., Rogers, C.F., Chow, J.C., Frazier, C.A., Sherman, L.E., Dietrich, D.L. (1998). Photoacoustic and Filter Measurements Related to Aerosol Light Absorption During the Northern Front Range Air Quality Study (Colorado 1996/1997). *Journal of Geophysical Research* 103(D21): 28,147-28,157.
(CD: moosm1998)

Moosmüller, H., Chakrabarty, R.K., Arnott, W.P. (2009). Aerosol Light Absorption and its Measurement: A Review. *Journal of Quantitative Spectroscopy and Radiative Transfer* 110: 844-878.
(CD: moosm2009)

Moosmüller, H., Arnott, W.P., Rogers, C.F., Bowen, J.L., Gillies, J.A., Pierson, W.R., Collins, J.F., Durbin, T.D., Norbeck, J.M. (2001). Time-Resolved Characterization of Diesel Particulate Emissions. 2. Instruments for Elemental and Organic Carbon Measurements. *Environmental Science and Technology* 35: 1935-1942.
(CD: moosm2001)

Mordukhovich, I., Wilker, E., Suh, H., Wright, R., Sparrow, D., Vokonas, P.S., Schwartz, J. (2009). Black Carbon Exposure, Oxidative Stress Genes, and Blood Pressure in a Repeated-Measures Study. *Environmental Health Perspectives* 117(11): 1767-1772.
(CD: morduk2009)

Mörsch, O. and Sorsche, P. (2001). Investigation of Alternative Methods to Determine Particulate Mass Emissions. UNECE/WP.29/GRPE report 2001.
(CD: morsch2001)

NAREL Technical Memorandum (2008). Technical Memorandum: Experimental Inter-Comparison of Speciation Laboratories. U.S. Environmental Protection Agency. http://www.epa.gov/ttn/amtic/files/ambient/pm25/spec/Multilab-Speciation-PE-2006.pdf accessed 8/4/2011.
(CD: narel2008)

NIOSH (1996). Elemental Carbon (Diesel Particulate). In *NIOSH Manual of Analytical Methods*. National Institute of Occupational Safety and Health, Cincinnati, Ohio, 1996.
(CD: niosh1996)

NIOSH (1999). Elemental Carbon (Diesel Particulate). In *NIOSH Manual of Analytical Methods*, Method 5040 Issue 3 (Interim). National Institute of Occupational Safety and Health, Cincinnati, Ohio, 1999.
(CD: niosh1999)

NIOSH (2003). Diesel Particulate (as Elemental Carbon). In *NIOSH Manual of Analytical Methods*. National Institute of Occupational Safety and Health, Cincinnati, Ohio, 2003.
(CD: niosh2003)

Ogawa, T., Araga, T., Okada, M., Fujimoto, Y. (1994). Effects of Diesel Fuel Properties on Particulate Emissions from D.I. Diesel Engine - Part 2: Chemical Analysis and Characterization of Diesel Oil. *JSAE Technical Paper* 9437494, 1994.
(CD: jsae9437494)

OICA (2003). Industry Comments on the Proposed Particulate Measurement Techniques. OICA contribution to PMP. 45th GRPE, January 13-17, 2003. http://www.unece.org/trans/main/wp29/wp29wgs/wp29grpe/grpeinf45.html accessed 06/10/2011.
(CD: oica2003)

Peterson, M.R. and Richards, M.H. (2002). Thermal-Optical Transmittance Analysis for Organic, Elemental, Carbonate, Total Carbon, and OCX2 in PM2.5 by the EPA/NIOSH Method -#83. In proceedings, Symposium on Air Quality Measurement Methods and Technology-2002, Edited by: Winegar, E.D. and Tropp, R.J., Air and Waste Management Association, Pittsburgh, Pennsylvania, 83-1-83-19, 2002.
(CD: peterson2002)

Petzold A., and Schönlinner, M. (2004). Multi-Angle Absorption Photometery - A New Method for the Measurement of Aerosol Light Absorption and Atmospheric Black Carbon. *Journal of Aerosol Science* 35: 421–441.
(CD: petzold2004)

Piock, W., Hoffmann, G., Berndorfer, A., Salemi, P., Fusshoeller, B. (2011). Strategies Towards Meeting Future Particulate Matter Emission Requirements in Homogeneous Gasoline Direct Injection Engines. *SAE Technical Paper* 2011-01-1212. DOI: 10.4271/2011-01-1212.
(CD: sae2011011212)

Quincey, P., Butterfield, D., Green, D., Coyle, M., Cape, J. (2009). An Evaluation of Measurement Methods for Organic, Elemental, and Black Carbon in Ambient Air Monitoring Sites. *Atmospheric Environment* 43: 5085-5091.
(CD: quincey2009)

Ramanathan, V. and Carmichael, G. (2008). Global and Regional Climate Changes Due to Black Carbon. *Nature Geoscience* 1: 221-227.
(CD: ramanathan2008)

Rodríguez-Castellanos, A., López-Torres, E., Solorza-Feria, O. (2007). Solar-Hydrogen-Fuel Cell Prototype as a Source of Renewable Energy Generation. *Journal of Mexican Chemical Society* 51(2): 55-58.
(CD: rodriguez2007)

Robert M.A., VanBergen S., Kleeman M.J., Jakober C.A. (2007). Size and Composition Distributions of Particulate Matter Emissions: Part 1-Light-Duty Gasoline Vehicles. *Journal of the Air and Waste Management Association* 57: 1414-1428.
(CD: robert2007)

Robertson, W.H., Herner, J.D., Ayala, A., Durbin, T.D. (2007). Investigation of the Application of the European PMP Method to Clean Heavy Duty Vehicles. 2007 Diesel Engine-Efficiency and Emissions Research Conference, Emission Controls Technology Session, August 12-16, 2007, Detroit, Michigan.
(CD: robertson2007)

Rosen, H. and Hansen, A.D.A. (1985). Estimates of Springtime Soot and Sulfur Fluxes Entering the Arctic Troposphere: Implications to Source Regions. *Atmospheric Environment* 19: 2203-2207.
(CD: rosen1985)

Schnaiter, M., Gimmler, M., Llamas, I., Linke, C., Jäger, C., Mutschke, H. (2006). Strong Spectral Dependence of Light Absorption by Organic Carbon Particles Formed by Propane Combustion. *Atmospheric Chemistry and Physics Discussions* 6: 1841-1866.
(CD: schnaiter2006)

Sharma, S., Brook, J.R., Cachier, Chow, J., H., Gaudenzi, A., Lu, G. (2002). Light Absorption and Thermal Measurements of Black Carbon in Different Regions of Canada. *Journal of Geophysical Research* 107(D24): 1-11.
(CD: sharma2002)

Sioutas, C., Delfino, R.J., Singh, M. (2005). Exposure Assessment for Atmospheric Ultrafine Particles (UFPs) and Implications in Epidemiologic Research. *Environmental Health Perspectives* 113(8): 947-955.
(CD: sioutas2005)

Slowik, J.G., Cross, E.S., Han, J.H., Davidovits, P., Onasch, T.B., Jayne, J.T., Williams, L.R., Canagaratna, M.R., Worsnop, D.R., Chakrabarty, R.K., Moosmüller, H., Arnott, W.P., Schwarz, J.P., Gao, R.S., Fahey, D.W., Kok, G.L., Petzold, A. (2007). An Inter-Comparison of Instruments Measuring Black Carbon Content of Soot Particles. *Aerosol Science and Technology* 41: 295-314.
(CD: slowik2007)

Swanson, J. and Kittelson, D. (2010). Evaluation of Thermal Denuder and Catalytic Stripper Methods for Solid Particle Measurements. *Journal of Aerosol Science* 41: 1113-1122.
(CD: swanson2010)

Sun, H., Biedermann, L., Bond, T. (2007) Color of Brown Carbon: A Model for Ultraviolet and Visible Light Absorption by Organic Carbon Aerosol. *Geopysical Research Letters* 34: L17813.
(CD: sun2007)

Sun, Y.-L., Zhang, Q., Schwab, J., Demerjian, K., Chen, W.-N., Bae, M.-S., Hung, H.-M., Hogrefe, O., Frank, B., Rattigan, O, Lin, Y.-C. (2011). Characterization of the Sources and Processes of Organic and Inorganic Aerosols in New York City with a High-Resolution Time-Of-Flight Aerosol Mass Spectrometer. *Atmosperhic Chemical Physics* 11:1581-1602.

Truex, T.J. and Anderson, J.E. (1979). Mass Monitoring of Carbonaceous Aerosols with a Spectrophone. *Atmospheric Environment* 13: 507-509.
(CD: truex1979)

UNEP (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. United Nations Environment Program. 2011.
(CD: unep2011)

U.S. EPA (2002). A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions. Draft Technical Report, EPA420-P-02-001, October 2002.
(CD: usepa2002)

U.S. EPA (2006). Request to Use 40 CFR Part 1065 Engine Testing Procedures for Light-Duty Testing. U.S. Environmental Protection Agency, CISD-06-20 (LDV, LDT, MDPV, HDV)
(CD: usepa2006)

U.S. EPA (2008). Kansas City PM Characterization Study, Final Report. EPA420-R-08-009, April 2008.
(CD: usepa2008)

U.S. EPA (2011). Report to Congress on Black Carbon. External Peer Review Draft, EPA-450/D-11-001, March 2011.
(CD: usepa2011)

U.S. EPA ISAPM Report (2009). Integrated Science Assessment for Particulate Matter. EPA/600/R-08/139F, December 2009.
(CD: usepa2009)

Wang, Y.-F., Huang, K.-L., Li, C.-T., Mi, H.-H., Luo, J.-H., Tsai, P.-J. (2003). Emissions of Fuel Metals Content from a Diesel Vehicle Engine. *Atmospheric Environment* 37: 4637-4643.
(CD: wang2003)

Wang, Y., Chung, A., Paulson, S.E. (2010). The Effect of Metal Salts on Quantification of Elemental and Organic carbon in Diesel Exhaust Particles Using Thermal-Optical Evolved Gas Analysis. *Atmospheric Chemistry and Physics Discussions* 10: 16941-16968.
(CD: wang2010)

Watson, J.G., Chow, J.C., Chen, L.-W.A. (2005). Summary of Organic and Elemental Carbon/Black Carbon Analysis. *Aerosol and Air Quality Research* (5)1: 65-102.
(CD: watson2005)

Yu, J.Z., Xu, J., and Yang, H. (2002). Charring Characteristics of Atmospheric Organic Particulate Matter in Thermal Analysis. *Environmental Science and Technology* 36: 754-761
(CD: yu2002)

Zhang, S., McMahon, W., Huai, T., Ayala, A. (2008). Final Results from CARB's Assessment of the European Reference Vehicle from the Particulate Measurement Program. In proceedings of the 18th CRC On-Road Vehicle Emissions Workshop, March 31-April 2, 2008, San Diego, California.
(CD: zhang2008)

Zhang, S., McMahon, W., Toutoundjian, H., Cruz, M., Frodin, B. (2010). Particulate Mass and Number Emissions from Light-Duty Low Emission Gasoline Vehicles. *SAE Technical Paper* 2010-01-0795, DOI: 10.4271/2010-01-0795.
(CD: sae2010010795)

Zheng, Z., Johnson, K.C., Liu, Z., Durbin, T.D, Hu, S., Huai, T., Kittelson, D.B., Jung, H.S. (2011). Investigation of Solid Particle Number Measurement: Existence and Nature of Sub-23 nm Particles Under PMP Methodology. *Journal of Aerosol Science* 42: 883-897
(CD: zheng2011)

VII. APPENDICES

Table 1. FTP PM Mass Emissions Rates from GDI Vehicles

(California Commercial E6 Summer Fuel)

Vehicle	MY	Fuel Injector			Total PM Mass(mg/mi)		
No.	Make	Type		Phase 1	Phase 2	Phase 3	FTP Weighted
1	2009 GMC	GDI - Wall-guided	Emissions	**35.13**	**1.29**	**1.53**	**8.38**
	Acadia		STDEV	2.84	0.43	0.21	0.75
			COV(%)	8.1	33.7	13.8	8.9
2	2008 Lexus	GDI - Wall-guided	Emissions	**25.12**	**0.55**	**1.75**	**5.97**
	IS350		STDEV	2.76	0.48	0.38	0.78
			COV(%)	11.0	87.6	21.7	13.1
3	2009 Mazda	GDI - Wall-guided	Emissions	**12.98**	**1.34**	**1.54**	**3.80**
	Speed3		STDEV	1.74	0.26	0.23	0.52
			COV(%)	13.4	19.1	14.7	13.7
4	2007 VW	GDI - Wall-guided	Emissions	**12.04**	**1.37**	**2.12**	**3.79**
	Passat		STDEV	1.15	0.23	1.07	0.40
			COV(%)	9.53	16.57	50.21	10.61
5	2009 Prosche	GDI - Wall-guided	Emissions	**12.46**	**0.53**	**1.57**	**3.29**
	Carrera		STDEV	3.73	0.47	0.45	0.69
			COV(%)	29.9	88.1	28.4	21.1
6	2008 VW	GDI - Wall-guided	Emissions	**7.05**	**2.04**	**2.01**	**3.07**
	GLI		STDEV	0.87	0.37	0.39	0.37
			COV(%):	12.4	18.0	19.2	12.2
7	2010 VW	GDI - Wall-guided	Emissions	**4.33**	**0.90**	**1.20**	**1.69**
	Jetta		STDEV	0.16	0.10	0.11	0.10
			COV(%)	3.7	10.8	9.2	5.7
8	2009 BMW	GDI - Spray-guided	Emissions	**4.77**	**0.70**	**0.71**	**1.55**
	335i		STDEV	0.54	0.22	0.26	0.10
			COV(%)	11.4	31.6	35.7	6.4
9	2009 BMW	GDI - Spray-guided	Emissions	**12.06**	**1.00**	**0.94**	**3.28**
	750i		STDEV	1.67	0.55	0.24	0.26
			COV(%)	13.8	55.1	25.5	7.8
		9 GDI Vehicle Avg:	Emissions	**13.99**	**1.08**	**1.49**	**3.87**
			STDEV	10.05	0.49	0.47	2.13
			COV(%):	71.8	45.0	31.3	55.0

Table 2. US06 PM Mass Emission Rates

Injector			USO6 PM mass (mg/mi)	
Type	**Vehicle**	**E6 Summer**	**Phase2Cert.**	**E10 Summer (Drum)**
Wall GDI	2009 GMC Acadia	**2.7026**	na	na
	STDEV	0.3776		
	COV(%):	13.97		
	2008 Lexus IS350	**0.8241**	na	na
	STDEV	0.1968		
	COV(%):	23.88		
	2008 VW Jetta	**0.1387**	na	na
	STDEV	0.0699		
	COV(%):	50.4		
	2010 VW Jetta	**1.3834**	**0.9557**	**1.2007**
	STDEV	0.3107	0.1623	0.2599
	COV(%):	22.5	16.98	21.6
Spray GDI	2009 BMW 335i	**1.2904**	**1.5660**	na
	STDEV	0.3684	0.4287	
	COV(%):	28.5	27.4	
PFI	2007 Kia Spectra EX	**0.2757**	na	na
	STDEV	0.0948		
	COV(%):	34.4		
	2009 GMC Hummer3	**7.6763**	**3.4184**	na
	STDEV	1.6730	0.4395	
	COV(%):	21.8	12.9	
	2009 Nissan Altima	**0.7246**	**0.9316**	na
	STDEV	0.0298	0.1217	
	COV(%):	4.1	13.1	

Table 3. CARB Test Results for Newer Low Mileage LDVs

Vehicle		FTP Composite PM (mg/mi)	US06 PM (mg/mi)	Average of FTP and US06 PM (mg/mi)
2007 VW Passat GDI-wall (21k)		3.79		
2008 Lexus IS350 GDI-wall (67k)		5.97	0.82	3.4
2008 VW Jetta GDI-Wall (2k)		3.07	0.14	1.6
2009 Porsche GDI-wall (124k)		3.29		
2009 GMC Acadia GDI-wall (13k)		8.38	2.70	5.5
2009 Mazda Speed3 GDI-wall (1k)		3.80		
2009 BMW 335i GDI-center (2k)		1.55	1.29	1.4
2009 BMW 750i GDI-center (0k)		3.28		
2010 VW Jetta GDI-wall		1.69	1.38	1.5
2002 Saturn SL2 PFI (43k)		0.81		
2000 Maxima PFI (115k)		0.82		
2002 Lexus PFI (66k)		0.46		
2005 Honda Accord PFI (19k)		0.16		
2006 Toyota Camry PFI (42k)		0.21		
2006 Saturn VUE PFI (32k)		0.31		
2007 Ford Focus PFI (15k)		0.25		
2009 Hummer PFI (21k)		0.99	7.68	4.3
2009 Nissan Altima PFI (29k)		0.71	0.72	0.7
2007 Spectra PFI (34k)		0.30	0.28	0.3
Average	10 PFI (only 3 for US06)	0.5	2.9	1.8
	9 GDI (only 5 for US06)	3.9	1.3	2.7

Table 4. U.S EPA Test Results for High Mileage and Oil Burning Tier 2 LDVs

Vehicle (all 2005 and newer)		FTP Composite PM	US06 PM	Average of FTP and US06 PM
GDI LDV 100+k		2.3	3.0	2.6
GDI LDT3 100+k		4.2	5.0	4.6
PFI LDV 100+k		0.3	0.9	0.6
PFI LDT2 100+k		0.6	2.4	1.5
PFI LDV 100+k		0.5	7.5	4.0
PFI LDT3 100+k		0.3	40.1	20.2
PFI LDV 100+k		0.3	1.9	1.1
PFI LDV 100+k		0.4	1.3	0.8
PFI LDV 100+k		0.4	1.1	0.8
PFI LDT2 100+k		1.3	19.7	10.5
PFI LDV 100+k		0.3	2.2	1.3
PFI LDT3/4 100+k		0.4	6.5	3.5
PFI LDV 100+k (OB)		9.5	37.8	23.7
PFI LDT3/4 100+k (OB)		1.3	28.8	15.1
PFI LDT3/4 <100k (OB)		1.0	9.4	5.2
PFI LDV <100k (OB)		0.8	1.9	1.4
PFI LDV <100k (OB)		1.2	3.2	2.2
Average, excluding non oil-burners	All 12 vehicles	1.0	7.6	4.3
	10 PFI vehicles	0.5	8.4	4.4
	2 GDI vehicles	3.3	4.0	3.6
Average, including oil burners	All 17 vehicles	1.5	10.2	5.8
	15 PFI vehicles	1.3	11.0	6.1

Table 5. Solid Particle Number Emission Rates Using Original PMP

Vehicle No.	MY Make	Fuel Injector Type	Fuel Type		Total PM Mass(mg/mi) Phase 1	Phase 2	Phase 3	FTP Weighted	Solid Particle Number (#/mi) Phase 1	Phase 2	Phase 3	FTP Weighted	Comments
7	2010 VW Jetta	GDI-Wall-guided	E6 Summer Fuel	Emissions	**4.33**	**0.90**	**1.20**	**1.69**	**9.4E+12**	**3.3E+12**	**3.8E+12**	**4.7E+12**	Current PMP
				STDEV	0.16	0.10	0.11	0.10	3.9E+11	3.0E+11	1.2E+11	1.7E+11	Method
				COV(%):	3.7	10.8	9.2	5.7	4.1	9.1	3.1	3.5	
			E10 Summer Fuel	Emissions	**5.04**	**0.68**	**1.08**	**1.69**	**1.1E+13**	**2.8E+12**	**4.1E+12**	**4.8E+12**	
				STDEV	0.11	0.02	0.06	0.01	5.9E+11	5.1E+11	2.3E+11	2.1E+11	
				COV(%):	2.2	2.5	6.0	0.7	5.5	18.4	5.7	4.4	
			Phase2Cert.Fuel	Emissions	**2.44**	**0.99**	**0.74**	**1.22**	**6.5E+12**	**3.6E+12**	**3.0E+12**	**4.0E+12**	
				STDEV	0.32	0.03	0.24	0.02	1.1E+12	2.3E+11	2.5E+11	3.7E+11	
				COV(%):	13.1	3.5	32.1	1.6	17.2	6.3	8.2	9.2	
8	2009 BMW 335i	GDI - Spray-guided	E6 Summer Fuel	Emissions	**4.77**	**0.70**	**0.71**	**1.55**	na	na	na	na	
				STDEV	0.54	0.22	0.26	0.10	na	na	na	na	
				COV(%):	11.4	31.6	35.7	6.4	na	na	na	na	
			Phase2Cert.Fuel	Emissions	**2.88**	**0.59**	**0.54**	**1.05**	**1.1E+13**	**1.1E+11**	**2.4E+11**	**2.4E+12**	Current PMP
				STDEV	0.44	0.24	0.11	0.24	9.7E+11	2.3E+10	2.8E+10	2.2E+11	Method
				COV(%):	15.3	40.1	21.0	22.7	8.7	21.7	11.5	8.9	
9	2009 BMW 750i	GDI - Spray-guided	E6 Summer Fuel	Emissions	**12.06**	**1.00**	**0.94**	**3.28**	na	na	na	na	
				STDEV	1.67	0.55	0.24	0.26	na	na	na	na	
				COV(%):	13.8	55.1	25.5	7.8	na	na	na	na	
			Phase2Cert.Fuel	Emissions	**3.66**	**0.65**	**0.91**	**1.34**	**9.3E+12**	**4.6E+11**	**8.5E+11**	**2.4E+12**	Current PMP
				STDEV	0.26	0.09	0.13	0.10	9.3E+11	2.3E+11	4.5E+11	2.7E+11	Method
				COV(%):	7.0	14.3	14.1	7.2	10.0	50.5	52.4	11.4	
10	2009 GMC Hummer3	PFI	E6 Summer Fuel	Emissions	**3.22**	**0.36**	**0.50**	**0.99**	**9.7E+12**	**2.0E+11**	**1.4E+12**	**2.5E+12**	Current PMP
				STDEV	1.12	0.24	0.28	0.38	1.1E+12	4.5E+10	3.3E+11	3.4E+11	Method
				COV(%):	34.9	67.4	56.4	38.8	11.6	23.2	24.2	13.6	
			Phase2Cert.Fuel	Emissions	**2.18**	**0.13**	**0.16**	**0.56**	**9.5E+12**	**3.8E+10**	**5.9E+11**	**2.1E+12**	
				STDEV	0.44	0.12	0.15	0.12	9.1E+11	1.2E+10	1.4E+11	2.0E+11	
				COV(%):	20.4	92.2	94.8	21.1	9.7	31.1	22.9	9.4	
11	2009 Nissan Altima	PFI	E6 Summer Fuel	Emissions	**1.72**	**0.44**	**0.48**	**0.71**	**3.6E+12**	**4.8E+10**	**6.9E+10**	**8.0E+11**	Current PMP
				STDEV	0.32	0.13	0.16	0.04	1.3E+12	1.8E+10	2.6E+10	2.7E+11	Method
				COV(%):	18.5	29.9	34.6	5.4	34.6	37.8	37.8	34.1	
			E10 Summer Fuel	Emissions	**1.45**	**0.11**	**0.26**	**0.43**	**3.8E+12**	**3.2E+10**	**7.4E+10**	**8.3E+11**	
				STDEV	0.74	0.10	0.17	0.17	8.5E+11	3.1E+10	6.3E+10	2.0E+11	
				COV(%):	50.9	90.5	65.7	39.8	22.2	95.2	84.4	23.7	

Table 6. Working Data. UNECE – WLTP-DTP-PM/PN Subgroup – List of Issues

Issue Title	Issue Description	Next Steps	Proposed solution	Consensus reached
CVS temp during regen	EU allows up to 190 deg C at the particulate filter. Same as Japan. CFR 1065 specifies 47 +/- 5 deg C at the filter. In some situations in USA, secondary dilution necessary to maintain lower temperatures	Data to be gathered on CVS temperatures during worst case regeneration tests to see if temperatures up to 190 deg C need to be permitted.	PM SG proposes that the filter face temperature can exceed 52 deg C during a regeneration event up to a maximum CVS temp of 190 deg C. Although the consensus was that an upper limit is not strictly necessary, as temperature will not reach the previously defined 190 deg C except in the case of CVS failure, some members preferred to retain 190 deg C. Open question is how to signify that vehicle is regenerating. This is not a problem as long as the current EU 5 procedure for periodic regenerating devices is used where the device loading sequence is stopped at the point when regeneration is about to commence. The regeneration is triggered manually in the next emissions test therefore there is no problem to exceed the 52 deg C limit. If the new test procedure is different, then some method of informing the emission test system that regeneration is taking place will be required.	**Yes**
CVS temperatures	Filter face temperature <= 52 deg C in EU and Japan, 47 +/- 5 deg C in USA.	Gather data on comparibility of PM measurements at <52C and 42-52C.	PM SG proposes that filter face temperatures to be less than 52 deg C. The lower temperature depends on dilution air temperature which we have proposed to be 25 +/- 5 deg C (see later). This solution still permits the use of heated PM sampling in the range of 47 +/- 5 deg C if preferred by the user. This proposal is based on work perormed during the PMP that showed no significant benefit to repeatability by using the heated PM sampling. CARB commented that diluted exhaust temperatures lower than 42 deg C could result in higher PM mass	**YES**
Amount of dilution required to avoid water condensation	This is a fundamental principle of CVS. The question is how do you prescribe the CVS settings to ensure it does not happen at any point from the vehicle exhaust mixing with the dilution air to the gas analysers, from bag or continuously, (which is a Lab Process Issue) and in the PM sampling system (which is our issue). EPA 1065 requires heating of all the surfaces to be higher than the maximum dew point of the diluted exhaust	Lab Process Group have proposed a modification of the specification used in Reg 83 for discussion. PM-PN subgroup have reviewed Lab Processes specification and confirmed it's acceptability subject to a few corrections (see WLTP-DTP-PMPN-05-02) and further investigation on a number of points (see A4, A6, A8, A9)	Accept Lab Processes Group proposal	**YES**

Transfer tube coupling sealing materials	*Potential for some elastomers to release particles if exposed to high temperature exhaust gas stream*	*Jon Andersson to draft improved text on transfer tube coupling and the need to ensure metal to metal contact to minimise exposure of sealing material to gas stream*	*Text should detail potential issues related to connectors made from certain non-matallic materials and indicate that elastomers should be as thermally stable as possible and only be used for sealing and not as a bridge between exhaust and transfer tube.*	***YES***
Exhaust Transfer Tube	Definition of amount of insulation required. Japan definition is : *the insulating materials shall have a thickness of at least 25mm and thermal conductivity not exceeding 0.1W/m*K at 400°C (Japanese regulation)* This definition is also used in the GTR#4 regulation. *CFR 1065 has specific requirements for the transfer tube from engine to CVS. These requirements have not yet been transferred to light duty vehicle emissions testing but must be considered in the future.* Technical comments/questions - As it may be difficult to measure/verify this specific recommendation, it might be advisable to supplement it with "use good engineering judgement" - the transfer tube from the exhaust pipe should be heated above the exhaust gas dew-point (70 deg C for Natural Gas) to avoid condensation and potential component loss - PM measurement for gasoline (positive ignition) vehicle needs the remote mixing tee or a heated (not only insulated) transfer tube because of the higher dew point.	Review once decision reached on A6 (RMT)	Proposal is to accept the definition of insulation as stated. In addition we suggest, as an option, the user can heat the transfer tube to inhibit condensation of the exhaust gas before dilution. Transfer tubes from 3.6 to 6.1m length must be insulated Heating the transfer tube to a temperature above that of the dew point of the exhaust gas should be allowed. Additional pollutants group will want to consider whether this (or use a remote mixing tee) is required for the measurement of water soluble compounds such as carbonyls	**YES**
Use of remote mixing tee	Reg 83 also allows the use of remote mixing tees designed to be close-coupled to the vehicle exhaust. Should this be permitted in WLTP GTR? If so, if the vehicle exhaust and dilution air are fully mixed in the transfer tube from the vehicle to the dilution tunnel inlet, is it necessary to have the the full dilution tunnel that is at least 2000mm long (10 * diameter) ?	Subgroup members to submit data on whether or not restricting transfer tube to 3.6m max length is sufficient to prevent condensation, in particular for Spark Ignition vehicle tests Wolfgang Thiel to draft list of data needed for subgroup to evaluate whether RMT should be permitted as an alternative to and/or in addition to a conventional dilution tunnel.	Proposal is to allow the use of RMT with DLT section for PM/PN measurements. The transfer tube from RMT to the sampling zone must be electrically conductive and earthed. Consensus was that the conventional dilution tunnel section can be shortened or eliminated if homogenous mixing at the point of sampling can be demonstrated. However CARB and JASIC prefer to retain DLT section with the RMT	**YES**
Exhaust Pressure At The Tailpipe	*Shall not cause the static pressure at the exhaust outlets on the vehicle being tested to; differ by more than ± 0.75 kPa at 50 km/h, or more than ± 1.25 kPa for the whole duration of the test from the static pressures recorded when nothing is connected to the vehicle exhaust outlets. The pressure shall be measured in the exhaust outlet or in an extension having the same diameter, as near as possible to the end of the pipe. Sampling systems capable of maintaining the static pressure to within ± 0.25 kPa may be used if a written request from a manufacturer to the Technical*		Lab processes proposal acceptable by subgroup based on clarification from Japan provided in Vienna	**YES**

	Service substantiates the need for the closer tolerance. Variation with the Japanese regulation which requires 0.1 kPa @ 70 +/- 2 kph (note Lab Process WG said this is an option of Japan, not mandatory) Minor variation with US regulation which requires only to be less than +/- 5 " H2O (+/- 1.25 kPa) unless written request to maintain static pressure to within +/- 1 " H2O (+/- 0.25 kPa)			
Dilution Tunnel Pressure At Mixing Point	*In order to minimise the effects on the conditions at the exhaust outlet and to limit* *the drop in pressure inside the dilution-air conditioning device, if any, the pressure at* *the mixing point shall not differ by more than ± 0.25 kPa from atmospheric pressure.* This needs to be clarified. Historically, the +/- 0.25 kPa was measured on the outlet of the dilution air filter (indicating the pressure drop across the filters). The definition of the mixing point needs to be clarified as the dilution air filtration and conditioning can be located some distance away from the point of exhaust dilution. Pressure drop due to mixing nozzle (if used) also needs to be considered It is assumed that the point of pressure measurement should be measured just before the mixing point.		PM SG proposal is to delete statement completely. Reason : the pressure at the mixing point defines the pressure at the vehicle tailpipe which is already specified as being +/- 1.25 kPa or +/- 0.25 kPa by special arrangement.	**YES**
Heat Exchanger	Reg 83 does not require the use of a heat exchanger if proportional sampling or compensation is available. Variance with CFR Part 86 which requires a heat exchanger for PM mass (to be confirmed) No variance with CFR 1065. Variance with the Japanese regulation which requires a heat exchanger for PM mass. (JASIC)		Lab processes specification is acceptable	**YES**
Recommended System Descriptions	The PDP and the CFV systems in the Reg 83 have slightly different schematics and need to be consolidated. Guidance is required within the regulation on the design of the transfer tube between the mixing chamber and the dilution tunnel / HTHC, PM and PN sampling zone (see earlier question whether a conventional dilution tunnel is required when using remote mixing close to the vehicle exhaust). Guidance is required (as previously mentioned) on the dilution tunnel dimensions and location of the PM, PN and THC sampling probes if the exhaust gas / dilution are homogeneously mixed upstream of the defined sample point of 10 times the diameter of the dilution tunnel.	Schematics will be reviewed once a decision has been made on RMT use (A6).	PM SG has proposed that use of RMT should be permitted for all tests. The schematic should be modified accordingly. The schematic should also include a section for double dilution as discussed below	**YES**

Pre-classifier	*It is recommended that a particle size pre-classifier (e.g. cyclone or impactor) be employed upstream of the filter holder. However, a sampling probe, acting as an appropriate size-classification device such as that shown in Figure 13, is acceptable* Comment that statement should be defined that the sample probe classification device is an alternative to the in-line particle size classifier Variance with CFR Part 86 and 1065 that permit only the use of the classifier with sharp edged probe Variance with Japan where the classifier must be located "immediately" before the filter holder.	Subject to confirmation from the small group WLTP need not specify that the pre-classifier has to be immediately before the filter holder. WLTP text should clarify that probe mounted or in-line classifiers are alternatives.	PM SG confirmed that CFR 1065 accepts the use of the classifier OR the shield fitted to the sample probe. PM SG also proposed that a classifier need not to be installed immediately before the filter holder.	**YES**
Secondary Dilution	*Reg 83 Recommended System Description does not* include the option of double dilution that is accepted in 1065, Part 86 and Japan regulation Japanese regulation states that secondary tunnel should have an inner diameter of at least 75mm.	Review data on worst case CVS regeneration test filter face temperature to determine whether secondary dilution may be required e.g. during DPF regeneration tests on higher inertia vehicles during real-world test cycles with minimum dilution factors.	PM SG proposes that double dilution is acceptable to reduce the diluted exhaust to less than 52 deg C at the PM filter if necessary. The accuracy and proportionality of the diluted exhaust flow into the secondary dilution section should be the same as in single dilution.	**YES**
Residence Times within the Dilution Tunnels	Residence time between the exhaust mixing point and filter must be between 1 and 5 seconds (residence time in secondary dilution must be more than 0.5 sec) Japanese reguylations say residence time in secondary tunnel should be at least 0.25 seconds.		Lab processes specification is acceptable	**YES**
Molar based CVS and PM flow rates	Molar based CVS and PM flow rates as opposed to volume flow based on standard temperature and pressure (0 deg C, 101.3 kPa) Note : Standard temperature base for Japan legislation is 20 deg C 101.3 kPa which is the same as Part 86 Note : The Laboratory Processes Working Group has proposed to retain volumetric based measurements to standard temperature / pressure conditions.		For Lab processes subgroup	**YES**
	Proportionality of sampling must be verified/reported for all components including PM mass Pressure transducers must be temperature compensated or temperature controlled Pressure, temperature, flow meter calibrations/checks Defined linearity limits/specifications	Transfer & dilution system etc small group to review	PM SG propose to use the 1065 specs for the transducers and logging rates for the PM sensors but not to adopt the full requirements of CFR 1065. Note : These should be cross-checked against those specified and defined by the Lab Process Sub-Group	**YES**

Parameter measurement specifications	Parameter measurement specifications (see attached Appendix)	Transfer & dilution system etc small group to review	All temperature measurements to have an accuracy of +/- 1 deg C or better Maximum rise time for temperature sensors (T10 - T90) of 15 seconds PM sample flow rate accuracy : 2.5% of point or 1.5% of maximum flow Accuracy of sample flow into secondary dilution section to be same as above (requires higher accuracy for the secondary dilution section sample and dilution air flow rates)	**YES**
Dilution air temperature	Dilution air temperature should be 15 deg C or above Part 1065 specifies Dilution air temperature (for PM) : 25 +/- 5 deg C measured close to the dilution point	Transfer & dilution system etc small group to gather information on current lab practices for dilution air inlet (e.g. from inside test cell, from other point indoors, from outdoors etc) and consider whether minimum dilution air temperature can be specified.	Propose to define as 25 +/- 5 deg to track the current settings for the test cell temperature (5% of points are allowed to be outside this tolerance as per 1065). Temperature should be measured as close as practically possible to the mixing point if there is any possibility of a temperature change from the controlled source (ie dilution air duct passes through an area of hot or cold).	**YES**
Secondary dilution transfer tube length	Transfer tube from main dilution tunnel to secondary dilution tunnel must not exceed 915mm	Review, if decision taken to permit secondary/double dilution - see A14	Proposal is that the secondary air should be injected as close as possible to where the PTT leaves the DLT	**YES**
Bend radii	Bend sections in transfer tubing must have largest possible curvature radii		Incorporate this advice in GTR text	**YES**
Particulate Mass Filter Selection	*A single particulate filter without back-up shall be employed for both urban and* *extra-urban phases of the cycle combined.* *Twin particulate filters, one for the urban, one for the extra-urban phase, may be used without back-up filters, only where the pressure-drop increase across the sample filter between the beginning and the end of the emissions test is otherwise expected* *to exceed 25 kPa.* Variation with Part 86 and CFR 1065 where multiple filter holders are required to measure individual test sections or phases to permit total PM mass calculations with different weighting factors for each phase. Depending on the final harmonized drive cycle and phases, multiple filter holders may be required. Technical discussion on whether the condition of multiple filter sets being required if the pressure drop exceeds 25 kPa is really necessary (unlikely ever to happen at current PM mass emissions limits).	Separate filters will be required for each phase of the test cycle as weighting of emissions from each phase is anticipated. Request to reopen question: What is meant by each phase of the test cycle ? Cold start and hot start phases , or low, mid, high speed portions ? Need to review error analysis especially if required on DI gasoline as well as DPF equipped diesels	PM Small Group understands that the WLTP Drive Cycle and Test Procedure may require multiple PM filters holders to be provided. We remind the Sub-Group that use of multiple filter sets will reduce the PM mass collected per filter and result in higher error due to the weighing of multiple filter sets. Proposal - single filter for the cold phase and separate single filter for hot phase (assuming cold / hot weighting factors will be required to be used)	**YES**

Particulate sample flow rate	*The particulate sample flow rate shall be proportional to the total flow of diluted exhaust gas in the dilution tunnel to within a tolerance of ± 5 per cent of the particulate sample flow rate* Variance with CFR 1065 test procedures that specifies a proportionality check every test : must log all flow data @ 1 Hz average - two alternative calculations/condition for acceptance	Check with EPA whether verification is really required every test	EPA does require every test. Proposal is that the check on proportional sampling should be documented on system commissioning and as required by inspecting Technical Authority (as current procedure).	**YES**
Sampling pump location	The sampling suction pump shall be mounted on the PM filter holder and PMb filter holder. In this case, the PM filter holder to be installed for the single-stage dilution method can be shared in common with the one to be installed for the double-stage dilution method.	JASIC to report back on reasons for this requirement	PM Small Group understands that Japan has confirmed that this is no longer applicable. Requirements will not be included.	**YES**
Dilute exhaust gas temperature measurement	CFR 1065 which specifies the thermocouple that must be used (bare wire 0.5mm +./- 0.025mm).		Specifying thermocouple type is not necessary	**YES**
Back-up filters	*The particulate sample shall be collected on a single filter mounted within a holder in the sampled dilute exhaust gas flow.* Technical discussion on the merits of specifying a back-up filter for the purpose of correcting for the mass associated with HC artefacts on the filter material. It was suggested that this may be necessary for CARB LEV III.	CARB to comment on whether backup filter required for artefact correction purposes.	PM SG understands that EPA/CARB at the present time will not permit the use of a secondary PM filter to be used to subtract the HC artifact rom the primary filter PM mass. However, the PM SG consider that this technique can imrpvove the PM mass measurement accuracy and should be considered. Further research is recommended. CARB continue to investigate for 2016MY.	**YES**
Probe location	*The sample probe shall be installed near the tunnel centerline, between 10 and 20 tunnel diameters downstream of the exhaust gas inlet to the tunnel and have an internal diameter of at least 12 mm.*		Requirement for probe to be near centreline can be deleted as unnecessary.	**YES**
Probe diameter	Variation with CFR 1065 for the specified internal diameter of the PM sample probe and transfer tube. Technical discussion regarding the minimum diameter for the PM sampling probe of 12 mm.		AVL analysis on particle losses showed that smaller diameter pipe could be used. Change to 8mm min ID to match to GTR #4	**YES**
Isokinetic sampling	Technical discussion regarding a new requirement regarding isokinetic sampling within the dilution tunnel. Varying opinions as to the necessity considering the size of the PM particles and the increased complexity required, especially for CVS systems fitted with variable or multiple flow rates (ref : 1065.145 4b)		Consideration of isokinetic sampling outside WLTP Phase 1 activity.	**YES**
Distance from probe to filter mount	*The distance from the sampling tip to the filter mount shall be at least five probe diameters, but shall not exceed 1,020 mm.* Variation with CFR 1065 as simple distance is replaced by residence time limits	Review based on information on typical distances and residence times.	AVL analysis showed less than 1 % PM loss up to 4m length. Proposal is that the distance from the probe tip to the filter should be less than 2m. Reason is that this would allow a single design to be used for single or double dilution techniques.	**YES**

Temperature at flow meter	*The temperature of the gas flow in the flow meter may not fluctuate by more than ± 3 K, except during regeneration tests on vehicles equipped with periodically regenerating aftertreatment devices. In addition, the sample mass flow rate must remain proportional to the total flow of diluted exhaust gas to within a tolerance of ± 5 per cent of the particulate sample mass flow rate. Should the volume of flow change unacceptably as a result of excessive filter loading, the test shall be stopped. When it is repeated, the rate of flow shall be decreased.* Technical discussion Regarding the unconditional necessity of a constant gas temperature in the flow meter. This is an historical carry-over from the use of dry and wet gas meters that do not have real time flow calculation at standard conditions. This requirement is unnecessary if a flow meter capable of mass flow rate measurement or real time flow calculation to standard reference conditions	WLTP text to clarify that temperature must be constant unless flow rate is subject to real-time temperature correction. System suppliers to advise on required frequency for real time flow correction.	PM SG confirmed that the requirement for stable gas temperature measurement in the flow meter is not required for meters with real time temperature monitoring and control. Those PM sampling systems that do have real time temperature monitoring should do so on a 1 Hz basis or faster (suggestion for discussion)	**YES**
Recommended minimum filter mass	*It is recommended that the mass collected on the 47 mm diameter filter (Pe) is ≥ 20 µg and that the filter loading should be maximized consistent with the requirements of paragraphs 1.2.3. and 1.3.3.* In Japanese regulation, there is no provision about maximum and/or minimum filter loading mass. (JASIC) New to check the latest version of CFR 1065	Small group to consider deleting this recommendation as it is not very helpful	PM SG recommends deletion of this statement. In the event of a vehicle with near zero PM mass emission it cannot be met in any case. The situation becomes worse in the event of multiple filters sets being required in the new test format. Feb 2011 PM SG agreed to keep general statement regarding 'recommend maximising PM loading' however, with no minimum recommended loading.	**YES**
Filter face velocity	*For a given test the gas filter face velocity shall be set to a single value within the range 20 cm/s to 80 cm/s unless the dilution system is being operated with sampling flow proportional to CVS flow rate* Variation with CFR 1065 that specifies 100 cm/s with maximum of 105 cm/s. CFR 1065 also includes validation of the filter face velocity and corrections for actual temperature and pressure. Variation with Japan regulation, face velocity must be between 35 and 100 cm/s.	Review based on data (including heavy duty data) on the impact of different filter face velocities on PM	PM SG proposal is 20 - 105 cm/sec. This is based on data (from E-66) that showed face velocity does not sigficantly affect PM collection effiiciency. Specification of wide velocity (and therefore sample flow) range allows user to adjust for PM filter loading as required.	**YES**

Filter paper type	*Fluorocarbon coated glass fibre filters or fluorocarbon membrane filters are required.* *All filter types shall have a 0.3 µm DOP (di- octylphthalate) collection efficiency of at least 99 per cent at a gas filter face velocity of at least 35 cm/s.* Minor variance with CFR 1065 that recommends the use of PTFE membrane filters but allows the use of fluorocarbon coated glass fibre filters. Minor variance with Japan The collecting filter shall have 99% or higher efficiency of collecting dioctylphthalate (DOP) with a particle diameter of 0.3 µm in the range of gas surface velocity of 35 cm/s or more, but 100 cm/s or less. Japanese regulation requires static electricity shall be eliminated using a Polonium static eliminator or a device with the similar effect prior to the weighing of the collecting filter. (JASIC) Discussed reports that HC contamination of the PTFE membrane filters has been experienced and they are also highly sensitive to electro-static charge. However, it is has also been reported that the HC adsorption artifact is smaller with the PTFE membrane filters (further technical review required)	Small group to consider whether membrane filter should be recommended or merely allowed and whether R83 text on nullifying static should be adopted. Seek input from PALL on correct filter face velocity at which to specify collection efficiency	PM SG proposal is to allow both PTFE membrane and PTFE coated glass fibre filters. The PTFE membrane offers a reduced affinity to HC artifacts. However, the PM SG suggests that wording should be inserted to warn that PTFE membrane filters are more susceptible to static charge accumulation and therefore charge neutralisation procedures should be robust and verified. (The methods for effective neutralisation and its verification should be covered by the Weighing Room SG). The effect of static charge on the filter causes unstable mass measurements and / or a higher mass to be measured. Static charge neutralisation proposals adopted. If the use of a secondary filter was allowed to correct for the HC artifacts then this would negate the advantage of the PTFE membrane filter. Ref requirement for collection efficiency of > 99 % at 35 cm/sec using 0.3 um DOP. The PM SG advises that the manufacturers have stated that DOP cannot be used for filter efficiency testing under this flow rate condition. PALL uses a flow velocity of approximately 5.3 cm/sec. For this reason, we suggest the wording should be changed so that the filter manufacturers specifications should be used as proof of filter efficiency. Additionally, the PM SG noted that the CFR 1065 reference to the ASTM-D29865a procedure is no longer valid as this procedure has been obsolete for several years.	**YES**
Filter holder design/stain area	*The filter holder assembly shall be of a design that provides an even flow distribution across the filter stain area. The filter stain area shall be at least 1075 mm2.* Variance with CFR 1065 which details the physical design and materials of the filter holder. Minor variance of CFR 1065 specifies at least 38mm diameter stain as opposed to a total surface area of 1075mm2 (equivalent to 37mm diameter stain) Japan specifies a minimum effective stain diameter of 37mm or more.		Specify at least 1075 mm2/37mm diameter	**YES**
CFR 1065 Requirements	Particulate Samplers : vacuum side leak check		PM SG recognises that leak checking of the PM sample line before testing is desirable but should not be made mandatory before every test as CFR 1065. Leak checking is typically included in test facility QC and correlation procedures. It could be included in the inspection by Technical Authority ?	**YES**

Dilution Air Filtration and Conditioning	*The dilution air used for the primary dilution of the exhaust in the CVS tunnel shall be passed through a medium capable of reducing particles in the most penetrating particle size of the filter material by ≥ 99.95 per cent, or through a filter of at least class H13 of EN 1822:1998. This represents the specification of High Efficiency Particulate Air (HEPA) filters.* Variation with CFR 1065 which requires a > 99.97 % reduction of particles at most penetrating size. Variation with Japan regulation : temperature of dilution air must be greater than 15 deg C Lab Process meeting has proposed use of H13 type dilution air filters.	US-EPA and CARB have confirmed they are content with 99.95% efficiency at the most penetrating particle size. JASIC to provide evidence in support of 99.97% minimum efficiency requirement being necessary		
Correction Of PM/PN Contamination In Dilution Air/From Dilution Tunnel	*For REG 83* *At the vehicle manufacturer's request, the dilution air may be sampled according to good engineering practice to determine the tunnel contribution to background particulate mass levels, which can then be subtracted from the values measured in the diluted exhaust.* Variation with CFR and Japan as measurement of the background PM mass using the diluted exhaust PM mass measurement probe and system is not permitted under CFR or Japan regulations. Variation with Reg 83 approach for PN where no tunnel background correction is permitted. USA and Japan permit only the measurement of the dilution air for purposes of measurement correction of its contribution to PM mass.	Subject to views from CARB & EPA tunnel background correction should be permitted for both PM and PN up to a maximum permissible level. Data on typical (tunnel) PM & PN background levels (concentrations, plus CVS flow and sampling point) should be gathered to determine an appropriate maximum permissible level. Tunnel background correction gives a result which is more representative of actual emissions.	EPA/CARB will not accept tunnel background corrections for PM/PN. This issue will be raised to DTP for a decision. However, if included in WLTP then a measurement procedure should be defined. - exhaust inlet should be blanked - measurements should be made using the same instruments used for PM/PN - system background test should have same settings as certification test (CVS flows, PM sampling flows etc). Tunnel background measurements should allow either; - corrections for PM mass / PN number made as ug at the filter and as #/cc for the PN counting system (rather than mg/km and #/km). System background values should be derived from a rolling average of several checks updated weekly; or - corrections for PM mass / PN number made as mg/km and #/km based on tunnel background measurements made immediately before or after the test at the same CVS flow rate. A maximum permissible correction of X ug or Y #/cc should be defined.	

Tunnel pre-conditioning	*In a test facility in which there may be possible contamination of a low particulate emitting vehicle test with residue from a previous test on a high particulate emitting vehicle, it is recommended, for the purpose of sampling equipment pre-conditioning, that a 120 km/h steady state drive cycle of 20 minutes duration followed by three consecutive Part Two cycles be driven by a low particulate emitting vehicle.* *After this preconditioning, and before testing, vehicles shall be kept in a room in which the temperature remains relatively constant between 293 and 303 K (20 °C and 30 °C). This conditioning shall be carried out for at least six hours and continue until the engine oil temperature and coolant, if any, are within ±2 K of the temperature of the room.* *Variance in reasons for pre-conditioning; for CFR 1065 the pre-conditioning is for the measurement system, not for the engine (vehicle)* *Technical comment :-* *The recommended pre-conditioning of the sampling system is difficult to perform in reality and there is little evidence that it is necessary.* *It was stated that there is some evidence has shown that the measurement is insensitive to previous vehicles.*	JASIC think 20 minutes operation at 120km/h will be not enough to reduce tunnel background in all cases. Investigate this issue during the validation testing. Modify existing text to clarify that longer/hotter pre-conditioning is permissible.	PM SG propose to leave procedure in the WLTP but modify the existing text to clarify that longer/hotter pre-conditioning is permissible	
CFR 1065 **The EPA CFR 1065 includes the following specific requirements for PM mass measurement that are not necessary for ECE Regulation 83.** **(This is a starter list of the main points for main PM/PN Group discussion)**	CFR 1065 specified that as a principle, temperature of the diluted exhaust should be controlled by dilution not by cooling. More recently, this has been clarified that temperature loss of the gas can occur but should only be after the final dilution point. This has implications for the design of the exhaust transfer, mixing, dilution tunnel and sampling.	Transfer & dilution system etc small group to review whether cooling should be prohibited	PM SG proposal is not to make any changes to WLTP draft to mention cooling. If the temperature of 52 deg C cannot be met by single dilution then the CVS flow rate can be increased or double dilution can be applied. Feb 2011 - Text being drafted for review.	
Minimum data logging rates	Specifications for minimum data logging rates (see attached Appendix)	Transfer & dilution system etc small group to review	Proposal is a minimum of 1 Hz for all parameters (although this frequency isn't strictly necessary for all parameters, e.g. dilution air temperature, 1Hz is specified for simplicity/consistency). Examples : Diluted exhaust temperature at PM filter PM sampling flow rate PM dilution air flow rate (if secondary dilution)	

			PM dilution air temperature for secondary dilution air if used	
Location of valve in relation to PM filter holder	*A valve shall be located downstream of the filter in the direction of flow. The valve shall be quick enough acting to open and close within 1 s of the start and end of test.* Technical discussion regarding the implications of this requirement for HEV testing. The above requirement was specified to avoid the possible contamination of the filter paper when the valve, which is subject to PM deposits as it is located upstream of the filter, is opened or closed. However, an isolating valve may be necessary in the case of the repetitive emission tests associated with the testing of hybrid electric vehicles where the test cycle may have to be repeated continuously until the battery comes to a stable state of charge. (In this special case where the filter holder needs to be removed while sampling is in progress, a manually operated shut off valve located before the filter holder might be an acceptable solution)	May need bypass for HEV case	PM SG confirmed that locating the valve selecting the filter is best to avoid contamination. With respect to Hybrid Electrical Vehicle testing, the need for an isolating valve before the filter should be considered if required by the final HEV test protocol. (Note : All PM sampling systems have bypass valves already so that the sample flow control can be established before the test begins)	
Weighing room ambient conditions:	Regional differences in requirements and tolerances for weighing room temperature, dew point temperature and relative humidity. Not all regions have requirements for all three parameters. Comment: overlap / double specification exists with dew point temperature and relative humidity but this may add robustness to variability in dew-point temperature measurements.	Review on the basis of experience of meeting the tightest tolerances and a cost-benefit consideration of different tolerance levels. Relative humidity will be used in preference to dew point.	Proposal: weighing room temp 22 +/- 2C; +/- 1C recommended. Weighing room relative humidity 45 +/- 8 % (i.e. c/o reg 83). Dew-point temp < 10.5 C (no tolerance). Specifications to apply to all filter conditionoing and weighing environments.	**YES**
Sample filter handling:	Various guidance provided. This could be consolidated for the GTR.	Consider specifying static nullifier as per Reg 83 and US Part 1065.	The filter shall be neutralised, e.g. by a Polonium neutralizer or device of similar effect. Recommend omitting grounding straps and tweezers as problematic and can cause filter damage.	**YES**
PM micro-balance calibration:	Region to region discrepancy in calibration weight requirements. No requirement is specified by US part 86 and R83. Japan att 42 requires 'E2' weights and US part 1065 requires weights to be NIST traceable within 0.1 % uncertainty. US part 1065 is only regional reg to put a specification on the magnitude of the cal mass used relative to that of the unused sample filter. Calibration frequency: discrepancy between zero/span requirements and annual cal requirements.	Review and draw on WHDC approach to mass traceability.	Full calibration every 12 months (i.e. linearity check & proof of ability to meet precision and resolution requirements – against a traceable national or international standard - as in GTR-4). Zero/span checking at the start of each weighing session by weighing one reference weight (nominal 100 mg). This check may be performed using either external or internal calibration weights.	**YES**

PM Sample Flow meter calibration	*Flow meter calibration* *The Technical Service shall ensure the existence of a calibration certificate for the flow meter demonstrating compliance with a traceable standard within a 12 month period prior to the test, or since any repair or change which could influence calibration.* Reg 83 requires a simple compliance at the flow rates used for certification but no accuracy or time period is specified. CFR 1065 requires a more complex process of linearization over the range of the flow meter. Technical discussion : what is the required accuracy of the PM measurement flow meter for Regulation 83 (assumed to be within 1% of reference flow meter) ? § 86.116-94 (c) (4) Calibrate the gas meters or flow instrumentation used for providing total flow measurement for particulate sampling. From Japan regulation: The measuring devices shall have the accuracies specified, and shall be serviced and maintained based on the handling procedures designated by the manufacturers of the devices, and verified and calibrated as necessary. CFR 1065 specifies the necessary accuracy for the PM sample flow meter (see table below).	WLTP should specify in detail calibration requirements. May be worth reviewing WHDC approach?		**YES**
CFR 1065 Measurement and Data Logging Requirements	See separate document			**YES**
CFR 1065	Different procedures / calculations for CVS calibration			**YES**
PM micro-balance:	Specification for micro-balance precision are tighter in US 1065 & J42 than for US 86 and R83. Various recommendations are given for micro-gram balance installation, static neutralisation & shielding. These could be consolidated for the GTR.	Various guidance on shielding etc will be consolidated. Data on impact of micro-balance precision will be reviewed to consider cost benefit of different specifications JASIC to submit data in support tighter microbalance requirements	Proposal: 1 µg resolution; 2 µg precision. Same as GTR4 (section 9.4.3.3).	
Sample filter conditioning:	Conditioning time: min and max requirements are different across regions. US 1065 has no maximum time. Reg to reg differences exist in max time permitted between removal of filter from stabilisation environment and emissions test; time allowed to return filter to stabilisation environment after the emissions test; and max conditioning time permitted.	Review experience on minimum time required to stabilise filters and experience of maximum acceptable times. JASIC to submit data on minimum post test filter conditioning time required	Pre-test: > 1h conditioning before weighing. < 1h between removal from weighing room & emissions test (<8h if filter holder is sealed). Post-test: < 1h before returning filter to stabilisation room. >1h conditioning before weighing.	

Reference filter weighing:	Various max times are given for time permitted between sample and ref filter weighing after the emissions test. Various criteria exist for acceptance of reference filter weighing results and actions that may be taken if initial results are out of tolerance. Region to region differences are significant. Comment: reference filter weight drift common. US part 86 contains text requiring ref filters to be covered at all times to reduce contamination but this requirement is not included in other regional regulations. Recommendations for balance exercise and the adoption of a substitution weighing method are given in part 1065 but not in any other regs.	Review and draw on WHDC approach.	TBD. Data under review by PM weighing small team.	
PM calculations:	Mass calculation formulae are ~ equivalent other than US 1065 which is generalised, and not specific to CVS systems. J42 permits double stage dilution. Procedures / allowances for background correction are not the same.	Review following decision on double dilution (A14) and background correction (A9).	TBD following A9 & A14 decisions & review by PM weighing small team.	
Regeneration	No procedures / equipment spec in any region for measuring PN during regeneration	Gather and review data on particle number emissions during DPF regenerations including data on PN concentrations, chemical composition, size distribution, sampling dilution ratios etc in order to determine whether it is appropriate to specify PN measurement during regenerations. Experimental outline for data gathering during validation phase to be developed by small group on regeneration.		
VPR efficiency requirement sufficient for DPF regeneration measurements ?	Review whether tetracontane and/or current VPR volatile removal efficiency requirement are appropriate for DPF regeneration measurements at up to 192 °C CVS temperature.		Retain current efficiency specification. If review concludes PN during regen is not feasible with VPR of this efficiency then PN during regerneration will be deferred to WLTP Phase 2.	**YES**
Average or second by second pcrf	Whether to specify use of average pcrf or second by second pcrf in calculating PN results or permit both.	Horiba to provide data to confirm negligible difference between the two approaches.	Retain existing use of average pcrf supplemented by requirement that systems be designed to ensure prf is stable over test	**YES**
VPR PCRF	Review requirement to validate VPR particle concentration reduction factor at 3 monodisperse particle sizes (as opposed to, for example, a single 50nm monodisperse size or using polydisperse aerosol). [to identify any potential simplification in validation]	Review based on data from (currently ongoing) JRC led VPR calibration programme.	Allow use of a polydisperse aerosol with 50nm mode for validation check	**YES**
Dilution air leak checks	Review dilution air filtration specification for PN measurement system and leak checks.		Retain Reg 83 requirements	**YES**
Thermal treatment of VPR calibration aerosol	In order to make accurate measurement of VPR particle concentration reduction factor the calibration aerosol must be thermally stable at the VPR operating conditions. Aerosols may require thermal conditioning to achieve this depending on aerosol material and generation method		The GTR should specify that the aerosol should be thermally stable at the VPR operating temperatures. A separate guidance documen on thermal treatment required to ensure for different aerosol materials and gneration methods may be beneficial.	**YES**

Evaporation Tube set point temperature	Current Reg 83 specification permits a range of 300-400C. A more precise control may be beneficial, in particular in ensuring consistent conditioning of samples during regeneration measurements.		350C +/-10C 0.25 - 0.4s residence time	**YES**
PNC flow check tolerance	Review 5% tolerance permitted on PNC flow check.		Retain 5% tolerance	**YES**
VPR solid particle penetration efficiency	Consider whether a minimum VPR solid particle penetration efficiency should be specified	JAMA to comment on proposed solution	Design criterion of minimum penetration efficiency of 70% for 100nm particles to supplement existing requirements on ratios of pcrf at 30 and 50nm to pcrf at 100nm.	
PNC calibration frequency	Review frequency of PNC calibration requirements	Awaiting draft text from TSI	Extend calibration interval to 13 months (subject to TSI views). Require PNC counting efficiency to be monitored v ref PNC, measurements with other PNCs, measurements on reference cars in other test cells and/or PNC wick to be replaced every 6 months	
PNC calibration aerosol material	Review PNC calibration aerosol material	JASIC to comment on whether single aerosol is preferred for PNC cut-off measurements or also for slope and provide data to support need for a single material	Calibration factor to be applied if cut off performance is measured using CAST rather than emery oil particles. Calibration guidance documents to be updated to specify that if CAST used for slope calibration particle size should be $\geq$70nm	

VIII. LIST OF ACRONYMS AND ABBREVIATIONS

AMS	Aerosol Mass Spectrometry
ARB or CARB	California Air Resources Board
BAU	Business as Usual
BC	Black Carbon
BrC	Brown Carbon
CAFCP	California Fuel Cell Partnership
CAST	Combustion Aerosol Standard
CDT	Clean Diesel Technology
CFM	Cubic Feet Per Minute
CFR	Code of Federal Regulations
CGDI	Center-Guided Gasoline Direct Injection
CMR	Chemically Mass Reconstructed
CM/S	Centimeters Per Second
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
CRC	Coordinating Research Council
CS	Catalytic Stripper
CVS	Constant Volume Sampling
CVT	Continuously Variable Transmission
DMS	Differential Mobility Spectrometer
DPF	Diesel Particulate Filter
E0	Gasoline with 0% Ethanol
E6	Gasoline with 6% Ethanol
E10	Gasoline with 10% Ethanol
E85	Gasoline with 85% Ethanol
EC	Elemental Carbon
EEPS	Engine Exhaust Particle Sizer
EUDC	Extra Urban Driving Cycle
EV	Battery Electric Vehicles
FORD	Ford Motor Company
FTP	Federal Test Procedure
GDI	Gasoline Direct Injection Technology
GHG	Greenhouse Gas
GPF	Gasoline Particulate Filter
GTL	Gas to Liquid
GVWR	Gross Vehicular Weight Rating
GWP	Global Warming Potential
HC	Hydrocarbons
HDE	Heavy-Duty Engines
HEPA	High Efficiency Particulate Air
HONDA	Honda Research and Development

HP	Horsepower
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ILCE_LD	Light-Duty Vehicle Inter-laboratory Correlation Exercise
IPSD	Integrated Particle Size Distribution
ISO	International Organization of Standardization
ISOR	Initial Statement of Reasons
JRC	Joint Research Center of the European Commission
LBS	Pounds
LDT	Light-Duty Trucks
LDT1	LDTs with GVWR of less than 6,000 lbs., and up to 3,750 LVW
LDT2	LDTs with GVWR of less than 6,000 lbs., and between 3,751 and 5,750 pounds LVW
LDV	Light-Duty Vehicles
LEV	Low Emission Vehicle
LII	Laser Induced Incadescence
LOD	Limit of Detection
LPG	Liquid Petroleum Gas
LPM	Liters Per Minute
LVW	Loaded Vehicle Weight
M^3/MIN	Cubic Meters Per Minute
MDPV	Medium-Duty Passenger Vehicles
MDV	Medium-Duty Vehicles
MG/MI	Milligrams Per Mile
MLD	Monitoring and Laboratory Division
MOVES	Motor Vehicle Emissions Simulator
MPFI	Multiport Fuel Injection
MY	Model Year
NEDC	New European Driving Cycle
NIMH	Nickel Metal Hydride
NIST	National Institute of Standards and Technology
NMOG	Non-Methane Organic Gases
NO_x	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking
OC	Organic Carbon
OEM	Original Equipment Manufacturer
OICA	International Organization of Motor Vehicle Manufacturers
PA	Photoacoustic
PAH	Polycyclic Aromatic Hydrocarbons
PC	Passenger Cars
PEM	Proton Exchange Membrane
PEMS	Portable Emissions Measurement Systems
PFI	Multiport Fuel Injection
PHEV	Plug-In Hybrid Electric Vehicle
PM	Particulate Matter
PM0.1	PM with an Aerodynamic Diameter of 0.1 Micrometers or Less
PMG	Particulate Matter Generator
PMI	Particulate Matter Index

PMP	Particulate Measurement Programme
PSD	Particle Size Distribution
PST	Power Split Transmission
SCR	Selective Catalyst Reduction
SFTP or US06	Supplemental Federal Test Procedure
SMPS	Scanning Mobility Particle Sizer
SOF	Soluble Organic Fraction
SOP	Standard Operating Procedures
SPN	Solid Particle Number
STN	Special Trends Network
SULEV	Super Ultra Low Emission Vehicles
SWRI	Southwest Research Institute
TC	Total Carbon
TD	Thermal Denuder
TWC	Three-Way Catalyst
UC	California Unified Cycle
UCDS	Unified Cycle Driving Schedule
UDC	Urban Driving Cycles
UDDS	Urban Dynamometer Driving Schedules
UFP	Ultrafine Particles
ULEV	Ultra Low Emission Vehicles
ULSD	Ultra Low Sulfur Diesel
UN-ECE	United Nation’s Economic Commission for Europe
UN-ECE-GRPE	United Nation’s Economic Commission for Europe - Group of Experts on Pollution and Energy
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
VMT	Vehicle Miles Travelled
VPR	Volatile Particle Remover
WGDI	Wall-Guided Gasoline Direction Injection Vehicles
ZEV	Zero Emission Vehicles