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Evaluation of Partial Flow Dilution Systems for Very Low PM Mass Measurements

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Abstract
Particulate matter (PM) mass measurement methodologies were improved considerably with the application of Title 40 Code of Federal Regulations Part 1065 for the 2007 standards for heavy-duty engines that emphasized PM. However, there is still a need to improve the understanding of and the confidence in mass measurements for light-duty vehicles, which are now being subjected to more stringent PM standards. The purpose of this study is to evaluate commercially available partial flow dilutors (PFDs), with a particular focus on their equivalency with the standard constant volume sampler (CVS) tunnel method and the ability to provide reproducible measurements at low PM emission levels. For the main PFD comparison, simultaneous testing was conducted with the three PFDs, over federal test procedure (FTP) and US06 tests. The results of the calibrations and proportionality tests all showed good performance for the PFDs. The exhaust flow meters (EFMs) for the PFDs showed measurements within 2% or less of a calibration source. The PFDs also showed good level proportionality and can easily meet the CFR 1066 requirements for light-duty vehicles and 1065 requirements for all tests performed. Larger differences were seen for the main comparisons between the CVS and the different PFDs during the FTP testing, with the relative difference of PM emissions between the PFDs and the CVS varying from − 16.5 to − 0.6%, with an average pooled difference of − 8.5%. These FTP differences only represented 0.00 to 0.11 mg/mile on an absolute basis, however, and could be attributed to difficulties making and weighing filter mass measurements at such low levels. For the US06 cycle, the differences between the PFDs and the CVS were not statistically significant and ranged from − 6.7 to − 0.7% and up to 0.07 mg/mile.

Keywords Particle emission · Vehicle emission · Emission control · Particle measurements

Abbreviations

σ	Standard deviation
Bag	Phase of the FTP bag measurement system
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR	Code of Federal Regulations
CO	Carbon monoxide
CO_2	Carbon dioxide
CVS	Constant volume sampling
DF	Dilution factor
EC	Elemental carbon as defined by NIOSH methods
EFM	Exhaust flow meter
EPA	United States Environmental Protection Agency
E10	Ten percent ethanol in gasoline blend by weight
FFV	Filter face velocity
FTP	Federal test procedure
GDI	Gasoline direct injection
ID	Inner diameter
ISO	International Organization for Standardization
LDVS	Light-duty vehicles
LEV	Low-emission vehicle

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MFC	Mass flow controller
NIOSH	National Institutes of Safety and Health method
NIST	National Institute for Standards and Technology
OC	Organic carbon
OD	Outer diameter
PFD	Partial flow dilution system
PM	Particulate matter
PTFE	Polytetrafluoroethylene
SEE	Standard error estimate
US06	US06 test cycle

1 Introduction

The ability to accurately characterize low-level emissions from vehicles is becoming more of an issue as the certification standards for vehicle emissions continue to become more stringent. Vehicle exhaust emissions have typically been measured using a constant volume sampler (CVS) in the past. A CVS captures the whole exhaust flow while maintaining constant volume flow. This enables emission rate calculation by the product of concentrations measured at CVS and constant volume flow rate. Another approach that can be used to sample vehicle exhaust is a partial flow diluter (PFD). A PFD uses a different approach by taking only a small fraction of the vehicle exhaust flow proportional to the exhaust flow at all times [1–6]. PFDs offer potentially significant cost savings, sampling flexibility, and performance benefits compared to the full-flow CVS tunnel. PFDs have been more prevalent for the measurement of emissions of large engines, since it becomes impractical to utilize a CVS for engines with very high exhaust volumes. PFDs play an important role for on-road testing such as Europe's real driving emission (RDE) regulations due to their compact size. PFDs are of particular interest to quantify very low particulate matter (PM) mass because of its potential to reduce adsorption artifacts. While the surface to volume ratio is higher for PFD, it is much easier to maintain the surface of the dilution tunnel clean leading to less adsorption artifact for PFD. More importantly, PFDs normally would take samples upstream of the transfer line, which would reduce the potential impacts of the storage-release effects of organic vapor from the walls [1].

The performance of PFD systems in comparison with full CVS systems has been evaluated in a number of studies over the past two decades [2, 4]. In the early 2000s, there was concern in the USA over allowing the use of PFDs for the measurement of PM mass for heavy-duty diesel engines over transient cycles as part of the International Organization for Standards (ISO) 16183 document. In conjunction with the development of this document, a study was conducted at the Southwest Research Institute (SwRI) to evaluate PFDs that were commercially available in the 2001 timeframe, including an AVL-SPC, a Horiba MDLT, and a Sierra BG2 [2]. The findings of this work showed that the PM emission rates measured by PFDs were lower than those measured by CVS, which was attributed to the slow response of the PFDs to changes in the exhaust flow rate during transient operation. In other works, Europe, Schweizer and Stein evaluated PFDs as a subproject of worldwide certification procedure for heavy-duty on-highway engines (WHDC) [4]. The results of this study showed better agreement between the PFDs and CVS, with no consistent and statistically significant difference between the two systems and that different PFD sampling parameters that were investigated had no or only minor influence on particulate mass and composition.

PFDs received greater attention with the implementation of significantly reduced PM emission standards for heavy-duty engines in the USA in 2007. A series of improvements to the gravimetric filter PM mass measurement method were implemented in 40 Code of Federal Regulations (CFR), Part 1065 [7], as part of the development of the 2007 PM standards. The use of PFDs for PM measurements was among the provisions included in 40 CFR Part 1065. In conjunction with the implementation of the 2007 PM standards, a comprehensive E-66 study was conducted by Khalek et al. to evaluate and improve low-level PM sampling for heavy-duty engines [8–10]. The E-66 study included an investigation of a number of commercially available PFDs for heavy-duty applications [10]. The results showed a considerable improvement in the performance of the PFDs compared to SwRI's previous 2002 work [2], including proportional sampling with a response time of 200 ms or less and correlations between engine exhaust flow and sample flow that showed correlations coefficients greater than 99% and a standard error of better than 5%. These performance improvements can be attributed to a variety of factors, including better and faster electronics and sensors, faster flow controlling, and improvement pneumatics. The PFDs were also able to show comparable performance with the CVS at PM levels below 10% of the 2007 standard for both steady-state and transient operation. However, Khalek et al. [10] investigated partial flow dilution as it applies to heavy-duty engine dynamometer emissions measurements and there are numerous differences between heavy-duty engine dynamometer and light-duty chassis dynamometer testing.

There is also considerable interest in the potential for using PFDs for emissions measurements for light-duty vehicles (LDVs). This is particularly in light of the reductions of the PM standards from 10 to 3 mg/mile in 2017 as part of the United States Environmental Protection Agency (US EPA) Tier 3 and the California Lower Emission Vehicle (LEV) III regulations, with a further reduction to 1 mg/mile in 2025 as part of the California LEV III requirements [11, 12]. PM emission levels and sampling environments are different between heavy and light duties. PM measurement for light-duty vehicles in the USA is based on 40 CFR Part 1066. Part 1066 permits use of PFD for light-duty vehicle PM measurement [13]. Foote et al. investigated two commercially available PFDs in 2013 for light-duty vehicles [1]. They reported their PM mass results with PFD-A correlated well, while the PM mass with PFD-B underestimated compared to that from CVS. It was unclear why one of the PFDs underestimated the gravimetric PM mass relative to the CVS system and further investigation was suggested. Ntziachristos and Samaras also conducted extensive evaluations of PFDs for both LDVs and light-duty engines [14]. Their results also showed that the PFDs had promise for low-level measurements for a wide range of engine sizes and applications. More recently, a comprehensive study of PM mass measurements from LDVs was conducted as part of the Coordinating Research Council's (CRC's) E-99 project to evaluate increasing filter face velocity (FFV) (from 100 to 175), reducing dilution ratio (DR) (from 7 to 3), using cumulative vs. individual filters, and comparing 3- and 4-bag federal test procedure (FTP) tests [15]. A commercially available partial flow diluter (PFD) was also evaluated in that study. The results for the PFD indicated reasonable performance relative to the full-flow dilution tunnel, but only included a single commercially available unit.

The purpose of this study is to compare the PFDs' ability to provide reproducible measurements at very low PM emission levels using commercially available PFDs and to provide a comparison against a CVS tunnel. This program focuses on evaluating the capabilities of commercial PFDs to meet LEV III/Tier 3 PM emission measurement requirements and is designed to address a number of open questions about the application of PFDs for LDV exhaust emissions testing including (1) whether PFDs show equivalency to full flow (CVS) exhaust sampling for two distinct driving cycles, (2) what the noise sources for PFD vs. CVS sampling are, (3) what is needed to "pre-condition" these sampling systems (PFD/CVS tunnel), (4) how sensitive the PFD performance is to exhaust flow measurement, (5) what the relative performance attributes and issues for individual PFD units are, and (6) what improvements can provide more efficient and accurate partial flow system performance in light-duty chassis dynamometer testing at Tier 3 PM standard levels.

For this study, a series of tests were conducted with three different PFDs and exhaust flow meters (EFMs) with and without vehicle exhaust. Initially, tests were conducted to evaluate the accuracy, response, and proportionality of both the EFMs and PFDs. This included a laboratory test that evaluated the EFMs over a range of different flow rates, a laboratory test that evaluated the sampling delays for an EFM and PFD for vehicle exhaust, and a test that evaluated the performance of the individual EFMs in monitoring vehicle exhaust flow. The main PFD comparison was conducted with a gasoline direct injection (GDI) vehicle over different combinations of FTP and US06 tests.

2 Experimental Setup and Analysis

2.1 Test Setup

2.1.1 Vehicles

The test vehicle was a 2016 Hyundai Sonata GDI vehicle with a PM emission rate of ~2 mg/mile for the FTP and ~5 mg/mile for the US06 cycle. It has a 2.4-L engine with a mileage of 14,700 miles and is certified to the California LEV III SULEV 30 PC Certification standard. This vehicle had a PM emission rate that was sufficiently high enough to provide filter mass levels that were readily measurable, but not too high to create filter plugging or contamination issues. This vehicle was inspected to ensure that it was in sound mechanical and operational conditions upon arrival using a standard checklist.

2.1.2 Test Fuel

Commercially available retail 10% ethanol in gasoline blend by weight (E10) California fuel was used for testing. One batch of fuel was used for the main PFD comparison tests in this study. A fuel change procedure with multiple drains and fills and preconditioning driving was performed on the vehicle prior to beginning the testing for this study.

2.1.3 Test Cycle

The FTP and US06 cycles were the two cycles used in this study because they are used in the certification procedure for LDVs. The FTP was performed as a standard 3-bag test with cold start, hot stabilized, and hot start phases. Prior to the FTP tests, the vehicle was preconditioned over an LA04 prep cycle followed by a cold soak of between 12 to 36 h.

The US06 test is a more aggressive testing cycle that is included as part of the certification testing procedure. The US06 tests were conducted immediately after the corresponding FTP test and the FTP bag analysis. A US06 preconditioning cycle was conducted right after the FTP test and immediately before the US06 emissions test.

2.2 PM Sampling and Measurement

The two PM sample approaches utilized in this study were a CVS PM and PFD PM sampler. Each of these systems is unique in its measurement of PM. The CVS method utilizes the full vehicle exhaust and PM is collected on filters under fixed constant flow conditions. The PFD samples a small fraction of the exhaust (typically around 1–2%) that is extracted in a manner proportional to the exhaust flow. Proportionality and accuracy in the exhaust flow measurement are factors for the PFDs that could affect the comparison between the CVS method and the PFD method. This can create some biases between the PFD and CVS methods. This section describes the configuration details of the PM sampling approaches for both sampling systems. The overall experimental setup is shown schematically in Fig. 1. For the FTP testing, the PFD could be setup to collect a cumulative filter over all three bags of the FTP or to sample PM separately for each of the individual phase, and it was decided to utilize the composite (or cumulative) method.

2.2.1 Full Flow Dilution (CVS)

For the CVS method, probes for both composite and by phase PM sampling were utilized. A multi-filter sampler that simultaneously collected PM on three different gravimetric filter samplers from the dilute CVS was utilized to evaluate different parameter changes in parallel. This design maximized the number of parallel measurements to minimize the confounding factors of test-to-test vehicle/driver variability. This sampler is designed to meet 40 CFR 1065 and 1066 requirements and utilized a single heated sampling probe, a particle impactor, a heated control chamber for the various filter holders, a residence chamber designed to provide a residence time of 2.5 s for each of the FFVs, compliant filter holders with filter cassettes, solenoid bypass valves, and four National Institute of Standards (NIST) traceable mass flow controllers (MFCs). The system is controlled via a LabVIEW program and was integrated into the College of Engineering-Center for Environmental Research and Technology (University of California, Riverside) (CE-CERT)'s driver's aid system for automatic flow control, logging, and monitoring.

The heated chamber contained several PM samplers designated probes A–C. The PM samplers were designed for varying FFVs while maintaining similar residence times. These probes all collected from a standard a 1-inch outer diameter (OD) (0.87-inch inner diameter (ID)) tube that extended into the CVS. A description of the PM samplers that were collected from each probe is provided below:

Probe A = CVS probe A (CVS_A) collected a cumulative PM filter over the entire duration of the 3-bag FTP tests. The flow rate for probe A for a 3-bag FTP was 100 cm/s for the bag 2 segment with flow rates that were 43 and 57% of that value for bags 1 and 3, respectively.

Probe B = CVS probe B (CVS_B) was connected to a flow splitter with three legs. This probe collected filters for the individual bags for the 3-bag FTPs. The flow for this probe was set at 100 cm/s, with an exception of one set of three FTP tests that was run at a second higher FFV of 130 cm/s. Note that this was the same nominal FFV that was used for bag sampling for probe A.

Probe C = CVS probe C (CVS_C or EC/OC) collected a cumulative PM filter over the entire duration of the 3-bag FTP. The filter media used with this probe was a quartz filter that was utilized for organic carbon (OC) and elemental carbon (EC) characterization using thermal optical analysis (TOA) off-line analysis methods. This measurement is typically referred to as the EC/OC measurement using the TOA analysis method. All EC/OC analysis were performed by an outside certified laboratory. EC/OC samples were collected for a subset of tests. CVS_C was set at a nominal flow of 100 cm/s for bag 2, and used the same flow weighting values as probe A for bags 1 and 3.

2.2.2 Partial Flow Dilution

The three main PFD systems used for this testing were AVL, Horiba, and Sierra systems. These were commercially

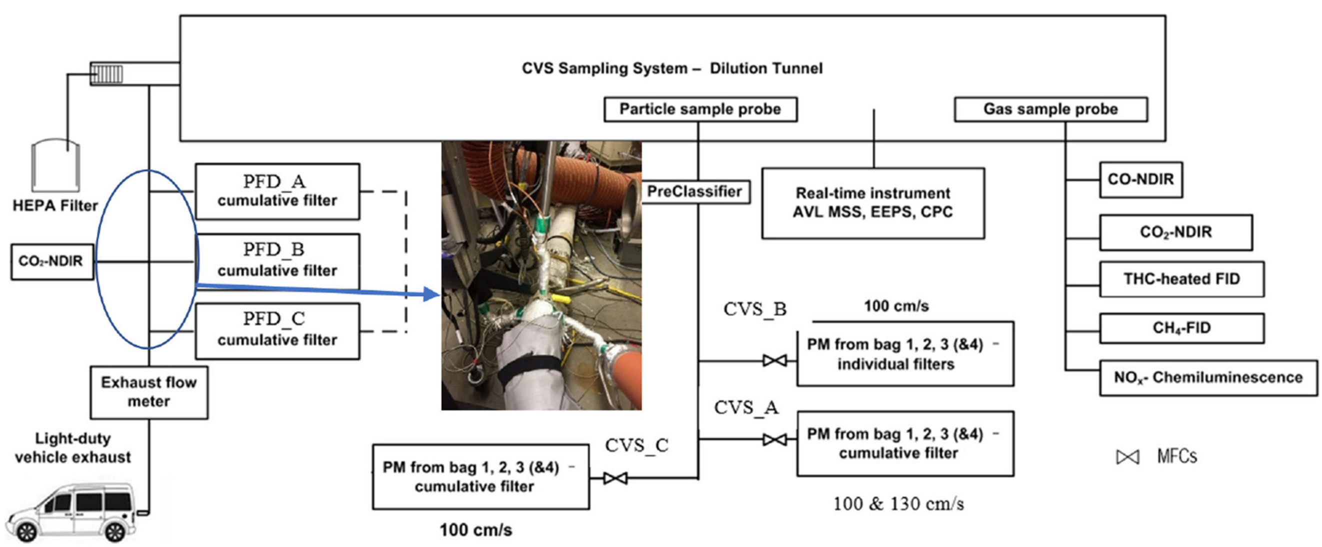

Fig. 1 Schematic diagram of sampling configuration for emission measurements

available PFDs that were on the market at the time of this project. These systems are designed to use a range of different EFMs in conjunction with their proportional PM samplers. The PFDs were all set up to sample from the raw exhaust at a point before it enters the dilution tunnel, as indicated in the test configuration graphic provided in Fig. 1. The flow proportionality was maintained by integrating the PFDs with a selected EFM that showed good performance in preliminary testing. PM filter weighing utilized the same practices as for the CVS system described earlier, with the flow rates for bags 1 and 3 being 43 and 57%, respectively, of the nominal bag 2 flow rate.

The partial flow systems were originally designed to operate at a maximum of 100 cm/s FFV. During this study, the PFDs were also tested at a higher FFV of 130 cm/s. Although the PFDs were not designed for these higher FFVs, it was expected they would perform satisfactory at the higher flow.

2.2.3 Exhaust Flow Measurement

Three exhaust flow measurement principles were evaluated in this project: ultrasonic, venturi, and a differential pressure annubar. AVL at the time of testing recommended the Sick Carflow150 (2.5 inches) EFM system (ultrasonic), Horiba offers their own EFM called the EXFM-ONE (ultrasonic), and Sierra offers a venturi meter called the ExhaustTrak. These EFMs are denoted EFM A–C, in no particular order. Each of the PFD manufacturers prefer using their own EFM, but they all agreed that testing with only one EFM would be preferred over all three EFMs being installed at once. Towards the later part of the testing, AVL introduced their new EFM, which is a differential pressure annubar type. AVL offered an integrated EFM, which uses differential pressure for its flow principles. The Sick, Horiba, and Sierra EFMs were used for the main part of this research, while the AVL EFM was used at the end of the study. The EFMS were placed in the raw exhaust prior to the sampling point for the PFDs and prior to the CVS, as shown in Fig. 1.

2.2.4 Dilution Factor

Dilution is used to prevent water condensation for the gravimetric PM sampling method [16–18]. For the CVS, the dilution factor (DF) is the ratio of total average CVS flow divided by the total average exhaust flow. For the PFD, it is the total volume through the filter divided by the extraction flow volume. The CFR requires a minimum dilution of 7 to 1 on a per bag basis. For the CVS, the phase with the lowest DF was bag 1 and for the PFD, it was bag 2. The reason for the different DF minimum phases is a result of the different weighting methods (FFV vs. extraction ratio).

2.2.5 PM Mass Emissions

PM sampling was conducted in compliance with the procedures in 40 CFR 1066 and associated references in 40 CFR Part 1065. Cumulative PM samples were collected over each FTP with flow-weighting MFCs. Total PM mass samples for both the CVS and PFDs were collected using Whatman 47-mm polytetrafluoroethylene (PTFE) filters. The filters were weighed before and after the test with a Part 1065-compliant microbalance in a room with temperature and humidity controls meeting Part 1065 requirements. Buoyancy corrections for barometric pressure differences were also made for the PM filter weights, as stated in 40 CFR Part 1065. The PM mass emission results from the filters were background corrected based on actual tunnel blanks that were collected periodically throughout the study. The tunnel blank values used were based on actual measurements. The background corrections for the CVS probes A and B were 11 μg, which exceeded the CFR limits of 5 μg. A possible reason for the high background correction is because of the contamination from other test vehicles that produced significantly high PM emission. The background corrected values for PFD A–C were 3, 5, and 4 μg, respectively. The tunnel blank values were based on six tunnel blank tests that were conducted over a span of 4 months. Further details regarding the tunnel blank tests are in the supplemental material.

2.3 Experimental Design

A series of three different tests were utilized to evaluate different components of the PFD sampling systems. This included EFM comparison tests, a test to evaluate the sampling proportionality of the three individual PFDs, and then a side-by-side comparison of the three PFDs where vehicle exhaust was sampled in parallel by the PFDs over a series of emission tests. This section describes the details of each of these tests.

2.3.1 EFM Comparisons

The purpose of the main EFM comparison test was to evaluate the accuracy, response, and proportionality of each EFM while operating with one PFD, which in this case was PFD A. The goal behind this test was to characterize the performance of each EFM under typical testing conditions with an in-use GDI vehicle. The factors that could impact EFM operation include cold start operation, and steady-state vs. transient operation. The EFM performance was evaluated based on raw and dilute CO_2 measurements. The raw measurements utilized CO_2 concentrations measured directly from the raw exhaust and the exhaust flow from the EFM as reported by the PFD to determine CO_2 mass emissions. Both the bag and modal CVS dilute CO_2 concentrations along with the CVS total flow were used to determine the dilute CO_2 mass emissions. To have a consistent PFD signal and configuration, a single designated PFD was chosen to evaluate the EFMs. Only one PFD and EFM pair was operating per triplicate LA4 tests. A single LA4 was run to precondition the vehicle prior to running the triplicate LA4s. The LA4s were separated by an approximately 10-min soak between tests. More details of the experimental setup for each of these tests are provided in Table 1.

Some additional tests were also performed to evaluate the calibrations of the EFMs as well as the EFM measurement noise for measuring vehicle exhaust under steady state conditions. These tests are discussed in greater detail in the Supporting Information. The 15+ point calibration check was performed by an outside laboratory on each of the EFMs, covering the following test points of 0, 2, 4, 6, 8, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 scfm, and a few other flow rates for some tests. The EFMs all showed good correlations over the full flow rate range examined in this calibration. The slopes of the regression lines varied from 0.9818 to 1.0027 and all the R^2 were greater than or equal to 0.9999. Some larger differences were seen at lower flow rates, where the EFMs showed differences that ranged from − 5 to 30%. The steady-state vehicle exhaust tests covered speeds from idle to 60 mph (representing exhaust flows from 4 to 60 lpm). For the steady state tests, EFM_A and EFM_B showed similar single standard deviations (1σ) over all the points, with the EFM_B average 1σ (0.37 scfm) being slightly lower than that for EFM_A (0.54 scfm). For EFM_D, the average 1σ was slightly less at 0.75, while EMF_C showed the highest average 1σ of 1.00, and for exhaust flows below 30 scfm, it was 1.35.

2.3.2 PFD Sampling Proportionality Test

PFD sample flow delays and inaccuracies can vary between PFD systems due to varying line lengths, response times, and design differences. PFD sample flow is not directly measured by a PFD, but is typically calculated from the difference of the total flow over the filter and the dilution flow. As the PFDs receive current signals for the flow measurements from EFM, the sample flow rates are adjusted according to the set extraction ratio. The purpose of this test was to evaluate PFD delays and possible accuracy differences between the PFD units while utilizing a common EFM over transient driving conditions. This allowed for an evaluation of PFD performance in terms of proportionality and flow rates to determine if the PFD systems were operating as designed before conducting the main side-by-side PFD test. One EFM, in this case EFM B, was used in conjunction with each of the PFDs to measure the exhaust flow and provide the signal for PFD proportional sampling for LA4 driving cycle. The inlet sampling port of the PFD was connected to a laminar flow element (LFE) with a HEPA filter instead of the exhaust transfer line. Therefore, the PFDs were sampling particle free test-cell air instead of

Table 1 Test vehicles and PFD settings

	Test #	Vehicle				Prep. cycle	Test cycle	EFM	Phase	PFD_A		PFD_B		PFD_C	
		Year	Model	Engine	California cert.					FFV (cm/s)	*r* (%)	FFV (cm/s)	*r* (%)	FFV (cm/s)	*r* (%)
EFM comparison	1–3	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30	LA 4	LA 4	EFM_A	1	100	0.926	100	0.926	100	0.926
									2	100	2.16	100	2.16	100	2.16
	1–3	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30	LA 4	LA 4	EFM_B	1	100	0.926	100	0.926	100	0.926
									2	100	2.16	100	2.16	100	2.16
	1–3	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30	LA 4	LA 4	EFM_C	1	100	0.926	100	0.926	100	0.926
									2	100	2.16	100	2.16	100	2.16
PFD comparison	1–6	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30 PC	LA 4	3-bag FTP	EFM_A	1	100	0.926	100	0.926	100	0.926
									2	100	2.16	100	2.16	100	2.16
									3	100	1.22	100	1.22	100	1.22
	7–9	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30 PC	LA 4	3-bag FTP	EFM_A	1	130	1.18	130	1.18	100	0.926
									2	130	2.74	130	2.74	100	2.16
									3	130	1.56	130	1.56	100	1.22
	1–6	2016	Hyundai sonata	GDI 2.4 L	LEV III SULEV 30	FTP, US06	US06	EFM_A		100	0.669	100	0.669	100	0.669

exhaust while following the LA4 test cycle. The LFE is a NIST traceable, high-quality, fast-responding flow meter with a valid certification. The LFE has a maximum sampling flow rate of 21 SLPM, and for the LA04 driving cycle, measured LFE flow was above this maximum value less than 1% of the time. For this test, the PFDs were configured to have an FFV of 100 cm/s and a DF of 7 at an extraction ratio of 1.48%. Similarly, the CVS was also operated at DF of 7. PM filters were not collected for either the CVS or the PFD. Referring to Fig. 1, the experimental setup for this test for the raw exhaust sampling included the LFE, EFM_A, and then each of the PFDs tested individually in sequence. The raw exhaust CO_2 measurements were not performed during this test. More details of the experimental setup for each of these tests are provided in Table 1.

2.3.3 PFD Side-By-Side Comparisons

Simultaneous measurements were conducted with each of the PFD systems sampling in parallel using one selected EFM. A schematic layout of the test setup is provided in Fig. 1, where EFM_A was used. Table 1 describes the PFD configuration parameters and testing cycles, which included nine repeats of the FTP and six repeats of the US06 test cycle. This provided sufficiently robust comparisons under certification conditions, cold start conditions, and more aggressive driving conditions. Six FTPs were conducted at an FFV of 100 cm/s and three additional FTP tests were conducted at a FFV of 130 cm/s. Although PFD_A and B were operated at the 130 cm/s FFV, PFD_C was not able to operate at a higher FFV with the sampling tube diameter of 0.25-inch OD. It was instead configured to 100 cm/s instead. The six US06s were all conducted at an FFV of 100 cm/s. Prior to these official tests, preliminary tests were conducted to ensure the PFDs were working according to specifications and to set up the appropriate dilution conditions for the testing. Performance checks included leak checks, calibrations, and that the exhaust flow rate signals from the EFM and PFDs matched.

3 Results and Discussions

3.1 PFD and EFM Performance Checks

3.1.1 EFM Comparisons

To help evaluate the accuracy of the EFM, CO_2 emissions rates obtained using the product of exhaust flow rate from the EFM and raw exhaust CO_2 concentrations were compared to the dilute CVS CO_2 emission rates from dilute bag over the LA4 cycles. The results are shown in Table 2 for the bags 1 and 2 averages for each of EFMs. The breakdown of the CO_2 emission rates and percentage differences between the EFM, CVS bag, and CVS modal CO_2 emission rates are provided in the Supplemental Section. Overall, the raw exhaust and CVS CO_2 emission rates were in relatively good agreement with a range from − 1.2 to 2.0% for bag 1 and from − 0.5 to 5.3% for bag 2. The differences between the raw exhaust and CVS CO_2 emissions rates were 2.0% or less for all EFM/test configurations, except for the bag 2 comparisons for EFM_A and B. The slightly higher bias for PFD_A and PFD_B for bag 2 could be attributed to the lower exhaust flow rates for bag 2 compared to bag 1. In particular, more detailed analysis of the differences on a second by second bases suggested that the relative differences were close to zero under conditions where the exhaust flow was greater than 20 scfm, whereas as the percentage difference increased for exhaust flows below 15 scfm. It should be noted that the stability of the extraction ratios for the different EFMs was also evaluated during these tests. These results are presented in the Supplemental Sections. EFM_A and EFM_B had relatively similar performances, but only one could be selected for the rest of this study. Coupling the low-percentage CO_2 emission rates differences together with the low variability for EFM_A, it was decided to use EFM_A for the PFD comparison tests.

Table 2 Average percent differences between raw exhaust EFM/PFD and dilute bag CVS CO_2 emission rates

EFM	Bag 1 (%)	Bag 1 (%)
A	− 1.2 ± 0.3	3.5 ± 0.1
B	2.0 ± 0.9	5.3 ± 0.6
C	1.7 ± 0.5	− 0.5 ± 0.8

3.1.2 PFD Sampling Proportionality Test

The purpose of this test was to evaluate the accuracy and proportionality of the PFD calculated sample flow system. Errors in the sample flow calculation (related to factors such as flow delays and flow accuracy) can lead to proportionality differences between the PFD units while utilizing a common EFM. Comparisons were performed over a hot start LA4, with a single test for each PFD. A correlation analysis was performed to evaluate the comparisons between the PFD and LFE sample flows. A summary of the sample flow correlations is provided in Table 3. The correlation shows slopes of 1.0034, 1.0358, and 0.9711 for PFD_A–C, respectively, and R^2 values of 0.995, 0.992, and 0.985 for PFD_A–C, respectively. When the regression is forced through zero, the slopes change slightly to 1.011, 1.006, and 0.9496, respectively, with similar R^2 values. There were a few outlier points in the correlations, which are shown in detail in the Supplemental Material. The outlier points occurred during the phase transition between phase 1 and 2 of the LA4 into the cycle. For these outlier points, the LFE reported typical values, while the PFD flow values were low. This also may be caused by delays in the PFD flow control response to the cycle phase

Table 3 Correlation results between the PFD and LFE sample flow rates for the PFD proportionality tests

Sample	LA4	EFM	PFD			Correlation			
			FFV	DF	Unit	SEE	R^2	Slope	Int.
1	Hot 2-bag	B	100	7	A	0.30	0.995	1.003	0.067
1	Hot 2-bag	B	100	7	B	0.38	0.992	1.036	− 0.250
1	Hot 2-bag	B	100	7	C	0.53	0.985	0.971	− 0.200

change signal from the data acquisition system. Similar correlation R^2 values were also found between the LFE sample flow and exhaust flows reported by the PFD, which are shown in further detail in the Supplemental Section. This is to confirm the accuracy of the proportionality and response relative to the exhaust flow.

These results are comparable to those seen in the previous CRC E-66 project. In that study, a number of PFD systems, including AVL-SPC, Cummins-AEI, Horiba-MLDT, Sensor-MPS, and a Sierra-BG3, were evaluated using a heavy-duty engine on an engine dynamometer. The PFDs achieved sampling proportional to the exhaust flow with a response time of 200 ms or faster, which was sufficient to run the PFDs in real time under transient engine operation [10]. This was considerably improved from an earlier 2002 study conducted at the Southwest Research Institute (SwRI), where the PFD response times were found to be too slow to provide for adequate sampling under transient engine operating conditions [2]. Foote et al. tested two PFDs with gasoline vehicles and also found both units were able to meet the proportionality requirements for traditional powertrains. Although they did find issues in proportionality for hybrid electric vehicle (HEV) powertrains that have zero flow conditions as part of their operation [1].

3.2 Side-By-Side PFD Emission Test Results

3.2.1 PFD Performance for the Side-By-Side Emission Tests

Table 4 shows the relative percent difference for PFD_B and PFD_C compared to PFD_A for the exhaust, sample, and total flows. The extraction ratio (*r*) and filter flow rate (Gtotal) had the lowest relative error, with differences being typically around 0.1% and differences for all tests being less than 0.5%. The exhaust flow (Gexh) and sample flow (Gprobe) differences for PFD_B and PFD_C relative to PFD_A varied between − 1.1 and 1.8%. Note the apparent Gexh from the PFD is determined by interpreting output signal of the EFM, which in this case was EFM_A. It is assumed that the exhaust flow (Gexh) differences may be a result of input signal processing errors by the PFDs or slight differences in calibration.

While the biases for the exhaust flow and sample flow among PFDs are important to characterize, biases in these parameters will only have an impact on the PM emission rate if they impact the extraction ratio. It is assumed that the bias of Gexh is due to systematic input signal processing error, which leads to another systematic bias of Gprobe. If our speculation is correct, then these systematic biases for Gexh and Gprobe will cancel out when determining extraction ratio (*r*) and final PM emission rate. In the comparisons here, the differences between the PFDs for exhaust flow and sample flow are generally biased in the same direction for PFD_B and PFD_C relative to PFD_A. For example, both the exhaust flow and sample flow rates are biased high by 1.1% for PFD_C relative to PFD_A. Table 4 shows that extraction ratio difference ranged from 0.0 to 0.4% independent from the systematic bias of Gexh and Gprobe, which confirms our assumption. Overall, the results of this test suggest that there should not be a bias in PM emission rates between the different PFDs due to sampling proportionality considerations.

The correlation between the exhaust flow and the sample flow was also evaluated for each of the PFDs. The correlation results between the PFD sample flow and the exhaust flow are presented in Table 5 for the cumulative data for the FTP tests

Table 4 Comparison of PFD measurements to PFD A by test and phase (FFV = 100, *n* = 6)

Test	PFD	*r*	%Gexh	%Gprobe	%Gtotal
FTP Ph1	A	–	–	–	–
FTP Ph1	B	0.1	0.0	0.2	0.01
FTP Ph1	C	0.1	*0.7*	*0.8*	− 0.01
FTP Ph2	A	–	–	–	–
FTP Ph2	B	0.1	*0.2*	0.3	0.01
FTP Ph2	C	0.0	*1.1*	*1.1*	− 0.01
FTP Ph3	A	–	–	–	–
FTP Ph3	B	0.1	1.7	*1.8*	0.02
FTP Ph3	C	0.0	*− 1.1*	*− 1.1*	− 0.01
US06	A	–	–	–	–
US06	B	0.0	− 0.5	− 0.4	0.0
US06	C	0.4	− 0.1	0.3	0.0

%r percent difference for the extraction ratio, *%Gexh* percent difference for the average exhaust flow, *%Gprobe* percent differences for the average sample flow rate by probe, *%Gtotal* percent difference for the average filter flow or total dilute plus sample flow

Gexh was measured by one system and reported by each of the PFD suppliers where Gprobe and Gtotal was measured separately for each of the three systems. The italicized data indicates the high and low percentages. All comparisons were based on PFD A

Table 5 Comparison of PFD measurements to PFD A by test and phase (FFV = 100, *n* = 6)

Test	Statistic	PFD A		PFD B		PFD C		Overall	
		Ave	95% Cl	Ave	95% Cl	Ave	95% Cl	Ave	95% Cl
FFV_100 *n* = 6	R^2	0.998	0.002	0.999	0.001	0.998	0.003	0.998	0.002
	SEE	0.010	0.014	0.006	0.003	0.005	0.028	0.007	0.014
	SEE/Gexh_mean	0.04%	0.04%	0.03%	0.05%	0.01%	0.06%	0.03%	0.05%
	SEE/Gexh_max	0.01%	0.01%	0.01%	0.01%	0.00%	0.01%	0.01%	0.01%
	b	0.0003	0.0017	0.0002	0.0009	0.0007	0.0036	0.0004	0.0017
	b/Gp_max	0.02%	0.10%	0.03%	0.12%	0.04%	0.21%	0.03%	0.11%
FFV_130 *n* = 3[1]	R^2	0.998	0.001	0.997	0.004	0.998	0.002	0.998	0.002
	SEE	0.010	0.007	0.012	0.013	0.000	0.000	0.007	0.014
	SEE/Gexh_mean	0.06%	0.08%	0.08%	0.13%	0.00%	0.00%	0.05%	0.09%
	SEE/Gexh_max	0.01%	0.03%	0.02%	0.04%	0.00%	0.00%	0.01%	0.03%
	b	0.0001	0.0005	0.0006	0.0011	0.0000	0.0008	0.0002	0.0008
	b/Gp_max	0.01%	0.04%	0.05%	0.10%	0.00%	0.09%	0.02%	0.07%

[1] %r is the percent difference for the extraction ratio, %Gexh is the percent difference for the average exhaust flow, %Gprobe is the percent differences for the average sample flow rate by probe, and %Gtotal is the percent difference for the average filter flow or total dilute plus sample flow. Gexh was measured by one system and reported by each of the PFD suppliers where Gprobe and Gtotal were measured separately for each of the three systems. All comparisons were based on PFD A.

[2] standard error estimate (SEE) is a measure of data spread about the correlation between exhaust flow and sample flow, *Gexh_mean* the average exhaust flow, *Gexh_max* maximum exhaust flow, *b* intercept for the correlation between sample flow and exhaust flow, *Gp_max* maximum sample flow

Averages (ave) and 95% confidence intervals (95% CI) are based on averages of FTP Ph1, Ph2, Ph3, and US06 test cycles. Overall ave. and 95% CI is based on the average results of PFD A–C listed in Table 5. Data includes the U06 outlier test discussed later in the report (note all the US06 tests were valid from a PFD operational perspective so the outlier was a result of other influences).

separated by FFV. The comparisons show high correlations between the sample and exhaust flow, with all three PFDs having R^2 values > 0.99 for both the FTP and US06 with a 95% confidence interval (95% CI) of 0.002. For this correlation, the standard error estimate (SEE) is the measurement of the data spread between the exhaust and sample flows divided by the average exhaust flow (Gexh_mean). The correlation intercept (*b*) divided by the maximum sample flow (Gp_max) represents the quality of the PFD proportionality. The quality of the PFD proportionalities (as represented by SEE/Gexh_mean and *b*/Gp_max) were very similar for all tests and all FFVs utilized. All PFDs showed an average SEE/Gexh_mean and *b*/Bp_max of 0.04 and 0.03%, respectively, for the 100 cm/s FFV tests. The FTP tests with an FFV of 130 cm/s had similar SEE/Gexh_mean and *b*/Bp_max values.

Although all PFDs were operating consistently and with highly correlated proportionality flow, there was some data that showed a poor correlation at high exhaust flow rates for PFD_C for the US06 cycle. The observation did not impact the overall proportionality statistics or its performance, so this may just be an observation for future consideration. Deeper analysis shows the pressure at FFV of 50-slpm sample flows reduced from 98 to 67 kPa, which resulted in a change in FFV from 100 to 132 cm/s. One observation is that at sample flows of 50 slpm, the low filter face pressure could be a result of a high-pressure drop from a 0.15-inch ID sample probe. The FTP tests did not show the same issue due to the lower peak sample flow rates.

3.2.2 PM Emission Rates for PFD Side-By-Side Tests

The PFD and CVS PM mass emission rates are presented in Fig. 2 for each FTP test and in Fig. 3 for each US06 test. The PM emission rates presented are based on current 40 CFR Part 1066 calculations for PFDs and CVSs for sample weighting onto a single filter. Correction factors for tunnel blanks, CVS flow corrections, and raw sample flow corrections were also included. Additionally, the CVS flow (Vmix) was corrected for raw exhaust removed prior to the CVS by the PFDs. In general, the combined flow corrections represented more than 5%, but less than 10% of the Vmix.

The PM emission rates show significant test-to-test variability for both the FTP and US06 tests. The FTP emissions varied from 1.15 to 1.84 mg/mile for CVS_A, with all PM samplers generally showing similar trends for a given test. The average FTP PM emission rate varied for different samplers from 1.21 to 1.49 mg/mile at FFV = 100 cm/s, from 1.02 to 1.29 mg/mile at FFV = 130 cm/s, and from 1.34 to 1.63 mg/mile for the US06 tests. Note PFD_C did not operate at the higher FFVs, so its data may not be as comparable to the other PFDs at FFV = 130 cm/s. The US06 PM emission rates for

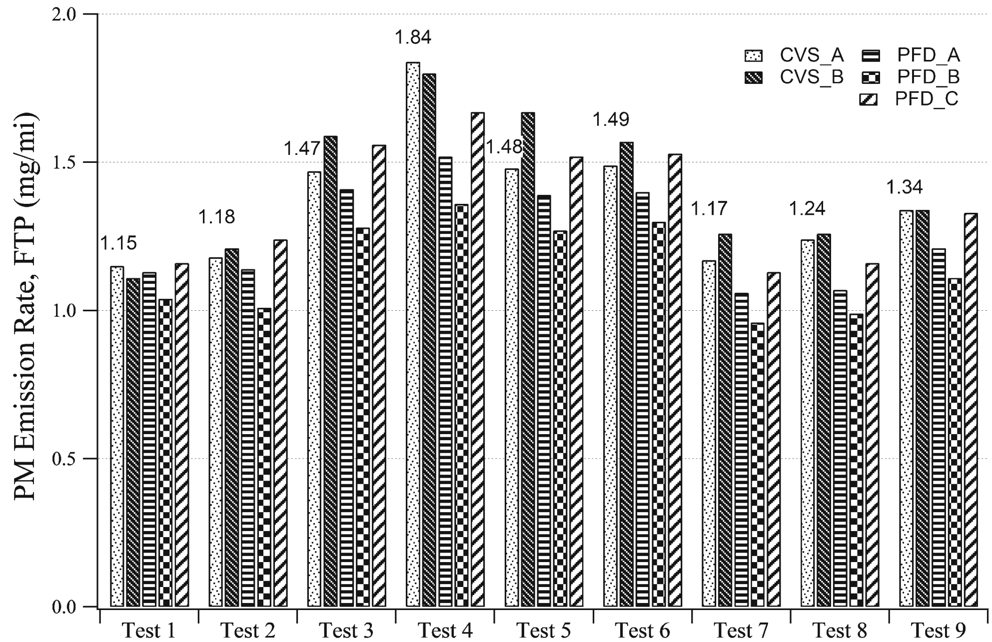

Fig. 2 PM emission rates for PFD and CVS measurements over the FTP. CVS_A is the CVS combined flow weighted PM sampler and CVS_B is the by phase PM sampler. The CVS flow weighting was performed by varying the FFV. The FFV for CVS_B was 100 cm/s, and the FFV for CVS_A was nominally 100 cm/s for bag 2 with appropriate flow weighing for the other bags. All the PFD samplers utilized a single filter with sample flow weighting (i.e., the sample fraction was varied by phase). PFD A and PFD B utilized nominal FFVs of 100 cm/s for the first six FTPs and 130 cm/s for the final three FTPs. PFD_C was operated at 100 FFV for all tests because the system could not maintain flow stability at 130 FFV.

CVS_A varied from 1.64 to 0.40 mg/mile for tests #2 through #6, but showed a much higher emission rate of 4.35 mg/mi for test #1. For the US06 test sequence, the first test was an outlier both in terms of the observed PM mass emission rates as well as in comparing the bias between the CVS and the three PFDs, which impacted the overall mean *t* tests analysis. The average FTP and US06 PM emission rates for each of the individual samplers for the different tests are presented in Fig. 4, where the error bars represent one standard deviation. The error bars between the FTP and US06 tests were similar. Since the first US06 test affected the mean significantly, it is a statistical outlier and may have been impacted by contamination. The first US06 data point was omitted from the analysis in Fig. 4 and Table 6 of this section.

The first US06 test value was more than two times higher than the average of the other test points and was three times higher than the standard deviation of tests two through six (i.e., a statistical outlier from the mean). High PM emissions for the first US06 test after the vehicle has not been tested or ran over a long span of time have been seen in other studies

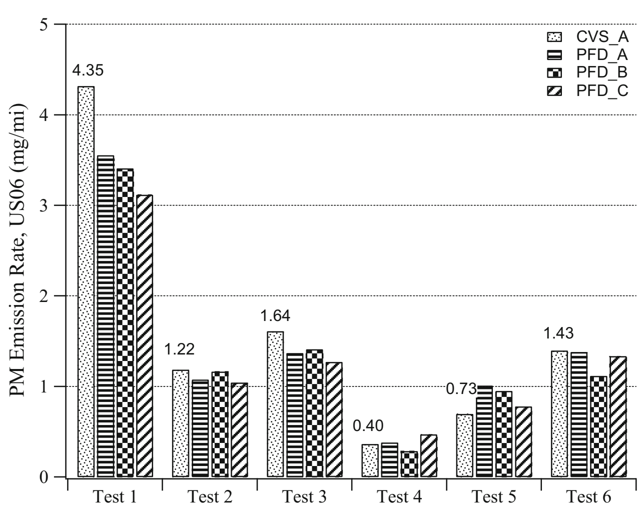

Fig. 3 PM emission rates for PFD and CVS Measurements over the US06

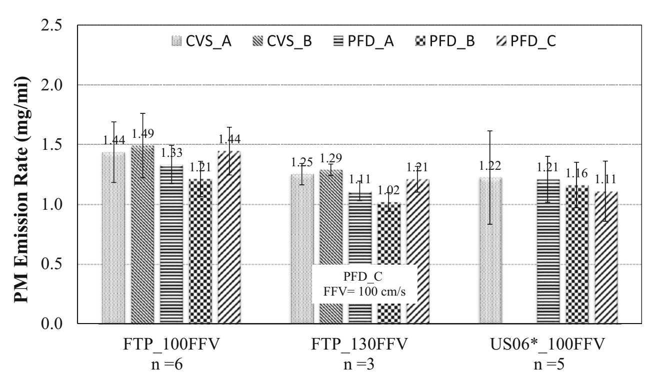

Fig. 4 Average PM emission rates for PFDs and CVS Measurements. CVS_A is the CVS combined flow weighted PM sampler and CVS_B is the by phase PM sampler. The CVS flow weighting was performed by varying FFV for each phase of the FTP phases. All the PFD samplers utilized a single filter with sample flow weighting (i.e., the sample fraction was varied by phase). PFD_C was operated at 100 FFV for all tests because the system had an issue with flow stability at 130 FFV.

Table 6 PFDs comparison for all test cycles at FFV = 100 cm/s and FFV = 130 cm/s

Description	Sample	FFV	CVS_A	CVS_B	PFD_A	PFD_B	PFD_C
FTP - ave. (mg/mile)	4	100	1.44	1.49	1.33	1.21	1.44
FTP - % dif	4	100	–	3.8%	− 7.2%	− 15.6%	0.6%
FTP *p* value	4	100	–	0.188%	*0.069*	*0.008*	0.818
FTP - ave. (mg/mi)	3	130	1.25	1.29	1.11	1.02	1.21
FTP - % dif	3	130	–	2.9%	− 11.2%	− 18.6%	− 3.4%
FTP *p* value	3	130	–	0.353	*0.016*	*0.003*	0.160
FTP - ave. (mg/mile)	9	varies	1.37	1.42	1.26	1.15	1.37
FTP - % dif	9	varies	–	3.5%	− 8.4%	− 16.5%	− 0.6%
FTP *p* value	9	varies	–	0.088	*0.005*	*0.000*	0.759
US06 - ave. (mg/mile	5	100	1.05	–	1.04	0.99	0.98
US06 - % dif	5	100	–	–	− 0.7%	− 6.2%	− 6.7%
US06 - *p* value	5	100	–	–	0.94	0.52	0.44

p - values calculated from the paired two-tail *t* test. The italicized data indicates the low p-value.

[19]. Xue et al. reported greater sensitivity of gravimetric method to more aggressive US06 cycle than FTP cycle [15]. It is speculated the PM mass on this first test may have been influenced by PM desorption from the tailpipe and transfer line. The fact that CVS PM showed the highest PM emission among all of the PM samplers suggests that there was desorption from the CVS wall as well.

3.2.3 PFD Comparisons

The average, relative percentage difference, and paired two-tailed *t* test statistics for the different PM samplers for the PFD side-by-side tests for both the FTP and US06 tests are presented in Table 6, where CVS_A was used as the basis for all the comparisons. The two CVS PM probes (A and B) both agreed well for the FFV = 100 cm/s (within 3.8%) and FFV = 130 cm/s tests (within 2.9%) and did not show statistically significant differences. The lack of differences in averages for the CVS PM measurements suggests the single filter combined method is in good agreement with the individual filter method by phase [15].

The PFD probes showed mixed comparisons relative to the CVS_A probe. For the FTP tests, for the pooled results, two of the PFDs reported statistically significant lower emissions that CVS_A, while PFD_C showed no difference with CVS_A. The differences on a relative basis varied from − 0.6 to − 16.5% depending on the PFD. Additional analyses comparing the PFDs with each other also showed that the differences in emission rates for the different PFDs were also statistically significant (see Supporting Information). There were not, however, any statistically significant differences in the CVS to PFD differences for the FTP tests run with the FFVs for PFD-A and PFD_B at the 100 cm/s compared to the 130 cm/s. The US06 results showed different trends, with no statistically significant differences between any of the PFDs and CVS_A, and relative differences ranging from − 0.7 to − 6.7%. It is possible that the better correlation over the US06 can be attributed to exhaust flow rates that were more typically above 20 scfm for the US06 cycle, which is where the optimal performance from the EFMs was found. While the differences for the FTP ranged up to 16% on a relatively basis, on an absolute basis, the emissions differences ranged from 0.00 to 0.22 mg/mile, which represents only up to 22% of the upcoming California LEV III standard of 1 mg/mile. Similarly, for the US06 cycle, the absolute differences were within 0.07 mg/mile for all the PFDs.

The results can also be evaluated in terms of the tunnel blank levels for comparison. As discussed above, the background corrections for the CVS probes A and B were 11 μg, while those for PFD A–C were 3, 5, and 4 μg, respectively. For comparison, the 11-μg tunnel blank level for the CVS is the equivalent of approximately 0.09 mg/mi, while the tunnel blanks for PFD A–C were equivalent to approximately 0.02, 0.03, and 0.02 mg/mi, respectively. So, the differences between the PFDs and the CVS were on the order of 1 to 2 times the tunnel blank levels.

The results of the PFD to CVS evaluation can be compared to those of previous studies. Using a higher PM source vehicle, with an FTP emission rate of ~ 2.0 mg/mi, Xue et al. [15] showed a low relative error rate of − 2.7 and − 5.9% between mean emissions for a PFD (DF = 5 FFV = 150) and a CVS system. Foote et al. compared two PFDs with CVS PM emission measurements for two gasoline vehicles with a range of PM emissions from 0.1 to 10.0 mg/mile [1]. The correlations between the CVS and the two PFD PM emissions had slopes of 1.03 and 0.74, respectively, indicating good measurement accuracy for one of the PFD systems, while the other PFD showed a negative bias relative to the CVS. For tests conditions producing PM emission rates ranging from 0 to 20 mg/mile, Maricq et al. found a slope of 1.03 ± 0.03 to 1.04 ± 0.03 for the regression analyses between a CVS and an AVL Smart Sampler SPC478. For PM emission rates below 3 mg/mile, the slopes declined to 0.92 ± 0.12 to 0.81 ± 0.18. The results for the lower PM emission rates, which are closer to the weighing uncertainty, are comparable to the results from the present study. PM mass emission rate comparisons for PFDs as part of the E-66 program showed more mixed results depending on the PM emission level [10]. At PM levels comparable to 10% of the 2007 PM standard for on-highway heavy-duty engines, some PFDs showed PM emissions that were not statistically different from those measured by the CVS system, while other systems showed results that ranged from 50 to 75% lower to as much as 3 times higher. At higher PM levels comparable to 80% of the 2007 PM standard for on-highway heavy-duty engines results were more varied, with some PFD/test condition combinations providing PM emissions within 10–20% of the CVS. However, many other PFD test condition combinations showed differences with the CVS ranging from 30% and up to 2.5 times higher. Although some PFDs showed PM emissions that were not statistically different from those measured by the CVS system, other systems showed results that ranged from 50 to 75% lower to as much as 3 times higher.

4 Summary/Conclusions

As progressively more stringent PM standards are being put in place for LDVs, there has been an increased emphasis on evaluating and improving the accuracy of PM measurements at low concentrations. For this study, three commercially available PFDs were compared, both unit-to-unit and against a CVS tunnel, particularly with regard to their ability to provide reproducible measurements at very low PM emission levels. The comparisons included an EFM comparison and calibration check, a PFD sample proportionality evaluation, and a side-by-side comparison of PFDs for FTP and US06 emission tests.

EFM Comparisons An evaluation of CO_2 emissions determined from EFM calculations and the CVS showed that differences between the EFM and CVS CO_2 emissions rates were 2.0% or less for all EFM/test configurations, except for some bag 2 comparisons.

PFD Proportionally Checks All the PFDs showed very good control of proportionality, easily meeting the 40 CFR Part 1066 and 1065 requirements for all tests performed. The biases in the PFD setup were generally within 0.1% for configured parameters, with the highest difference being 0.4%. Differences in exhaust flow and sample flow were larger at around 1%, but the biases were generally in the same direction so that it did not have a significant impact on the extraction ratio, which would be the main contribution to bias in the PM emission rates.

Emissions Results The side-by-side PFD emission test comparisons showed different results depending on the PFD and the test cycle. Comparisons between the PFDs and CVS PM emission rates had relative differences between − 16.5 and − 0.6% for the FTP, with an average of − 8.5%. Smaller differences between PM emission rates for the PFDs and the CVS were found for the US06, ranging from − 6.7 to − 0.7%. The larger errors for the PM mass emissions, as compared to the EFM and proportionality checks could be due to greater complexities of the PM measurement itself, including weighing precision and tunnel blanks/contamination and related storage and release effects. The lack of a cold start in the US06 test may account for the smaller errors with US06. Another possible reason for the better correlation over the US06 can be attributed to exhaust flow rates that were more typically above 20 scfm for the US06 cycle, which is where the optimal performance from the EFMs was found.

The results of this program show that commercial PFDs show good promise in meeting LEV III/Tier 3 PM emission measurement requirements at PM emissions levels near 1–3 mg/mile. PFD technology has improved considerably over the past two decades and is now fully capable of meeting proportionality requirements over a full range of transient conditions. One of the advantages of using PFDs at emissions levels of 1 mg/mile or lower is that they have the potential to reduce the impacts of background contamination, which can be significant at such low emission levels. Differences between PFD and CVS emission rates are currently on the order of 1 to 2 times tunnel blank levels, representing less than ~ 20% of the most stringent future 1 mg/mi LEV III standard. It is suggested that further research be continued to better understand the differences between CVS and PFDs in terms of factors such as tunnel contamination, the dynamics of the proportional sampling, and exhaust flow measurement in measuring transient emissions under a range of different conditions, and other differences in operating parameters, such as residence time, dilution ratio, and dilution air temperature. This could include the testing of greater numbers of vehicles or over a wider range of driving conditions. Solid particle number measurement, which minimizes tunnel blank effects, could also be useful in comparing PFD and CVS measurement. Overall, it is expected that the role of PFDs in measuring progressively lower emission levels will continue to expand, and that PFD technology will be a key element in meeting future emission measurement challenges.

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Compliance with Ethical Standards

The authors declare that they have no competing interests.

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