



Determination of Suspended Exhaust PM Mass for Light-Duty Vehicles

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Yang Li, Jian Xue, Kent Johnson, Thomas Durbin, Mark Villela, Liem Pham, Seyedehsan Hosseini, Zhongqing Zheng, Daniel Short, George Karavalakis, Akua Asa-Awuku, and Heejung Jung

University of California

Xiaoliang Wang

Desert Research Institute

David Quiros, Shaohua Hu, Tao Huai, and Alberto Ayala

California Air Resources Board

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Abstract

This study provides one of the first evaluations of the integrated particle size distribution (IPSD) method in comparison with the current gravimetric method for measuring particulate matter (PM) emissions from light-duty vehicles. The IPSD method combines particle size distributions with size dependent particle effective density to determine mass concentrations of suspended particles. The method allows for simultaneous determination of particle mass, particle surface area, and particle number concentrations. It will provide a greater understanding of PM mass emissions at low levels, and therefore has the potential to complement the current gravimetric method at low PM emission levels. Six vehicles, including three gasoline direct injected (GDI) vehicles, two port fuel injected (PFI) vehicles, and one diesel vehicle, were tested over the Federal Test Procedure (FTP) driving cycle on a light-duty chassis dynamometer. PM mass emissions were determined by the gravimetric ($M_{\text{Gravimetric}}$) and IPSD (M_{IPSD}) methods. The results show a systematic bias between methods, with the M_{IPSD} underestimating particle mass relative to $M_{\text{Gravimetric}}$ ($M_{\text{IPSD}} = 0.63 \times M_{\text{Gravimetric}}$), although there is a relatively strong correlation ($R^2=0.79$) between the methods. The real-time M_{IPSD} showed that more than 55% of the PM mass comes from the first 100 seconds of the FTP for GDI vehicles.

Introduction

As emissions from vehicles and engines have continued to decline, accurate measurements of low level pollutants for regulatory compliance are becoming more important. For particulate matter (PM), the gravimetric method is the basis for

regulatory measurements in the United States (US). With the implementation of the 2007 regulations for heavy-duty diesel engines, which essentially required the application of diesel particle filters (DPFs), the US Environmental Protection Agency (EPA) developed 40 CFR Part 1065 [1], which addresses detectability issues associated with ultra-low PM emissions used for heavy-duty engine certification [2]. The new method includes provisions to improve both the sampling of PM and the measurement of PM filters on a gravimetric balance. For PM sampling, the improvements include defined sample flow rates, recommendations on the amount of dilution, new requirements on the temperature at which PM is collected ($47 \pm 5^\circ\text{C}$), and a pre-classifier to eliminate any variability that might be associated with particles larger than $2.5 \mu\text{m}$. For the gravimetric analysis itself, requirements have been added for balance performance, weighing room conditions, electrostatic charge, and filter handling.

In January 2012, the California Air Resources Board (CARB) adopted the Low Emissions Vehicle (LEV) III regulations [3], which lowered the PM emissions standards for light-duty vehicles (LDVs) from 10 mg/mile to 3 mg/mile beginning with model year (MY) 2017 and to 1 mg/mile beginning with MY 2025. US EPA also has proposed the Tier 3 Vehicle Emission and Fuel Standards Program, which lowers PM emission standards for LDVs to 3 mg/mile beginning in 2017 MY [4]. This study investigates an alternative measurement method as a supporting element to the current gravimetric method for LDVs emitting at the 1 mg/mile. At these low PM emission levels, there are other challenges to the current gravimetric method. For example, artifacts from the adsorption and/or desorption of semi-volatile gas molecules on the PM filters can

lead to unpredictable variability in the determination of PM mass. This has raised interest in better understanding the accuracy and precision of gravimetric PM measurements at these low emission levels.

The European Union (EU) has implemented a solid particle number (SPN) emission standard as a complementary metric to the PM mass standard. The European Particle Measurement Programme (PMP) measurement protocol is based on the measurement of solid particles, which are defined as particles that do not volatilize at temperatures of 300°C and above [5]. The current EU SPN standard also excludes sub 23 nm particles, which are mostly volatile, but may be responsible for adverse health effects.

The integrated particle size distribution (IPSD) method developed by Liu et al. [6], determines PM mass by measuring particle size distributions (PSDs) and applying size dependent particle effective densities, as initially discussed by Maricq and Ning [7]. The IPSD method measures suspended particle mass, and therefore is not affected by filter artifacts. The IPSD method allows for simultaneous determination of particle mass, particle surface area, and particle number. Initial work by Liu et al. [6] showed an agreement within 10 to 20% with 1065 compliant gravimetric measurements at low emission levels for heavy-duty diesel engines. As IPSD can simultaneously obtain PM as well as PN, it has the potential to explain the relationship between the current gravimetric method and total particle number methods. IPSD also has the potential to complement the current gravimetric method by providing greater sensitivity and direct conversion between particle mass and number emissions.

Ristimäki, et al. [8] developed a fitting algorithm to determine particle effective density based on parallel measurements made by a Scanning Mobility Particle Sizer (SMPS), and Electrical Low Pressure Impactor (ELPI). Later, Dekati [9] modified an ELPI by adding a mobility channel upstream of the impactor stages to measure effective density, and to directly report real-time particle mass. The instrument was marketed as the Dekati Mass Monitor (DMM), where real-time particle effective density is calculated from the relationship between unimodal mobility and aerodynamic particle size distributions. Lehmann et al. [10] compared gravimetric PM mass to that determined by the DMM over various transient cycles using heavy-duty diesel vehicles. They reported that the DMM overestimates particle mass by 20 to 40% compared to the gravimetric method. Mamakos et al. [11] also reported that the DMM overestimates particle mass compared to gravimetric, ELPI and SMPS measurements by 44%. Although the DMM can measure and apply real-time particle effective density, it does not account for bimodal size distributions and has a lower size resolution than other particle sizing instruments, which may have contributed to the observed discrepancies in measuring transient vehicle-emitted particle mass.

The primary objective of this study was to compare the particle mass determined by the IPSD and gravimetric PM methods. Six vehicles were tested over the FTP driving cycle.

Measurements included gravimetric PM mass and M_{IPSD} determined from particle size distributions measured by an EEPS.

Experimental

Experimental Setup

EEPS measurements and gravimetric filter samples were drawn in parallel directly from a constant volume sampling system (CVS), as shown in Figure 1. The dilution air was filtered using a HEPA filter. PM was collected on a 47 mm Whatman Teflon®-membrane filter with pore size of 2 µm hosted in a filter holder (GELMAN Sciences 2220). A single PM filter sample was taken over the entire FTP cycle to minimize filter adsorption artifacts. As this was a research study focusing on evaluating the feasibility of the IPSD measurements, it was felt that this would provide the most accurate PM mass measurements and minimize the impacts of artifacts on the M_{IPSD} to PM mass comparison. The filter face velocity was maintained at 100 cm/s, consistent with Part 1065, but other provisions of Part 1065, such as control of the temperature at the filter face to 47±5 °C and meeting requirements on residence time, were not implemented, since it was not practical to implement these elements for both the PM mass and the EEPS measurements. A cyclone (cutoff size of 2.5 µm), which is recommended (but not required) by CFR Part 1065, was not used in this study because larger micron-sized particles have never been observed in PSD measurements at this facility during tunnel blank testing.

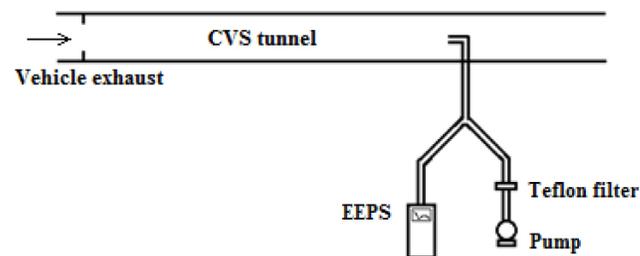


Figure 1. Schematic diagram of the PM sample system

Vehicles and Fuels

Six vehicles were tested in this study, including three GDI vehicles, two PFI vehicles, and one diesel vehicle. These vehicles included a 2012 Mazda 3, a 2012 Kia Optima, a 2012 Mercedes Benz E350 coupe, a 2012 Nissan Versa, a 2009 VW Tiguan, and a 2009 VW Jetta. The Mazda 3, Kia Optima and Mercedes Benz were GDI vehicles. These vehicles were selected to represent different emission levels, and a range of current technologies in the modern fleet. The Mazda 3 was equipped with a 2.0 L, 4-cylinder, wall guided GDI engine, and a TWC (three way catalyst). The initial mileage of the Mazda 3 was 19,155 miles and it is certified to meet California PZEV emissions standards. The Kia Optima was equipped with a 2.4 L, 4 cylinder engine, wall guided GDI engine. The initial mileage of the Kia Optima was 12,595 miles and it is certified to meet the U.S. Tier 2 Bin 5/LEV2 emission standards. The Mercedes Benz was equipped with a 2.4 L, 6-cylinder, spray guided GDI engine, and a TWC. The initial mileage of the

Mercedes Benz was 10,830 miles and it is certified to meet U.S. Tier 2 Bin 5/PZEV emissions standards. The Nissan Versa was equipped with a 1.6 L, 4-cylinder PFI engine, and a TWC. The Nissan Versa had an initial mileage of 2,883 miles and it is certified to meet the U.S. Tier 2 Bin 5/LEV2 ULEV emission standards. The VW Tiguan was equipped with a 2.0 L, 4-cylinder turbo charged PFI engine, and a TWC. The VW Tiguan had an initial mileage of 57,325 miles and it is certified to meet the U.S. Tier 2 Bin 5/ULEV II emission standards. The VW Jetta is equipped with a 2.0 L, 4-cylinder turbo charged diesel engine, and a diesel particle filter (DPF) and a Lean NOx Trap (LNT) system. The VW Jetta had an initial mileage of 114,331 miles and it is certified to meet California ULEV II emissions standards. Vehicle specifications are also summarized in [Table 1](#).

The vehicles were all tested with either the fuel in the tank at the time it was received (an in-use California fuel) or a 10% ethanol gasoline in the case of some of the gasoline vehicles. Number 2 diesel fuel was purchased from a local gas station for the Jetta TDI vehicle.

Table 1. Vehicle specification

Vehicle Number	Make/Model	Model Year	Engine Technology	Mileage	Emission Category	After-treatment
1.GDI	Mazda 3	2012	WG GDI	19k	California PZEV	TWC
2.GDI	Kia Optima	2012	WG GDI	12k	Tier 2 Bin 5/ California LEV II	TWC
3.GDI	Mercedes Benz E350	2012	SG GDI	10k	Tier 2 Bin 5/ California PZEV	TWC
4.PFI	Nissan Versa	2012	PFI	2k	Tier 2 Bin 5/ California ULEV II	TWC
5.PFI	VW Tiguan	2009	TC PFI	57k	Tier 2 Bin 5/ California ULEV II	TWC
6.DIE	VW Jetta	2009	TDI	114k	California ULEV II	DPF LNT

WG: Wall Guided, SG: Spray Guided, PFI: Port Fuel Injection, TC: Turbo Charged, TDI: Turbo Charged Direct Injection Diesel, TWC: Three Way Catalytic Converter, DPF: Diesel Particle Filter, LNT: Lean NOx Trap

Driving Cycles and Measurement Procedure

Vehicles were tested over the Federal Test Procedure (FTP) driving. The FTP is the primary emission certification test for all LDVs in the U.S. and is designed to represent city driving conditions. The cycle distance is 11.04 miles with an average speed of 21.2 miles per hour (MPH). The FTP is a "3 bag" or 3 phase cycle. The first phase is the "cold start" phase, which represents operation when the vehicle is first started for the day. Because the engine and TWC are cold, the majority of the particle and gaseous emissions are produced during this phase of the cycle. Phase 2 occurs immediately after phase 1 and is known as the stabilized phase, representing driving after the engine and aftertreatment systems are warmed up. Immediately after phase 2 is a "hot soak" period, where the engine is turned off for 10 minutes. After the hot soak period, phase 3 is started which is identical to phase 1. Vehicles were tested in this study over the FTP cycle between one and four times. Vehicles with fewer tests were brought in toward the end of the study to augment the available data and provide a broader range of vehicles with different PM characteristics. It

should be noted that for the present study, some FTP tests were run with a cold soak period that was outside of the 12 to 36 hour window specified in the regulations, as the goal of the study was to examine the $M_{\text{Gravimetric}}/M_{\text{IPSD}}$ correlation over a wider range of test conditions.

Emissions Measurement and Analysis

Vehicles are tested at the University of California, Riverside Center for Environmental Research (CE-CERT) Vehicle Emissions Research Laboratory (VERL). The facility is equipped with a Burke E. Porter 48- inch single barrel light duty dynamometer.

PM Mass Emissions

Because of the very low levels of PM emissions expected from the vehicles chosen to be tested, PM mass samples were collected cumulatively over the entire FTP cycle, with one sample collected for each test. The typical weighting factors for each phase of FTP cycle were not used in this study to allow a straight comparison with the M_{IPSD} . This procedure was used for both the conventional and GDI vehicles. Tunnel blanks were estimated based on 12 samples that were collected in conjunction with this study, as well as other programs that were ongoing in the laboratory. Blank filter subtraction was not conducted for gravimetric PM results presented in this study to show the potential magnitude of measurement artifact. Total PM mass was determined by weighing the Teflon®-membrane filter before and after collection with a 1065-compliant microbalance in a temperature and humidity controlled clean room chamber.

Particle Size Distribution Measurement

The EEPS [12] measures particle size distributions based on electrical mobility classification and electric current measurement [13]. Particles are first charged by two unipolar chargers to acquire reproducible charge distributions independent of their initial conditions. Charged particles are then separated in an electric field based on their electrical mobility, deposit on multiple ring electrodes, and create a current that is measured by multiple electrometers. The EEPS measures particle sizes from 5.6 to 560 nm in 32 channels at 10 Hz. The EEPS uses a sophisticated inversion algorithm to convert electrometer currents to size distributions. The main uncertainties in the particle size distribution arise from the particle charge distribution, diffusion, multiple sizes depositing on each electrometer, and noise in current measurement. Due to the lack of knowledge about the charge distributions and the proprietary instrument kernel functions, an analysis of the EEPS size distribution uncertainty is presently not possible. Several previous studies found that the EEPS generally agrees with SMPS for laboratory generated sodium chloride (NaCl) particles, but underestimates sizes and concentrations for soot particles >100 nm [14, 15, 16]. Therefore, the estimated mass from EEPS may be biased low in this study. A new EEPS instrument kernel function is being developed for soot particles [16] to match SMPS size distributions and will be tested in our future studies.

IPSD Method

The IPSD method determines total particle mass by integrating the fractional mass obtained by multiplying the effective density by particle volume concentrations for each size bin from the particle size distribution measurements, as shown in Equation (1) [6].

$$M_{IPSD} = \sum_i \rho_{eff_i} \cdot \left(\frac{\pi D_{p,i}^3}{6} \right) \cdot n_i \quad (1)$$

The particle effective density is defined as particle mass per particle volume defined by mobility diameter, and it is a function of particle size. The effective particle density can be influenced by particle composition and morphology. Interestingly, Maricq and Xu [7] found particle effective density distributions are similar between exhaust particles from light duty diesel and GDI vehicles. For accumulation mode particles (>30 nm in diameter), the effective density distribution from Maricq and Xu [7] was utilized as shown in Equation (2).

$$\rho_{eff} = 1.2378 \cdot e^{-0.0048D_p} \quad (D_p > 30 \text{ nm}) \quad (2)$$

For nucleation mode particles below 30 nm in diameter, a density (1.46 g/cm³) of hydrated sulfuric acid was assumed following Zheng et al.'s [17] calculation. Figure 2 shows the effective particle density distribution applied in this study for the IPSD method. We additionally applied a constant density of 1 g/cm³ for all sizes for PFI vehicles to examine the difference in using two different density estimates. The IPSD particle mass was calculated by equation (1) for all density distributions.

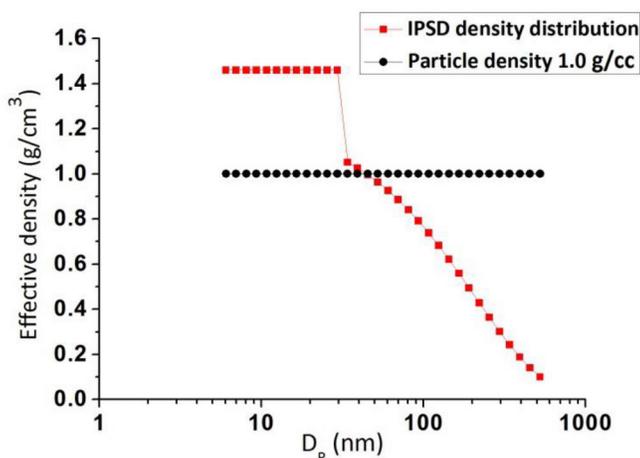


Figure 2. Particle effective density functions used in this study.

Results and Discussion

This section discusses the results and findings of this study.

Gravimetric PM Mass Emissions ($M_{Gravimetric}$)

Figure 3 shows the gravimetric mass emission rates for the individual tests for each test vehicle based on cumulative PM filters. It should be noted that these cumulative PM emission

rates are not weighted like typical regulatory measurements and may overestimate the actual FTP emission rate. The PM mass emission rates varied from vehicle to vehicle. The GDI vehicles had PM mass emission rates ranging from <1 to ~6 mg/mile, with the Mercedes Benz (GDI3) having the lowest PM emission rates for the GDI vehicles. The Mercedes Benz was a spray-guided GDI technology which gave lower PM emission rates than the wall-guided GDI vehicles tested in this study. The PFI vehicles showed emissions rates from <1 to ~3 mg/mile. Three of the tests on the Nissan Versa (PFI4) were <1 mg/mile, while the first test on the Nissan Versa was ~2 mg/mile. The PM emission rates for the VW Jetta diesel (DIE6) with aftertreatment were <1 mg/mile.

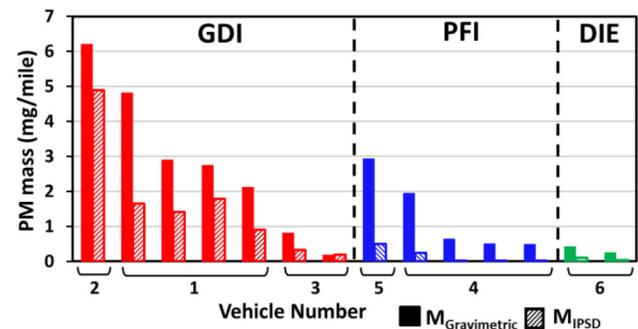


Figure 3. Gravimetric PM mass ($M_{Gravimetric}$) and M_{IPSD} emission results.

IPSD Mass Emissions (M_{IPSD})

Figure 3 also shows the M_{IPSD} emission rates based on the IPSD method for the individual tests for each test vehicle. The M_{IPSD} mass emission rates varied from vehicle to vehicle, but consistently were lower than $M_{Gravimetric}$. The vehicles all had FTP M_{IPSD} emission rates near or below 0.5 mg/mile with the exception of the GDI Mazda 3 (GDI-1), which had FTP M_{IPSD} emission rates on the order of ~1-2 mg/mile, and the GDI Kia Optima (GDI-2), which had a M_{IPSD} emission rate of ~5 mg/mile. For the PFI vehicle tests where the gravimetric PM mass emissions were <1 mg/mile, the M_{IPSD} emission rates were very low (<0.1 mg/mile), indicating that the gravimetric PM measurements did not appear to be fully explained by IPSD-calculated mass, M_{IPSD} .

M_{IPSD} vs Gravimetric PM Mass ($M_{Gravimetric}$)

Figure 4 shows the linear regression slope for M_{IPSD} versus gravimetric mass was 0.63. This slope is lower than one, in contrast to a slope slightly greater than one that was reported by Liu et al. [6] from measurements of PM emissions from a 2004 heavy-duty engine over an FTP cycle. It should be noted that there are a number of differences between the conditions for the Liu et al.'s [6] study and current study in the experimental set up and method due to the measurement differences between heavy-duty and light-duty vehicles. Liu et al. [6] used a secondary dilution tunnel and a residence chamber for the gravimetric PM measurements, while the exhaust going to the EEPS was diluted using two secondary dilutors and then put through a 30-sec residence chamber prior to be measured by the EEPS. In another study, Liu et al. [18] applied the IPSD method to medium-duty diesel engine exhaust over steady state engine operating conditions using a

slow but more accurate particle sizing instrument, the SMPS, which showed a one-to-one relationship between the gravimetric PM and M_{IPSD} . They used effective density linearly interpolated from measurements by Park et al. [19], which were obtained from the same diesel engine model as SMPS measurements, but at different loads.

Zheng et al. [17] showed that EEPS underestimate the size of soot aggregate compared to a fast-SMPS. A fast-SMPS developed by Shah and Cocker [20] showed good agreement with a conventional SMPS for a range of scanning speeds from 2.5 to 60 seconds [17]. Wang et al. [16] also showed the concentration of diesel particles is underreported by the EEPS relative to the SMPS for measurements greater than 200 nm. We believe this is one of major reasons that the current study showed an underestimation for M_{IPSD} .

There are other important aspects to consider when comparing the M_{IPSD} and gravimetric PM results. In principle, if both gravimetric and M_{IPSD} measure the same particle mass then they should agree with each other. In reality, the gravimetric method collects vehicle exhaust particles as well as condensable volatile organic compounds onto the filter medium resulting in a positive bias, as shown in Figure 4 where the regression line crosses the x-axis at a positive value. Our filter blank was 8 μg . This translates into 0.16 mg/mile, which is somewhat smaller than the positive intercept of 0.57 mg/mile on the x-axis of Figure 4. The regulations allow for blank filter subtraction up to 5 μg per phase; however, the adsorption of gaseous species onto filters from vehicle exhaust remains an important consideration when quantifying gravimetric PM for vehicles meeting the LEV III standards. On the other hand, the M_{IPSD} reflects only suspended particle mass and is not affected by the contribution of gas-phase artifacts.

Another key parameter in conversion to mass is the particle effective density function with respect to the particle mobility diameter. Data for the GDI and light duty diesel were relatively close to the regression line, while data for PFI vehicles were generally lower in emissions and showed more scatter in Figure 4. As mentioned earlier, this study used Maricq and Xu's [7] particle effective density function, which has been widely used for light duty diesel and GDI exhaust particles. It is possible that a different particle effective density might be needed for PFI vehicles. Use of constant particle effective density, which assumes PM from gasoline PFI vehicles is internally mixed and of the same shape, reduced the scatter (data not shown here). A more representative particle effective density for PFI engines may need to be measured. In general, it may additionally be necessary to re-examine the validity of Maricq and Xu [7]'s particle effective density functions for light-duty diesel and GDI engines under the various engine operating conditions of the FTP test.

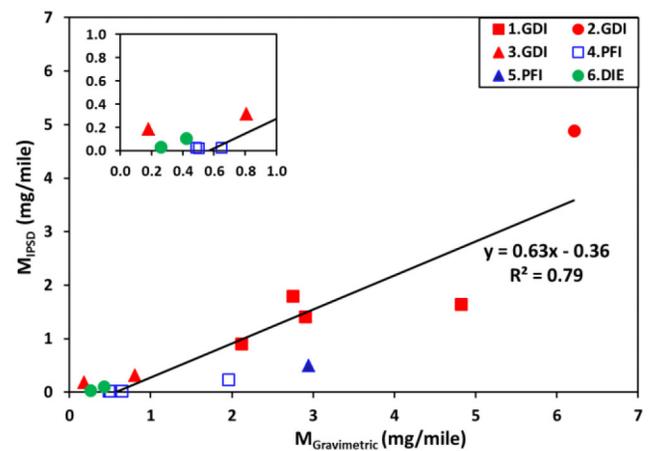


Figure 4. Correlation of M_{IPSD} and gravimetric PM mass ($M_{Gravimetric}$) in FTP test cycle emissions.

PN vs PM

Total particle number calculated by integrating the particle size distributions measured by EEPS was plotted against the gravimetric PM mass in Figure 5. The total PN is comparable to the values seen for the other light duty vehicles, which ranged from approximately 1×10^{11} to 1×10^{13} particles/mile. The correlation between gravimetric PM mass ($M_{Gravimetric}$) versus total PN was relatively poor below 1 mg/mile, which is consistent with the results of a previous study by Maricq [21]. Total particle number was also compared with M_{IPSD} . A much better correlation was found between M_{IPSD} and PN. This is not totally unexpected, as the M_{IPSD} is calculated from the EEPS PN via equation 1. The stronger correlation between total PN and M_{IPSD} in Figure 6 indicates that the sensitivity of the EEPS for measuring PSDs and particle mass should be adequate for measuring at LEV III emission levels.

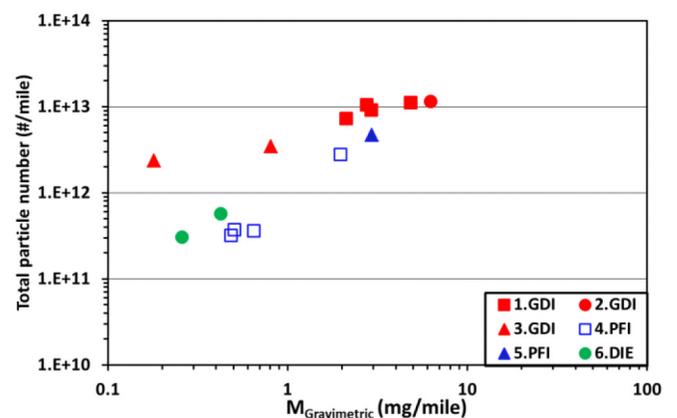


Figure 5. Total particle number versus gravimetric PM mass ($M_{Gravimetric}$) from various light duty engine technologies over FTP cycles.

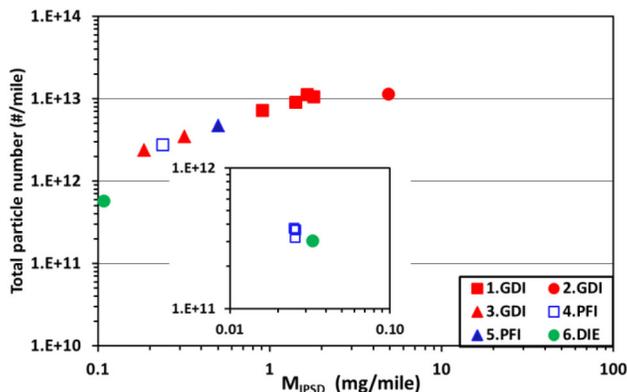


Figure 6. Total particle number versus M_{IPSD} emission rates from various light duty engine technologies over FTP cycles.

Real-Time PM Emissions

Real-time M_{IPSD} emissions rates are shown in Figure 7 for one of the GDI test vehicles. The blue line shows the cumulative M_{IPSD} percentage as a function of time throughout the cycle. The real-time results show that the PM emissions are predominantly produced during the cold start portion of the FTP. The first 100 seconds of the cold start phase accounted for 55% of total M_{IPSD} . This is somewhat consistent with Zhang and McMahon [22]'s work that showed about 67% of total PM mass comes from phase 1 for wall-guided GDI vehicles using the gravimetric method. The complete cold start transient phase accounted for 83% of total M_{IPSD} . This is somewhat similar to typical trends for THC emissions from PFI gasoline-powered vehicles. The real-time and cumulative particle mass graphs, determined by the IPSD method, point to where the most significant portion particle mass is emitted during the cycle. The real-time data can help automobile manufacturers in developing strategies to reduce particle emissions.

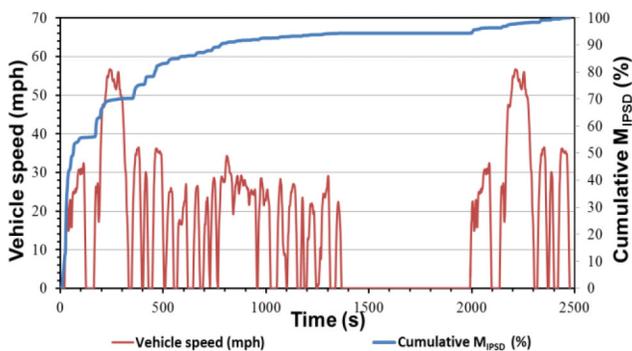
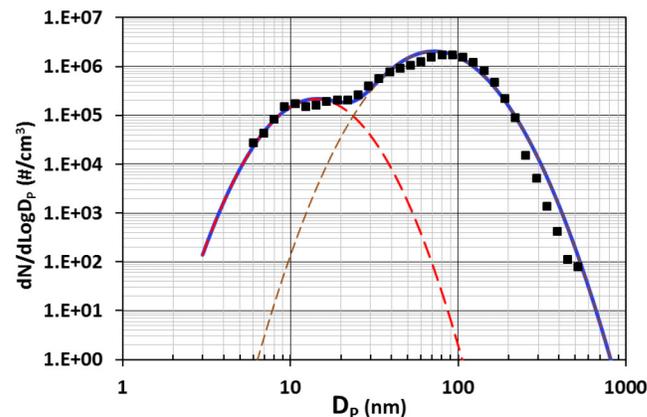


Figure 7. Cumulative M_{IPSD} measurement over FTP cycle for Mazda 3.

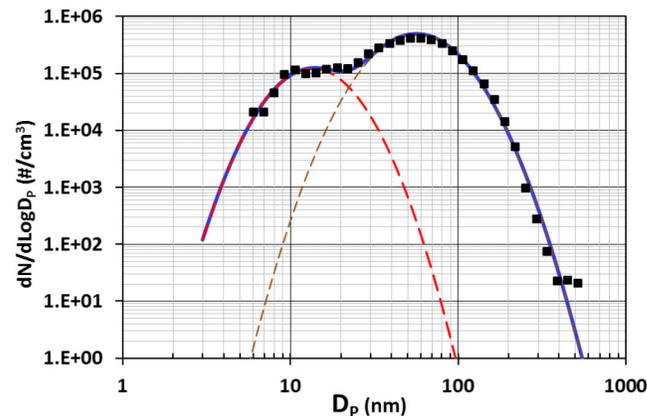
Average Particle Size Distributions

Figure 8 shows average particle size distributions for an FTP test cycle. Geometric mean diameters (GMD) and geometric standard deviations (GSD) determined by a bi-modal fit program are shown in Table 2 for each test/vehicle. This was done to evaluate whether the EEPS measured particle size distributions fall into a reasonable range in terms of GMD and GSD. It is known that GSDs are rather tight at about 1.7 for diesel, and maybe a bit larger for GDI [23]. The results of this

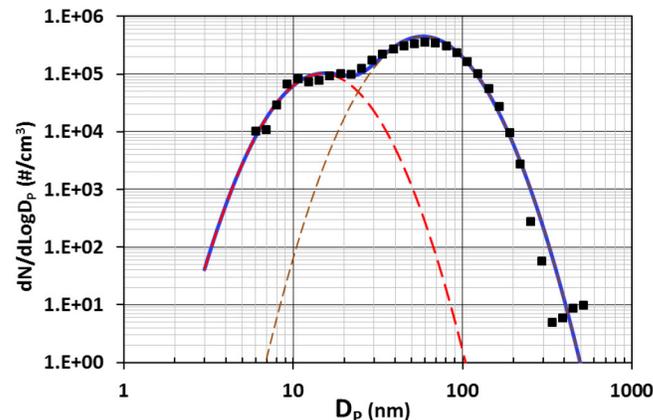
study show GMDs of accumulation modes range from 42 to 72, 46 to 58, 35 to 52 nm, while GSD varies from 1.5 to 1.6, 1.6 to 1.9, 1.6 to 2.0 for GDI, diesel, and PFI vehicles, respectively. It is notable that GMDs for PFI vehicles tested in this study are lower than those of the diesel and GDI vehicles. On average, diesel exhaust particle size distributions were in the right range in terms of GSD while individual GSDs showed either narrower or wider distributions. On the other hand, particle size distributions for GDI vehicles show narrower distributions than expected. This is probably due to the underestimation of aggregate mobility size by EEPS.



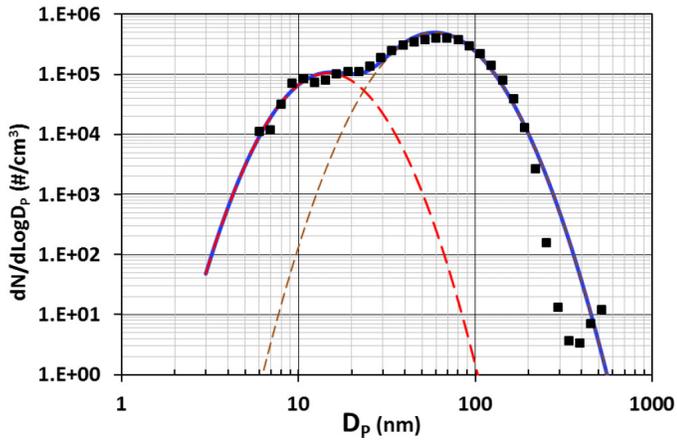
(a). Vehicle 2 FTP cycle



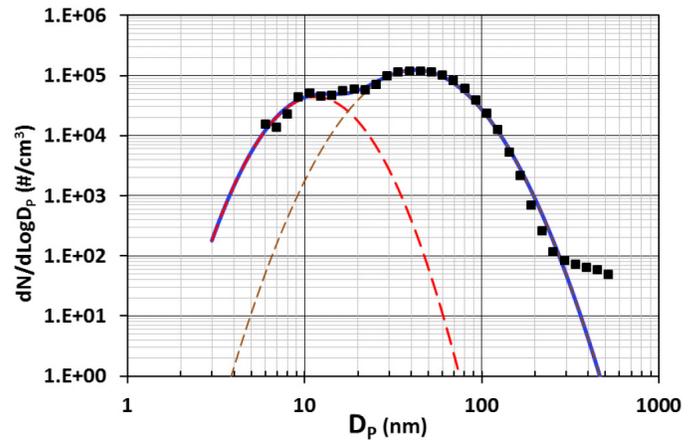
(b). Vehicle 1 FTP-1 cycle



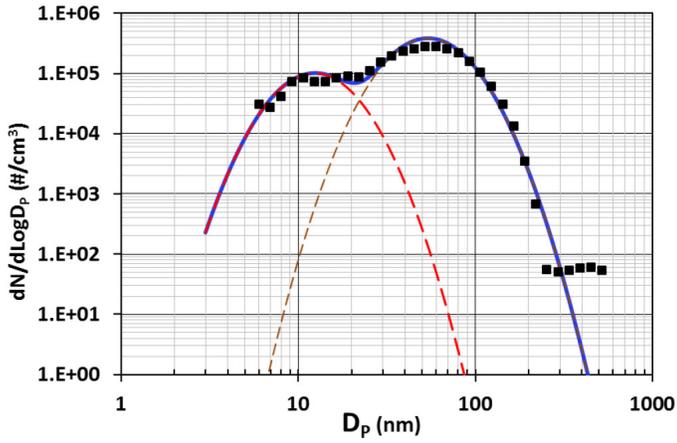
(c). Vehicle 1 FTP-2 cycle



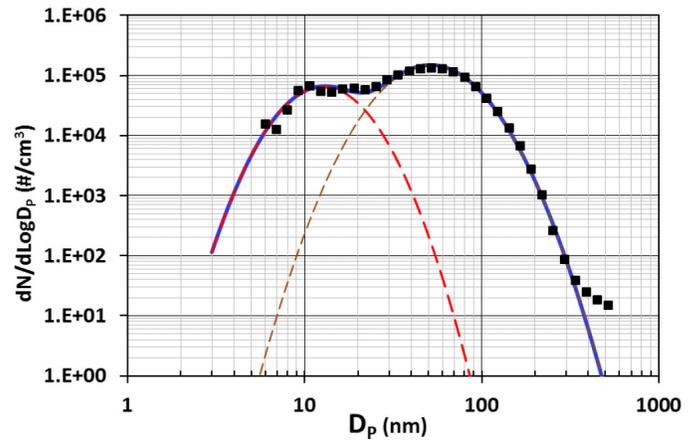
(d). Vehicle 1 FTP-3 cycle



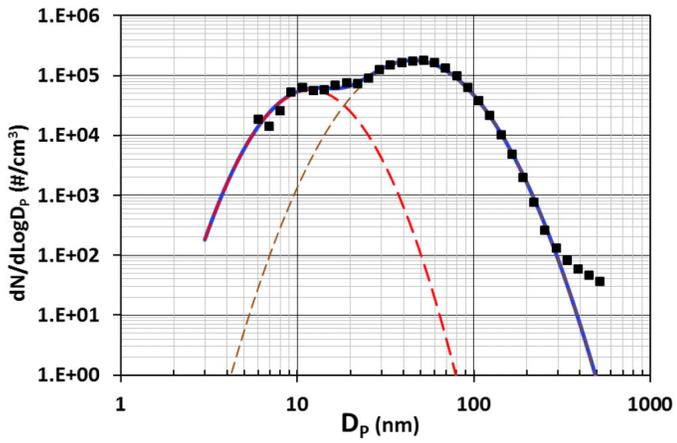
(g). Vehicle 3 FTP-2 cycle



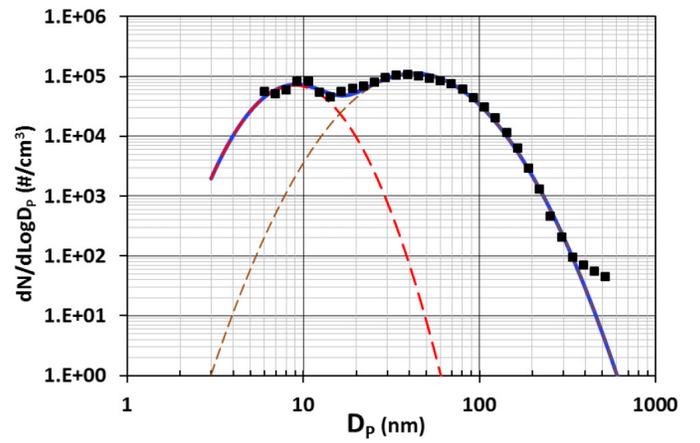
(e). Vehicle 1 FTP-4 cycle



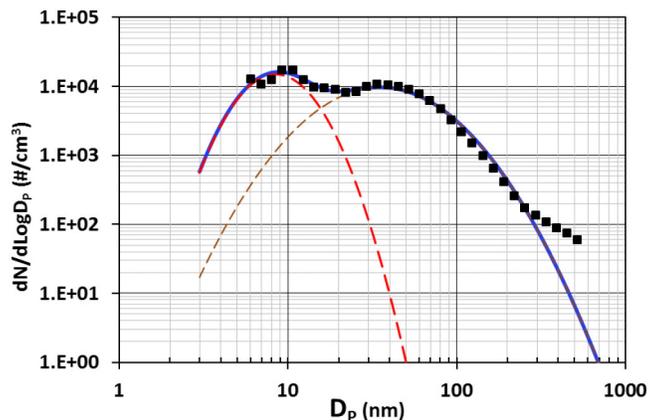
(h). Vehicle 5 FTP cycle



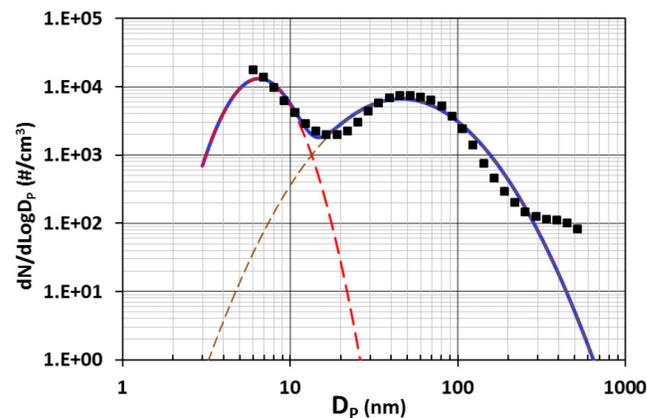
(f). Vehicle 3 FTP-1 cycle



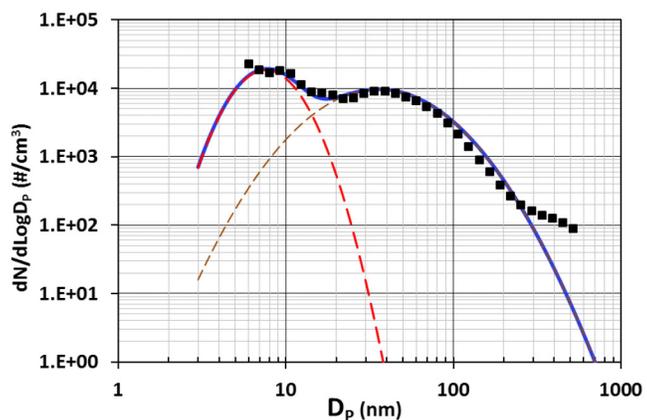
(i). Vehicle 4 FTP-1 cycle



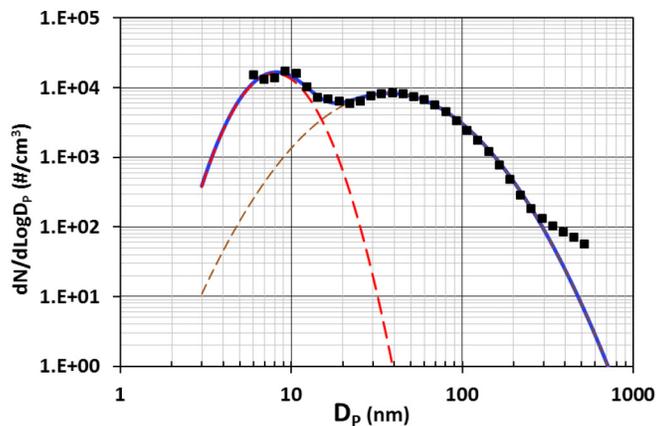
(j). Vehicle 4 FTP-2 cycle



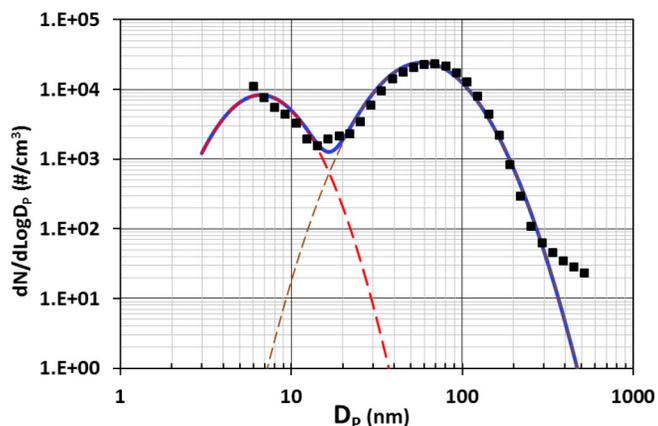
(n). Vehicle 6 FTP-2 cycle



(k). Vehicle 4 FTP-3 cycle



(l). Vehicle 4 FTP-4 cycle



(m). Vehicle 6 FTP-1 cycle

Figure 8. EEPS cycle averaged particle size distributions with a bi-modal fit (a)-(n). The order of PSDs are the same as that in Figure 3.

Table 2. GMD and GSD of EEPS cycle averaged particles size distributions

	Vehicle/Test	GMD (nm)/GSD	
		Nuc-mode	Acc- mode
GDI	2/FTP	14.2/1.5	71.9/1.6
	1/FTP-1	13.6/1.5	56.4/1.6
	1/FTP-2	14.9/1.5	58.3/1.5
	1/FTP-3	14.7/1.5	59.1/1.6
	1/FTP-4	12.3/1.5	54.1/1.5
	3/FTP-1	11.9/1.5	45.4/1.6
PFI	3/FTP-2	11.5/1.5	42.3/1.6
	5/FTP	12.7/1.5	51.5/1.6
	4/FTP-1	8.9/1.5	42.5/1.7
	4/FTP-2	8.5/1.5	35.4/2.0
DIE	4/FTP-3	7.6/1.4	35.9/2.0
	4/FTP-4	8.0/1.4	37.5/2.0
	6/FTP-1	6.6/1.5	58.4/1.6
	6/FTP-2	6.5/1.4	45.9/1.9

SMPS vs EEPS

In order to evaluate EEPS measurements relative to a reference instrument, the SMPS, measurements were conducted over steady-state conditions. Figure 9 shows two preliminary results for a GDI vehicle operating at 30 and 60 mph (vehicle #1 in Table 1). The reported distributions represent 7.5 minutes at each speed, enabling 3 scans for the SMPS. This reduced measurement bias from a slight drift in the particle size distributions during the steady state tests. Figure 9a upper graph shows that the EEPS and SMPS agree well while Figure 9b upper graph shows the EEPS underestimates accumulation mode particle size distributions. The latter is consistent with earlier observations by Wang et al. [16] and Zheng et al. [17]. The integrated particle mass graphs (lower graphs of Figure 9ab) show the M_{IPSD} determined by EEPS measurement ranges from 57 to 92% of M_{IPSD} determined by SMPS measurements. An improvement of the EEPS inversion matrix is the best solution to correct this discrepancy, and developments made by Wang et al. [16] on the EEPS inversion matrix will be evaluated for light-duty vehicles in a separate paper [24].

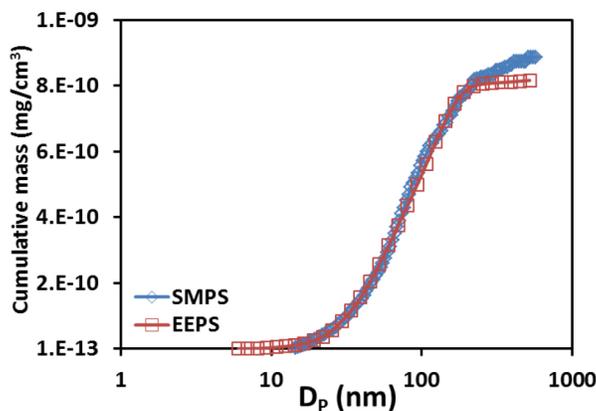
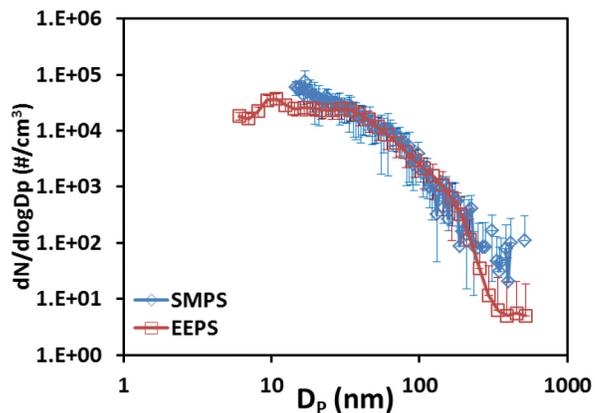
Summary and Conclusions

This study provides an evaluation of the potential for using the IPSD method to determine PM mass for current and future technology vehicles. The IPSD method combines particle size distributions with a size dependent particle effective density. Three GDI vehicles, two PFI vehicles, and one diesel vehicle with model years ranging from 2009 to 2012 were tested over the FTP cycle. PM mass, M_{IPSD} using an EEPS, particle number, and real-time particle mass were measured. The major findings from this study are listed below.

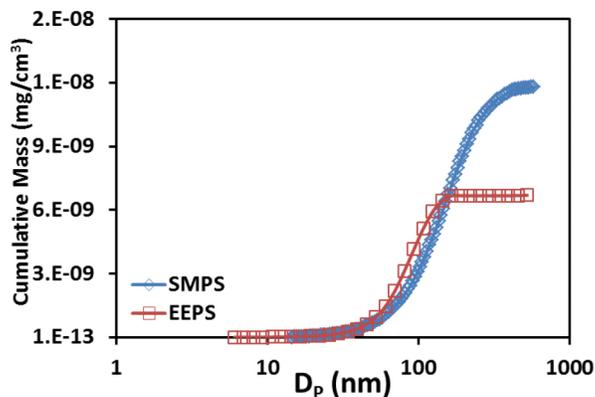
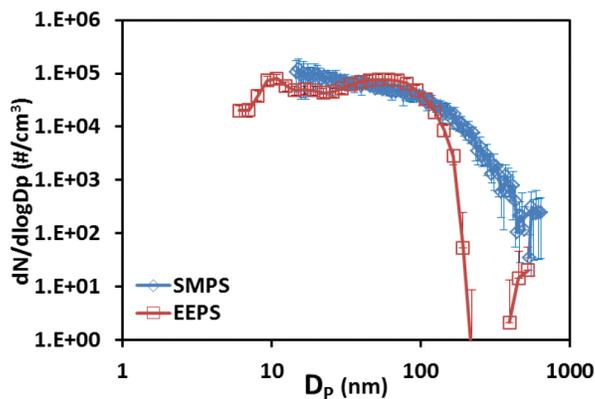
- PM emission rates based on the gravimetric method for the FTP were below 1 mg/mile with the exception of the GDI Mazda 3 and Kia Optima, which had emission rates on the order of 2-6 mg/mile.
- M_{IPSD} emission rates based on the IPSD method for the FTP were below 0.5 mg/mile with the exception of the GDI Mazda 3 and Kia Optima, which had emission rates on the order of 1-5 mg/mile.
- The results show that the IPSD method tends to underestimate particle mass emission rates relative to the gravimetric method, over the range of selected particle effective density functions. There is a relatively good correlation between the M_{IPSD} and $M_{Gravimetric}$ emission rates, however, with an R^2 of 0.79.
- A good correlation (less spread of the data) was found between M_{IPSD} and total PN. This indicates the sensitivity of the EEPS for measuring size distribution and PM mass should be adequate for measuring at LEV III emission levels.
- The real-time M_{IPSD} results show that the PM emissions are predominantly produced during the cold start portion of the FTP for the GDI vehicle. Total M_{IPSD} 83% was emitted during the cold start transient phase, and 55% within the first 100 seconds.
- Cycle averaged particle size distributions show that GMDs of accumulation modes range from 42 to 72, 46 to 58, 35 to 52 nm, while GSD varies from 1.5 to 1.6, 1.6 to 1.9, 1.6 to 2.0 for GDI, diesel, and PFI vehicles, respectively. Particle size distributions for GDI vehicles show narrower distributions than expected. This is probably due to the underestimation of the aggregate mobility size by EEPS.
- Steady state test results show that the M_{IPSD} determined by EEPS measurements can vary from 57 to 92% of the M_{IPSD} determined by SMPS measurements, depending on the discrepancy between the two instruments. It is necessary to further investigate this issue.

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(a). GDI, steady state test 30 mph



(b). GDI, steady state test 60 mph

Figure 9. Particle size distribution and cumulative M_{IPSD} comparison between SMPS and EEPS. (a) GDI, steady state test 30 mph (b) GDI, steady state test 60 mph

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Contact Information

Corresponding author:

Heejung Jungw
heejung@engr.ucr.edu

Z. Zheng and E. Hosseini are currently at AVL and Terry Hayes Associates, respectively.

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