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Measuring particulate matter emissions during parked active diesel particulate filter regeneration of heavy-duty diesel trucks

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ABSTRACT

Heavy-duty diesel trucks (HDDTs, $>33,000$ pounds gross vehicle weight rating) are commonly equipped with diesel particulate filters (DPFs) to meet the California model year (MY) 2007 PM emissions standard. Particulate matter (PM) emissions were measured from nine parked active DPF regenerations of two HDDTs, a 2007 and 2010 MY, using a novel ambient-dilution wind tunnel. This work specifically evaluated PM mass emissions during regeneration by measurements from the following instruments: TSI DustTrak DRX 8533, TSI Engine Exhaust Particle Sizer 3090 (EEPS) and TSI Scanning Mobility Particle Sizer 3936L88 (SMPS), filters by gravimetric analysis, and for one test a Dekati Mass Monitor 230-A (DMM). Active regeneration by fuel injection upstream of the DPF began with the Soot Combustion Regime, where PM emissions had a count median diameter (CMD) of >30 nm and some faint gray smoke was observed flowing from the tunnel. During brief moments of the Soot Combustion Regime, the DustTrak DRX reported more than half of the mass was >1 μm. As active regeneration continued, aftertreatment inlet temperature increased to >500 °C, beginning the Fuel Combustion Regime, defined conversely where the CMD of the emissions was <30 nm. Under both regimes, discrepancies were observed between EEPS and SMPS size distributions and improved agreement was attained after performing a post-hoc EEPS correction procedure. The accuracy of the DMM was equivocal; the average DMM emissions rate was within five percent of the gravimetric filter, but the mass distribution was substantially shifted relative to SMPS and EEPS distributions. Uninterrupted parked active regeneration resulted in 13 g PM emissions from the 2007 MY and 1.8 g PM from the 2010 MY based on filter measurements. The PM mass emissions rates, based on measurements from real-time instruments, show that the contribution of Soot Combustion Regime to total regeneration emissions decreased from 75% to 5% between the 2007 and 2010 MY.

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1. Introduction

Diesel particulate matter (PM) emissions from mobile sources are a key regulatory priority for the California Air Resources Board (CARB) and the United States Environmental Protection Agency (U.S. EPA) (US) (EPA, 2002; Lloyd & Cackette, 2001). The PM emission standard for a 2007 model year (MY) or later heavy-duty diesel truck (HDDT, $>$33,000 pounds gross vehicle weight rating) is 0.01 g/bhp-h; other regulated pollutants include carbon monoxide 15.5 g/bhp-h, non-methane hydrocarbons 0.14 g/bhp-h, and nitrogen oxides 0.20 g/bhp-h (nitrogen oxide standard was not required until 2010). Engine operation modifications and exhaust aftertreatment devices such as the diesel particulate filter (DPF) and selective catalytic reduction (SCR) are key approaches to meet these stringent standards.

Periodically, DPFs must be regenerated to remove accumulated particulates such as soot and organic materials. Regeneration is initiated either actively by fuel injection upstream of the DPF or passively during aggressive engine duty cycles generating high exhaust temperatures. During regeneration, large quantities of PM are emitted, mostly as semi-volatile or sulfate materials (Barone et al., 2010; Cauda et al., 2007; Herner et al., 2011; Khalek et al., 2011; Kittelson et al., 2006). However, the scientific community has not reached consensus on the most appropriate sampling method for new-technology vehicle emissions (Khalek et al., 2011; May et al., 2013).

Real-time PM instrumentation has been successfully applied to vehicle emission studies measuring passive DPF regeneration. For example, Khan et al. (2012) compared various portable emissions measurement systems (PEMS) and showed strong correlation (R^2=0.78) between the Dekati Mass Monitor (DMM, 0–1.3 μm) and gravimetric measurements from a calibrated 1065-compliant mobile emissions laboratory. Another successful study, Z.G. Liu et al. (2009), measured particle size distribution (PSD) using the TSI Engine Exhaust Particle Sizer (EEPS, 5.6–560 nm) and applied an effective density function from Maricq & Xu (2004) to calculate PM mass. However to the best of our knowledge, PM emissions have not been reported during parked active DPF regeneration where no useful work is produced by the engine. Many HDDTs persistently operate at light engine loads (e.g. inner-city buses and drayage trucks), do not initiate passive DPF regeneration, and therefore a parked active regeneration is conducted to remove accumulated PM deposits. Furthermore, many in-use HDDTs used for long-haul operation also may require an occasional parked active DPF regeneration. Therefore, the PM emissions during parked active DPF regeneration are expected to be observed from a variety of HDDT applications.

This study presents PM emissions during parked active DPF regenerations of a 2007 and 2010 MY HDDT measured using a novel ambient-dilution wind tunnel. The broad objective of this study is to evaluate PM emissions explicitly during regeneration without any applied engine load under controlled conditions using ambient air. The present objective is to evaluate the performance of the following PM instrumentation when challenged with ambient-diluted regeneration emissions: TSI DustTrak DRX 8533, TSI Engine Exhaust Particle Sizer (EEPS, 3090), TSI Scanning Mobility Particle Sizer (SMPS, 3936L88), and Teflon-coated borosilicate filters with gravimetric analysis. For one regeneration, a Dekati Mass Monitor 230-A was included for direct mass measurements. This work classifies parked active DPF regeneration emissions into two distinct regimes defined by count median diameter (CMD) of the distribution. The characteristics, merits, and limitations of each real-time instrument are discussed.

2. Materials and methods

2.1. Facility

Experimental work was conducted at the California Air Resources Board (CARB) Depot Park Facility located approximately 10 km southeast of downtown Sacramento, CA. Within the Depot Park Facility boundaries, there are several small private roads with sparse traffic and combustion sources. The impacts of transient local source emissions on test results were assumed negligible because no sudden increases in particle number concentration were observed during ambient monitoring and the study location was located greater than 500 m from the nearest public roadway (Zhu et al., 2002). We assume the ambient dilution air was stable over the measurement period and represents a typical urban or suburban background. Although the contribution to measurements is quantified, we did not apply any background correction for our measurements.

2.2. Testing vehicles and setup

Two Kenworth HDDTs were tested in this study; one was outfitted with a 2007 Cummins engine with a diesel oxidation catalyst (DOC) and a DPF (2007 MY), and another a 2010 Cummins engine with a DOC, DPF, and SCR aftertreatment system (2010 MY). Commercial-grade ultralow sulfur diesel fuel ($<$15 ppm sulfur) was used during the testing of these vehicles. Prior to the study, the odometers read 391,000 miles and 18,600 miles for the 2007 and 2010 HDDTs, respectively. Aftertreatment equipment was neither replaced nor ash cleaned within one year of this study.

Figure 1 illustrates the routing of exhaust gases into the ambient-dilution wind tunnel. A circular steel deflection plate was affixed 50 cm downstream of and perpendicular to the exhaust transfer tube to induce rapid mixing. Temperature measurements on horizontal and vertical traverses were made at various distances from initial mixing to ensure the mixture of exhaust gases and ambient air was homogenous at the sampling location (Dwyer, 2013). The ambient-dilution wind tunnel flow used during this study of 9000 ft^3/min (CFM) resulted in a residence time of 7.2 s. A sampling probe facing