

**CRC Report No. E-99-2**

**Very Low PM Mass Measurements  
Phase 2: Evaluation of Partial Flow  
Dilution**

**Executive Summary**

**August, 2017**



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5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022**

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**Very Low PM Mass Measurements Phase 2:**  
**Evaluation of Partial Flow Dilution**

**Prepared for:**

**Dr. Christopher J. Tennant**  
**Coordinating Research Council Inc.**  
**5755 North Point Parkway, Suite 265**  
**Alpharetta, GA 30022**  
**(678) 795-0506**

**August 2017**

Dr. Kent C. Johnson<sup>1</sup> PI  
Dr. Heejung Jung<sup>1</sup> Co-PI  
Dr. Thomas D. Durbin<sup>1</sup> Co-PI  
Dr. Georgios Karavalakis<sup>1</sup>  
Dr. Wayne Miller<sup>1</sup>  
Mr. Liem Pham<sup>1</sup>  
Mr. Jiacheng Yang<sup>1</sup>

Dr. David Kittelson<sup>2</sup>

<sup>1</sup>University of California  
CE-CERT  
Riverside, CA 92521  
951-781-5799  
951-781-5790 (fax)

<sup>2</sup>University of Minnesota

## **Acknowledgments**

The authors thank the following organizations and individuals for their valuable contributions to this project.

We acknowledge funding from the Coordinating Research Council under the E-99-2 project.

We acknowledge Mr. Mark Villela, Mr. Daniel Gomez, Mr. Kurt Bumiller, and Mr. Edward O'Neil of the University of California, Riverside for their contributions in conducting the emissions testing for this program. We acknowledge Mrs. Lauren Aycock and Mrs. Grace Johnson for their contributions in filter weighing.

## Executive Summary

Present motor vehicle particulate matter (PM) emissions measurement regulations (Code of Federal Regulations [CFR] 40, Parts 1065 and 1066) require gravimetric determination of PM collected onto filter media. There have been discussions about whether current sampling and measurement practices are sufficiently accurate in quantifying PM at the upcoming 3 mg/mi standards, and even more so at the 1 mg/mi PM emissions standards for low-emission vehicle (LEV) III light-duty vehicles. Although PM mass measurement methodologies were improved considerably with the application of 40 CFR Part 1065 to the 2007 PM standards for heavy-duty engines, there is a need to improve the understanding of and the confidence in mass measurements for light-duty vehicles given the potential for significant impact on the automotive industry.

CRC's E-99 Phase 1 project was launched to investigate long-standing questions about the measurement of particulate matter (PM<sub>2.5</sub>) emissions from motor vehicle exhaust at very low levels. E-99 phase 1 evaluated the impacts of increasing filter face velocity (FFV), decreasing dilution factor (DF), and collecting cumulative filters on PM filter measurements. Two of these, increased FFV and single filter, have been included in EPA Part 1066 regulations. The resulting increase in signal to noise of filter weighing eases concerns about measurement variability at 3 mg/mi; however, these concerns remain at 1 mg/mi. The purpose of E-99 Phase 2 (E-99-2) is to evaluate commercially available partial flow dilution (PFD) devices, particularly in regard to their equivalency with the standard CVS tunnel method and ability to provide reproducible measurements at low PM emission levels.

This project is designed to address a number of open questions about the application of PFDs for light duty vehicles (LDV) exhaust emissions testing, including:

- whether partial flow units show equivalency to full flow constant volume sampling (CVS),
- what the noise sources for PFD versus CVS sampling are,
- what is needed to “condition” or “manage contamination” for PFD and CVS sampling systems,
- how sensitive PFD performance is to exhaust flow measurement,
- what improvements can provide more efficient and accurate partial flow system performance in light-duty chassis dynamometer testing at Tier 3 PM standard levels, and

To answer these questions, a series of tests were conducted with different PFDs and exhaust flow meters (EFMs), with and without vehicle exhaust. Initial tests were conducted to evaluate the accuracy, response, and proportionality of both the EFMs and PFDs. The main PFD comparison was then conducted with one gasoline direct injection vehicle over different combinations of FTP and US06 tests. Additional tests were conducted to evaluate sources of contamination (PM absorption and desorption) to the raw exhaust transfer line and sample system walls for CVS and PFD systems. These tests were performed on three commercially available PFDs (Horiba, Sierra, and AVL) and four EFMs (Sick, Horiba, Sierra, and AVL).

### Approach

There are five main tasks designed to answer the above questions. These are: 1) EFM accuracy, 2) PFD sample flow, 3) EFM evaluation, 4) PFD comparison, and 5) Contamination. The vehicle tests were representative of a moderately low PM emission source of around 1.5 mg/mi for the FTP and US06 test cycles. A summary of the results and conclusions of this study are provided for each task.

### ***Exhaust flow meter accuracy test (Task 1 and 3)***

The EFM accuracy was grouped into two specific tasks Task 1) laboratory confirmation of calibration and Task 3) vehicle exhaust flow measurement. Accredited laboratory evaluations of all four EFMs were conducted over a 15 point linearity calibration from 0 to 100 scfm with a few more points up to the maximum flow (300 scfm). Nine of the linearity points were specifically targeted at low flow to be representative of a typical FTP cycle averaged exhaust flow for light duty vehicles. The vehicle tests were performed at selected steady state and transient conditions. The steady state conditions were designed to evaluate the EFMs measurement noise which could have a significant impact on the partial flow control system. The transient conditions were designed for comparison to a carbon balance based CVS reference method. The summaries of the results are presented below:

- **Flow calibration (full flow range):** 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.
- **Flow calibration (< 15 scfm range):** During low flow operation, all the EFMs showed differences that ranged from -5% to 30%. These relative errors may not be repeatable, so the user of EFMs should be cautioned during low flow operation and engine off conditions (for example: Hybrids).
- **Vehicle exhaust:** The PFD  $CO_2$  mass emissions compared with the CVS  $CO_2$  emission within 2.0% for the LA4 bag-1 and within 5.0% for bag-2. The higher percent difference for bag-2 may be the result of lower average exhaust flow.

### ***PFD sample flow (Task 2)***

PFD sample flow delays and inaccuracies may be different between PFD systems due to varying line lengths, response times, and approaches. Sample flow measurements using PFDs are not typically measured, but calculated by the subtraction of total filter flow and dilution air flow. Biases in sample flow accuracy and delays will directly bias the PM mass comparison between PFDs and the CVS method. This task was designed to quantify any differences.

In general, the findings were very positive. The correlation slope of the PFDs sample flow with a reference flow meter ranged from 1.034 to 0.971, with an  $R^2$  greater than 0.99, and no observed flow delays. Similar  $R^2$  were found when comparing a reference flow meter with the exhaust flow meter. Thus, PFDs appear to calculate sample flow without measurable delay and are relatively accurate (from +3% to -3%).

### ***PFD and CVS comparisons (Task 4)***

For the main PFD comparison, simultaneous testing was conducted with the three PFDs, utilizing one EFM and one CVS system during FTP and US06 driving. Findings regarding PFD performance include:

- **Performance:** All PFDs showed a very good level of proportionality, easily meeting the 1066 and 1065 requirements for all tests performed.
- **PFD comparison FTP:** The relative FTP difference between the PFDs and the CVS varied from -16.5% to -0.6% (n=9). The means were statistically different for two PFDs based on the paired 2-tailed t-test. The difference between each of the PFDs was also around 16%.
- **PFD comparison US06:** The relative US06 difference between the PFDs and the CVS ranged from -6.7% to -0.7% (n=5). None of the mean differences were statistically

significant based on a paired 2-tailed t-test. Differences between each of the PFDs were also around 6%.

- **Tunnel Blanks:** The tunnel blanks for the CVS were higher than the PFDs and exceeded the 5 µg limit allowed by 1066. The high CVS tunnel blanks may suggest tunnel blanks vary with the condition of the transfer line and vehicle exhaust temperature. If 13 µg of filter contamination were assumed to be present for the CVS, this would change the overall FTP comparison from -8.5 to -0.2%.

### ***Contamination (Task 5)***

Sample system wall contamination is a known issue for PM sampling. To evaluate the impacts of contamination and possible differences between the CVS and the PFDs, a series of tests were performed with the tunnel in a “clean” vs. “contaminated” condition. A natural gas burner was utilized to obtain a “clean” tunnel and a high PM emitting vehicle was used as a source of contamination for the tunnel to obtain the “contaminated” condition. Findings regarding the contamination testing include:

- **Soot-loading/Cleaning:** It was hard to contaminate the sample lines for both the CVS and PFD with a 3.0 mg/mi PM vehicle on a thirty minute “soot loading” type of cycle. Ten days of testing, with a 50 mg/mi emitting vehicle, significantly contaminated the sample system. Once contaminated, it took several cycles to clean the sample system where one 20 minute cycle was expected.
- More than 90% of the PM mass removed from the walls was organic carbon with a particle size distribution ranging from 10 - 20 nm.
- **Emission Levels:** There was no quantifiable FTP or US06 PM emission impact resulting from the “contaminated” and/or “clean” sample system states for both the PFD and the CVS samplers while using the 3.0 mg/mi PM vehicle. There was noticeable difference after the 50 mg/mi diesel vehicle where the emissions more than doubled from 0.08 to 0.20 g/mi. One cleaning cycle did not suffice to decrease the emissions for the FTP or US06 test cycles.
- **Tunnel Blanks (TB):** The CVS TB went from 15 µg to 5 µg after one cleaning cycle and after additional cleaning decreased even further to 3 µg. After contamination by the high emitter vehicle, the CVS TB increased back to 16 µg. None of the PFDs show an increase in the TB value over the same contamination interval suggesting PFD contamination may be different than a CVS.

### **Future work**

The E-99 Program revealed several confounding influences for the quantification of vehicle PM emissions that suggest areas for further investigation. This includes understanding test-to-test variability, which still exceed 100% between tests conducted over a 12 month time period, and further investigation of tunnel contamination and tunnel cleaning, where PM and PM-soot impacts appear to range from 10% to 25% of the 1 mg/mi standard under research conditions. The impacts may increase when one considers all the variables relevant to OEM certification testing, but it is generally believed that sampling the PM exhaust closest to the tailpipe will minimize the impact of contamination. To address the impact of contamination, future tests should evaluate sample line contamination with a more detailed comparison between a single PFD and CVS setup with various raw transfer line configurations (line from the tailpipe to the CVS or PFD inlet) and PFD sample location (sample close to the tailpipe or far from the tailpipe).