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Very low particle matter mass measurements from light-duty vehicles

Jian Xue[a], Kent Johnson[a,*], Tom Durbin[a], Robert Russell[a], Liem Pham[a], Wayne Miller[a], Jacob Swanson[b], David Kittelson[c], Heejung Jung[a,*]

[a] Center for Environmental Research and Technology (CE-CERT), Bourns College of Engineering, University of California, Riverside, CA, USA
[b] Minnesota State University, Mankato, USA
[c] University of Minnesota, USA

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ABSTRACT

Recently, there are discussions about whether current sampling and measurement practices for the regulated gravimetric PM measurement are sufficiently accurate in quantifying PM at the proposed 3 and 1 mg/mi emission standards for light-duty vehicles. In this study, a series of modifications were made to the existing gravimetric PM measurement method, aiming to preserve the integrity of the method while increasing the robustness and decreasing the testing variability. The experiments were conducted with a Higher (~2 mg/mile) and a Lower (0.1–0.2 mg/mile) PM Source Vehicle over the Federal Test Procedure (FTP) and US06 cycles, providing PM emissions with various solid/semi-volatile compositions and size distributions. The results showed the suggested modifications, i.e., increased filter face velocities (from 100 to 150 cm/s) and combined filters (single filter vs. 3/4 filters), could increase the collected filter mass without introducing statistically significant differences in the measured PM mass emission rates. No statistically significant improvements were seen in the measurement variability with the Higher PM Source Vehicle. For the Lower PM Source Vehicle; however, the 4-phase cumulative filter showed a statistically significant reduction in PM mass measurement variability, while not impacting the measured PM mass emissions, but these improvements must be weighed against the increased testing costs/time required for the longer test time.

1. Introduction

Present motor vehicle particulate matter (PM) mass emission regulations (Code of Federal Regulations [CFR] Title 40 Parts 1065 and 1066) require gravimetric determination of PM collected onto filter media from a diluted exhaust stream (CFR, 2001,2002). These regulations were put in place to address issues in making PM measurements for the 2007 PM standard for heavy-duty engines (HDEs), when diesel particulate filters were essentially implemented in the U.S (Khale, 2005a, 2005b, 2005; Swanson, Kittelson, & Dikken, 2009).

Reductions to PM mass emission standards are now also being implemented for light-duty vehicles (LDVs). These regulations have been of particular interest since reductions in corporate average fuel economy levels have led to the introduction of gasoline direct injection (GDI) vehicles, which generally have higher PM mass emission rates relative to more traditional port fuel injection (PFI) gasoline vehicles. The PM emission standards for LDVs will be lowered from 10 to 3 mg/mi for the United States Environmental

* Corresponding authors.
E-mail addresses: kjohnson@cert.ucr.edu (K. Johnson), heejung@engr.ucr.edu (H. Jung).

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Protection Agency (EPA) Tier 3 and the California Lower Emission Vehicle (LEV) III standards by 2017, with an additional reduction to 1 mg/mi expected in 2025 as part of the California LEV III requirements (CARB, 2012; USEPA, 2013). While the 2007 changes to the PM measurement methodology considerably improved measurement practices, there is a remaining need to improve the understanding of and confidence in mass measurements for LDVs, given the implementation of these new standards.

Currently, the protocol for light-duty chassis dynamometer testing (CFR Part 1066) refers to the heavy-duty engine testing regulations (CFR Part 1065) for most PM measurement parameters, even though the equipment and methods used to determine PM emissions in light-duty chassis dynamometer laboratories are generally quite different from those used in heavy-duty engine dynamometer laboratories. For example, most heavy-duty laboratories have secondary dilution tunnels to manage the dilution factor (DF), filter face temperature, and condensation for PM measurements, but for LDVs, secondary dilution tunnels are not typically used. The HDV Federal Test Procedure (FTP) is also a single phase test with a single filter, while the LDV FTP test is composed of three phases utilizing one filter per phase along with different weighting factors to determine cycle averaged PM emissions.

Recently, there has been discussion about whether current sampling and measurement practices are sufficiently accurate in quantifying PM at the proposed 3 mg/mi standards, and even more so at the 1 mg/mi PM emissions standards for LEV III LDVs (CFR, 2011, 2012). Studies by Hu et al. (2014) have suggested that the gravimetric method is sufficiently accurate to measure PM emissions at the levels for both the 3 and 1 mg/mile standard. There is uncertainty, however, if these methods can be more widely implemented under the conditions seen for certification testing, and a number of strategies are still being investigated to further improve the understanding of and confidence in mass measurements for LDVs at low levels. Increasing the filter face velocity (FFV) is one of them. Currently, the FFV specified in CFR Part 1065 is up to 140 cm per second (cm/s), which represents approximately 84 l per minute (lpm) through a 47 mm-diameter filter. Increasing FFV has been shown to reduce filter efficiency based on model predictions from the University of Minnesota, but it is unknown what the real filter efficiency will be (see Section S1 in Supporting Information (SI)). Zhang and McMurry (1987, 1991) examined the dependence of the PM collected on a filter on the FFV and found that higher FFVs could minimize sampling artifacts associated with gas phase adsorption, but can also increase volatilization of the PM, although this was for ambient particles that are largely semi-volatile. Similar results were reached in the CRC E-66 study (Khale, 2005a, 2005b, 2005)..

Combining filters is another method to increase the filter mass collected that can be utilized for the LDV FTP test. A single cumulative filter approach as opposed to using one filter per phase was examined by Andersson et al. (2007), but using different filter media of TX40. They found that a relatively low coefficient of variation of 15% could be obtained for exhaust PM levels of ~1 mg/mile using a cumulative filter method. Maricq, M. M., Szente, J., Loos, M., & Vogt., R. (2011) also suggested that use of a single filter can reduce both the magnitude of artifacts and uncertainty.

Lowering the DF, or the ratio of the volumetric flow rate of the dilution air to that of the raw engine/vehicle exhaust, is another strategy to increase the mass collected on a filter. Although it is desirable to reduce DFs, this approach raises the possibility of increasing water condensation and other uncertainties (Hood & Silvis, 1998; Kittelson, Arnold, & Watts, 1999; Maricq, Chase, Podsiadlik, & Vogt, 1999). Other strategies for improving PM mass emission measurements include using more advanced weighing strategies, such as using an automated robotic weighing system, and utilizing real-time or other measurement methods or methodologies (Park, Kittelson, McMurry & P. H, 2003; Swanson & Kittelson, 2008; Bushkuhl, Silvis, Szente, & Maricq, 2013; Xue et al., 2015, 2016, 2017; Quiros & Zhang, 2015; Quiros, Hu et al., 2015; Li et al., 2014).

The goal of this study was to investigate PM sampling methodologies that extend beyond the recommendations of CFR Part 1066 and 1065. The objective was to evaluate how differences in sampling methodology could improve accuracy, reduce variability, and increase the signal-to-noise ratio of the measurement. The modifications investigated were limited to varying FFV and using cumulative filters, with some testing also to examine DF effects. The results provide the most detailed information available to date to characterize the fundamental limitations of the current gravimetric PM method and its application for LDVs. This is becoming increasingly important given the introduction of a wider range of vehicle technologies designed to achieve increased fuel economies that may have a wider range of PM emission rates. This information may also provide value for low level PM mass sampling for ambient or other low PM emitting sources.

2. Experimental section

2.1. Test vehicles, test cycles, and study design

Vehicles were tested over two regulated driving cycles, the FTP cycle and the US06 cycle. The FTP is the primary emission certification test for all LDVs in the U.S., and the cycle to which the 3 mg/mi and 1 mg/mi standards will be applied. The FTP includes 3 phases designed to represent different types of driving. This includes a "cold start" phase 1, which represents operation when the vehicle is first started for the day, a "stabilized phase" 2, which represents driving after the vehicle is warmed up, and "hot start" phase 3, which is a repeat of phase 1 conducted after the engine has been turned off for 10 min. The different phases are then weighted using the factors of 0.43 for the cold start phase, 1.0 for the stabilized phase and 0.57 for the hot start phase to obtain a composite emission rate for the full cycle. The FTP can also be run as a 4 phase test by repeating the phase 2 stabilized driving cycle immediately after phase 3. The 4-bag FTP was introduced in the 1970s, but was subsequently modified to allow 3 phase testing as well. For the 4 phase FTP test, weighting factors of 0.75 are used for phase 1 and phase 2, and 1.0 for phases 3 and 4 to obtain a composite emission rate for the full cycle that is mathematically the same as for the 3-bag FTP, assuming that phase 2 and phase 4 are essentially equivalent. The 3-bag and 4-bag FTPs have been shown to be equivalent with the use of these appropriate weighting factors Danielson (1979). During preliminary testing for this study, we also found that PM emission rates for 3-bag and 4-bag FTPs