

An Evaluation of Particle Size Distributions and Particle Number-Based Reductions from Various PM Emission Control Technologies

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ABSTRACT

For diesel emission control technologies, reduction efficiencies of Particulate Matter (PM) control systems have been traditionally reported based on mass-based criteria. However, particle number-based criteria are now receiving increased attention. In this paper, results of real-time particle size distribution and number based evaluation of the effectiveness of multiple PM control technologies are reported on an HDD engine. An Engine Exhaust Particle Sizer (EEPS) was used for comparative analysis. The technologies that were evaluated included diesel oxidation catalysts (DOC), a DOC with an uncatalyzed wall-flow filter as a continuously regenerating diesel particulate filter (CR-DPF) system, a DOC with a catalytically coated wall-flow filter as a catalyzed CR-DPF (CCR-DPF), and a DOC with a partial filter as a continuously regenerating partial filter (CR-PF). Engine testing was performed using transient Federal Test Protocol (FTP) cycles using both ultra low sulfur diesel (ULSD) and low sulfur diesel (LSD) on a MY2000 Cummins ISM 350ESP test engine. Particle number-based reduction efficiencies were compared with mass-based efficiencies. With ULSD fuel, the CR-DPF and CCR-DPF demonstrated high reduction efficiencies using both mass-based and number-based methods, while the DOC and CR-PF showed higher mass-based reduction efficiencies when compared to number-based efficiencies. With LSD fuel, the DOC and CR-PF showed higher number-based reduction efficiencies when compared to mass-based efficiencies. The CR-DPF and CCR-DPF were highly effective at reducing both nuclei mode particles and accumulation mode particles. The higher number based reductions for DOC and CR-PF with LSD fuel are likely due to the suppression of sulfuric acid nuclei mode

particles, which are present in higher quantities with the engine operating with LSD compared to ULSD.

INTRODUCTION

There have been strong global efforts to reduce emissions of Particulate Matter (PM) from diesel engines, as they are known to be associated with both environmental damage as well as chronic and acute health effects. Of specific concern are diesel nanoparticles (particles less than 50 nm in diameter), which can become entrained in the alveolar regions of the lung, where they may become difficult to remove and can enter the bloodstream [1]. In the United States, emissions regulations are solely based on mass measurements of PM, and not on particle number. While nanoparticles are a major part of the PM emissions based on particle number, they do not significantly contribute to the PM mass. Hence there is increased attention on expanding the scope of regulations to include particle number emissions as well. Upcoming Euro VI regulations for heavy duty diesel engines to be introduced in 2013/2014 will include a particle number limit in addition to a mass limit.

Diesel particles can be characterized as nuclei-mode particles, typically with diameters from 3 to 30 nm, accumulation mode particles, with diameters between 30 to 500 nm and coarse mode particles with diameters greater than 500 nm. On a mass basis, most of the particles present in diesel exhaust are in the accumulation mode, which are formed during the combustion process in the engine. As exhaust gases exit the tailpipe and contact ambient air, sulfuric acid and hydrocarbons become supersaturated and convert from gas to particle to form potentially harmful nuclei-mode nanoparticles.

Emission controls devices range in their effectiveness to control PM emissions from diesel engines. The California Air Resources Board (CARES) verifies retrofit technologies under three distinct classifications based on their ability to control PM emissions. Level I devices which include Diesel Oxidation Catalysts (DOCs) are defined as those that reduce PM by greater than 25%. Level II devices which include partial filters (PFs) reduce PM by greater than 50%. Level III devices include Diesel Particulate Filters (DPFs) which reduce PM by greater than 85% [2]. It should be noted that these regulatory classifications are based only on PM mass based measurement techniques, pointing to the need to characterize the impact of these devices on particle number and size distributions.

Several commonly used emission control technologies are evaluated in this paper. Diesel Oxidation Catalysts (DOC) primarily reduces PM mass by oxidizing soluble hydrocarbons in PM. Diesel Particulate Filters (DPF) reduces both soluble hydrocarbons and soot components of PM. The Partial Filters which employ a DOC upstream of a flow through metallic substrate reduce soluble hydrocarbons and a portion of the soot.

The primary objective of this study was to evaluate the effectiveness of various Level I, Level II, and Level III devices based on their ability to control PM nanoparticles, using similar test methods that were used to verify their performance based on PM mass. As these devices were verified for use used for both low sulfur diesel and ultra-low sulfur diesel fuel, the testing included both fuels. The reductions with number-based methods were compared with those using mass-based methods, and particle size characterization studies were used to explain any differences.

A secondary objective of this paper is to determine the impact of system subcomponents, including a bare DPF, a catalyzed DPF and a partial filter.

METHODS

Various commercially available and development-stage emission control technologies manufactured by Johnson Matthey were evaluated in this study. Experiments were carried out in an engine dynamometer test cell at Southwest Research Institute's Department of Emissions Research and Development in San Antonio, Texas.

TEST ENGINE

A Model Year (MY) 2000 Cummins ISM 350ESP heavy-duty diesel engine was used for this work. [Table 1](#) describes the details of this engine.

Table 1. Test Engine Details

Engine Model	Cummins ISM350ESP
Model Year	2000
Displacement	10.8 Liters
Advertised Rated Power	350 hp@ 1800 rpm
Advertised Peak Torque	1350 ft-lb@1200 rpm
Serial Number	35010881
CPL Number	2608
Engine Family Name	YCEXH0661MAH
Date of Manufacture	June 2000

TEST FUELS

Experiments were conducted using two types of diesel fuel, a low sulfur diesel (LSD) fuel which conformed to CFR Part 40, Part 86.1313-1994, and an ultra low sulfur diesel (ULSD) fuel which conformed to specifications given in CFR 40, Part 86.1313-2007. The properties of the two test fuels are shown in [Table 2](#).

Table 2. Test Fuel Properties

Item	ASTM Method	Specifications	
		LSD Fuel	ULSD Fuel
Cetane No.	D613	47.7	46.5
Distillation Range			
IBP, F	D86	356.2	375
10% point, F	D86	408.0	423
50% point, F	D86	500.2	509
90% point, F	D86	586.2	603
EP, F	D86	646.0	648
Gravity, API	D1298/D4052	36.81	36.1
Total Sulfur, ppm	D2622/D5453	394	9
Hydrocarbon composition			
Aromatics % vol	D1319	28.2	30.6
Olefins %	D1319	2.4	1.8
Flashpoint (min), F	D93	145.9	166
Viscosity, centistokes	D445	2.4	2.6

Table 3. Test Samples

#	Device	Substrate Size (dia X length)	CPSI	DOC PGM (norm - g/ft3)	Filter PGM (norm - g/ft3)	Fuel Tested
1	DOC-ULSD	10.5" X 6"	400	1	-	ULSD
2	DOC-LSD	10.5" X 6"	400	1	-	ULSD, LSD
3	CR-PF-LSD					LSD
	DOC-LSD	10.5" X 6"	400	1	-	
	PF	10.5" X 6"	-	-	0	
4	CR-PF-ULSD					ULSD
	DOC-ULSD	10.5" X 6"	400	1	-	
	PF	10.5" X 6"	-	-	0	
5	CR-DPF					ULSD
	DOC-ULSD	10.5" X 6"	400	1	-	
	DPF	10.5" X 12"	200	-	0	
6	CCR-DPF1					ULSD
	DOC-ULSD	10.5" X 6"	400	1	-	
	CSF1	10.5" X 12"	200	-	0.25	
7	CCR-DPF2					ULSD
	DOC-ULSD	10.5" X 6"	400	1	-	
	CSF2	10.5" X 12"	200	-	1	

TEST SAMPLES

The test samples included two diesel oxidation catalysts (DOCs), a DOC with an uncatalyzed wall-flow filter as a continuously regenerating diesel particulate filter (CR-DPF) system, a DOC with a catalytically coated wall-flow filter as a catalyzed CR-DPF (CCR-DPF), and a DOC with a partial filter as a continuously regenerating partial filter (CR-PF). These samples are described in [Table 3](#). Two versions of DOC were tested, designated as DOC-LSD and DOC-ULSD, designed for LSD fuel and ULSD fuel respectively. The DOC-LSD employed a catalyst formulation that was more sulfur-tolerant than DOC-ULSD, but could be used with ULSD as well. These two DOCs were tested upstream of a common partial filter, resulting in two versions of CR-PF,

one with the DOC-LSD and the other with DOC-ULSD to be used with LSD and ULSD fuels respectively. The same DOC-ULSD was also used in with CR-DPF and two CCR-DPF configurations. The two CCR-DPF configurations differed in the choice of catalyst coating on the filter. [Table 3](#) also shows relative PGM loadings for the catalysts used in this study, with DOC and Filter loadings normalized separately. All parts were degreased for 4 hours at 500°C prior to test, except CSF2 which was field aged with over 32,000 miles accrued while operating on a school bus application.