

Emissions Performance and In-Use Durability of Retrofit After-Treatment Technologies

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ABSTRACT

In-use testing of diesel emission control technologies is an integral component of EPA's verification program. Device manufacturers are required to complete in-use testing once 500 units have been sold. Additionally, EPA conducts test programs on randomly selected retrofit devices from installations completed with grants by the National Clean Diesel Campaign. In this test program, EPA identified and recovered a variety of retrofit devices, including diesel particulate filters (DPFs) and diesel oxidation catalysts (DOCs), installed on heavy-duty diesel vehicles (on-highway and nonroad). All of the devices were tested at Southwest Research Institute in San Antonio, Texas. This study's goal was to evaluate the durability, defined here as emissions performance as a function of time, of retrofit technologies aged in real-world applications.

A variety of operating and emissions criteria were measured to characterize the overall performance of the retrofit devices on an engine dynamometer. This paper focuses on pollutant removal efficiency, which is calculated from measurements of the engine's baseline emissions as compared to emissions with the emission control device installed. Results show emissions reduction effectiveness in line with those originally verified for the devices. Testing also revealed DOCs and DPFs significantly reduced emissions of gaseous and particle-bound PAHs as well as mobile source air toxics.

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INTRODUCTION

The U.S. Environmental Protection Agency (EPA) technology verification program evaluates the performance of diesel emission control technologies, also referred to as after-treatment devices or retrofits, as a part of the National Clean Diesel Campaign. As retrofit technologies are introduced into the market and states rely on these technologies to improve their air quality, it is important to confirm the performance and durability of after-treatment technologies currently in service.

Background

As part of the Energy Policy Act of 2005, the Diesel Emissions Reduction Act (DERA) authorizes funding to help fleet owners reduce diesel emissions. Retrofitting or replacing older and dirtier (sometimes unregulated) engines, often referred to as legacy fleet engines, are two common practices employed to help reduce population exposure to diesel pollution. The Energy Policy Act of 2005 specifically identifies school buses as priorities for funding to reduce children's exposure to pollutants in diesel exhaust [1]. EPA's Clean School Bus USA Program has been the driving force in upgrading the nation's school bus fleets. This has been accomplished through bus replacement, idle reduction, and retrofit projects. Between

2008 and 2012 nearly 40% of awarded DERA grants funded school bus projects. Over 70% of these school buses were retrofitted with diesel oxidation catalysts (DOCs) or diesel particulate filters (DPFs). Many of the DOC projects also included the installation of closed crankcase ventilation (CCV) systems. In addition to retrofitting, EPA's engine regulations have been phased in for all new engines and as fleets turn over, the newer and cleaner engines are utilized thus improving emissions, especially for on-highway engines.

For over a decade, EPA's retrofit program has developed and reviewed test methods, including alternative test procedures, for evaluating device effectiveness. A key objective of the program continues to be independent confirmation that technologies not only achieve verified levels of emission reduction performance, but that they also remain durable while in-use in real world applications.

Some question the health benefits of retrofit DOCs because of their limited PM reductions. However, in the Clean School Bus Program, DOCs are often installed because the exhaust temperature duty cycle of the engine may not support a passive DPF and maintenance is less burdensome for fleets. For older school buses with relatively low annual mileage,

active DPFs may not be as cost effective compared to other options. Therefore, both DOC and passive DPF technologies are the desired after-treatment options for the Clean School Bus Program.

EPA's testing also focused on addressing emission reduction opportunities in other sectors, such as nonroad equipment used in construction, ports and industrial applications. Since the legacy fleet of nonroad equipment have long useful lives, using DOCs as a maintenance-free technology with duty cycle flexibility seemed to be a good fit. EPA saw an opportunity in this sector and encouraged technology manufacturers to provide after-treatment technologies for application to nonroad engines. EPA set up the nonroad testing program to encourage technology vendors to verify and confirm existing technologies for nonroad applications.

Previous Studies

There are many studies available investigating a variety retrofit technologies under different conditions and test cycles. Hosoya and Shimoda conducted a study assessing DOCs ability to reduce emissions from heavy-duty engines following Japan's 13-mode diesel cycle based on the palladium and platinum content of the catalyst [2]. Their results indicate that the platinum based DOC was more likely to reduce particulate matter, hydrocarbons and carbon monoxide than palladium based DOC. While Hosoya and Shimoda's study presents interesting findings on DOC reductions based on different catalyst formulation and engine conditions, this study does not address long-term, in-use emission reduction durability. Comprehensive studies to date have not evaluated the long-term performance of in-use DOC and DPF retrofits.

Liu et al. examined after-treatment DPF and selective catalytic reduction (SCR) systems and the effects they have on reducing pollutants such as mobile source air toxics (MSATs) and polycyclic aromatic hydrocarbons (PAHs) [3]. Data was provided analyzing the effects the engine and after-treatment device may have on the reduction of unregulated pollutants. The testing described by Liu, et al. is similar to that described in this paper in that the MSAT and PAH emissions were analyzed from DPF (and SCR) testing and results indicated large reduction of pollutants. One difference is that Liu et al. tested one DPF and SCR system while DOCs were not tested.

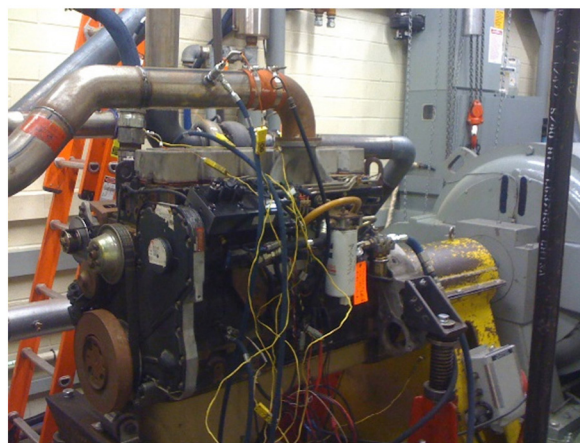
There are a number of studies assessing DOC and DPF reduction of heavy-duty diesel emissions [4, 5, 6, 7]. These studies measured regulated and unregulated pollutants. Although there have been other studies evaluating the performance characteristics of after-treatment devices, there is little published data from devices used in service for extended normal fleet operation. In our study, we procured and tested multiple retrofit devices that were manufactured through normal production and installation practices.

METHODS

In 2011, as part of EPA's National Clean Diesel Campaign Retrofit Technology In-Use Program, three in-use DOCs from school buses were tested for emissions reduction performance. Regulated and unregulated emissions were measured after the DOCs were installed downstream of an on-highway medium heavy-duty diesel engine (1999 Navistar T444E B190, see [Figure 1](#)) over one cold-start and three hot-start Heavy-Duty Diesel Engine Federal Test Procedure (HDDE-FTP) driving cycles.



1999 Navistar T444E Engine at SwRI (On-Highway)



1999 Cummins QSL9 Engine at SwRI (Nonroad)

Figure 1. Engine Photos of Test Cell at SwRI

In 2012, four on-highway DPFs from school buses were also tested on the same engine for emissions reductions performance.

In 2013, two additional DOCs were tested for emissions reduction performance on a 1999 Cummins QSL9 Tier 2 nonroad diesel engine ([Figure 1](#)). One device was from an on-highway waste hauler application and the other was a new device. The purpose of the nonroad testing was to determine the effectiveness of DOCs verified for on-highway applications in reducing emissions from a nonroad engine by testing over the nonroad transient cycle (NRTC). Even though the selected DOCs were originally verified for on-highway applications, the technology manufacturers expected similar emissions reductions for nonroad applications.

Measured emissions include hydrocarbons (HC), non-methane hydrocarbon (NMHC), oxides of nitrogen (NO_x), nitrous oxide (N_2O), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM). Nitrogen dioxide (NO_2) was not directly measured; instead, it was calculated as the difference between measured concentrations of NO_x and NO. Volatile organic compounds (VOCs), carbonyls (aldehydes and ketones), and PAH were also measured.

In this paper, we present our testing and emission performance findings of the four DPFs and three DOCs for on-highway, plus two DOCs for nonroad applications. Detailed information for the on-highway and nonroad test engines is shown in [Appendix A](#). All testing was completed at Southwest Research Institute (SwRI) in San Antonio, Texas.

Test Engine

On-Highway Engine

On-highway DOCs and DPFs were tested downstream of a 1999 model year Navistar T444E, 7.3 liter, medium heavy-duty diesel engine rated at 190 hp in an emissions test cell at SwRI. The engine is turbocharged and has electronically controlled direct fuel injection. Engine and test details are provided in [Table 1](#). A full-load torque and power map for the Navistar T444E engine was generated prior to initial baseline emission testing. This torque map generated with the engine in its baseline configuration was used to de-normalize the HDDE-FTP transient cycle for testing both baseline and retrofit configurations.

Table 1. EPA In-Use Test Type and Engine Information

Year	Devices	Test Type	Test Engine
2011	3 DOCs (on-highway)	On-Highway heavy-duty diesel engine FTP according to 40 CFR Part 86, Subpart N. One cold-start and three hot-start transient cycle tests	1999 Navistar International T444E B190, rated power 190 HP @ 2300 rpm, 7.3 liter displacement, SN: 900581
2012	4 DPFs (on-highway)	On-Highway heavy-duty diesel engine FTP according to 40 CFR Part 86, Subpart N. One cold-start and three hot-start transient cycle tests	1999 Navistar International T444E B190, rated power 190 HP @ 2300 rpm, 7.3 liter displacement, SN: 900581
2013	2 DOCs (nonroad)	Nonroad transient duty cycle, according to 40 CFR Part 86, Subpart E. Three hot-start transient cycle tests	1999 Cummins QSL9, Tier 2 non-road diesel engine, model 6TAA-9004, Rated power 242 kW @ 2000 rpm, 8.8 liter displacement SN: 45906153

Nonroad Engine

DOCs were tested downstream of a 1999 model year Cummins QSL9, 8.8 liter, Tier 2, nonroad diesel engine rated at 325 hp. The engine was chosen after consultation with retrofit device manufacturers suggested its configuration and employed combustion technologies were consistent with common nonroad engines. The engine is turbocharged and has electronically controlled direct fuel injection. Engine and test details are given in [Table 1](#). After initial maintenance and a check that no engine fault codes were present, the engine was deemed acceptable for this test program. A full-load torque and power map for the Cummins QSL9 engine was generated prior to initial baseline testing to de-normalize the NRTC information into a single command cycle used for all emissions testing.

Test Fuel

The test engines were fueled with ultra-low sulfur diesel (ULSD) fuel that met specifications in 40 CFR 86.1313-2007 [8]. The same batch of fuel was used within each test sequence.

Test Devices

Device Procurement and Uncertainty

To replicate practical conditions, EPA's aim was to procure after-treatment retrofit devices that have been operated under real world conditions. The tested devices were procured by EPA and SwRI from public school districts and acquired from the device manufacturers. These devices were typically used for two to four years in the field. During the procurement process, the retrofit devices were initially evaluated on the vehicle by visual examination and a check of the vehicle's onboard diagnostic system for any active fault codes. If acceptable, the device was removed and sent to SwRI for testing. In practice, there is some uncertainty with a vehicle's history. However, fleet managers were consulted and, when feasible, provided the maintenance records of the vehicle and device. SwRI and EPA, working with the device manufacturers, made all possible efforts to get the history of each vehicle and/or device to assure that the vehicle and/or device was properly maintained and used. This assured EPA that the devices were not misused and were reasonable representative samples of typical in-use operation.

Devices Used for On-Highway Engine Testing

In 2011, three field-aged DOCs from two DOC manufacturers that were installed on school buses from two school districts were tested. For the purposes of this report, these are labeled as DOC-1, DOC-2 and DOC-3. At the time of testing, the devices had been in use for approximately three years and accumulated 25,000 to 40,000 miles.

In 2012, four field-aged DPFs from two DPF manufacturers were tested, and these are labeled as DPF-1, DPF-2, DPF-3 and DPF-4. DPF-1 and DPF-2 were procured from a school bus fleet at Montgomery County Public Schools in Maryland while DPF-3 and DPF-4 were procured from a school bus fleet

at Dripping Springs Independent School District in Texas (photos in [Figure 2](#)). At the time of testing, the devices had been in use for approximately three to four years and accumulated 40,000 to 60,000 miles. The mileage is an estimate since many school bus fleets, including the two mentioned here, rotate DPFs between buses for the purposes of periodic DPF cleaning and service maintenance of the bus.



Figure 2. Photos of School Buses from which DPFs were Procured

Devices Used for Nonroad Engine Testing

In 2013, two diesel oxidation catalysts were tested. DOC-4 was previously used in an older on-highway waste-hauler, application for approximately two years and accumulated over 65,000 miles. DOC-5 was provided by the device manufacturer as a new product and was degreened for 25 hours before testing. DOC-5 is the only degreened retrofit device tested in this program.

The device history and vehicle information for all DOCs and DPFs are shown in the [Appendix B](#). Each device was also confirmed by its respective manufacturer to be the appropriate size and fit for its respective test engine.

Test Procedures and Equipment

All testing was performed on an engine dynamometer in a test cell at SwRI as shown in [Figure 3](#). The on-highway emission testing was performed according to procedures specified in 40 CFR, Part 86, Subpart N for heavy-duty on-highway diesel engines [8]. We generally followed the regulatory test procedures from Part 86; however, some test methods from Part 1065 were incorporated (such as double dilution sampling system for PM measurement) and we added two repeat hot start HDDE-FTPs after the initial cold/soak/hot start cycle [9]. Composite emissions were calculated by adding 1/7 of the cold-start value and 6/7 of the average of the three hot-start values consistent with the regulations. The composite emission values were compared to the baseline emission values to determine the emission reduction efficiencies of each device. An initial emission test was conducted to confirm the on-highway engine was compliant with the 1998-2003 emissions standard.

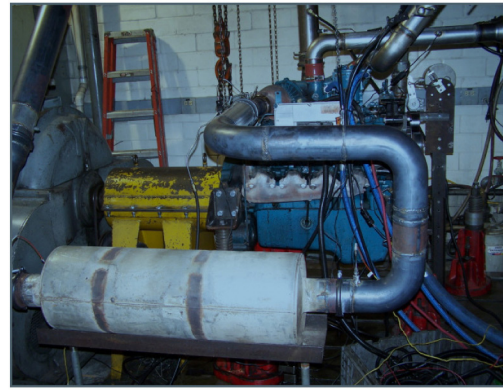


Figure 3. A Retrofit Device Connected to the Engine at SwRI

The nonroad emission testing was performed according to the requirements in 40 CFR, Part 89, Subpart E for nonroad diesel engines [10]. Devices were tested over the NRTC as described in 40 CFR, Part 1039, Appendix VI [11]. The emissions performance test sequence included operation over the three hot-start NRTC cycles. For each measured species, the three hot-start emission values were averaged to get an average hot-start emission value. The average emission values were compared to the baseline emission values to determine the emission reduction efficiencies of each device.

A preliminary emission test was conducted prior to beginning the test plan to confirm the engine's emission levels within the Tier 2 nonroad emission standards. The test cycle was a ramped modal cycle (RMC) that replicated the 8-mode ISO 8178 C1 duty cycle given in 40 CFR, Part 89, Subpart E, [Appendix B](#), for variable speed engines with maximum power at or above 19 kW. The RMC equivalent to the 8-mode C1 duty cycle is given in 40 CFR, Part 1039. The RMC was only used to confirm the engine's emission values to its original certification emission levels.

Measured Regulated Pollutants

All emissions were sampled and measured using dilute sampling techniques with a full flow constant volume sampler (CVS) dilution tunnel system as described in 40 CFR 86.1310-90 for on-highway applications and 40 CFR 89.419 for nonroad applications. A schematic of the emissions sampling system is shown in [Appendix C](#) for both on-highway and nonroad testing.

HC emissions were measured using continuous sampling techniques and a heated flame ionization detector. Methane (CH_4) emissions were measured from proportional bag samples of dilute exhaust using a gas chromatograph equipped with flame ionization detector according to SAE Recommended Practice J1151-2011 Methane Measurement Using Gas Chromatography. NMHC emissions were determined from HC and CH_4 emissions as specified in 40 CFR 86.1342-94. NO_x and NO emissions were measured continuously using separate chemiluminescent analyzers. NO_2 emissions were calculated as the difference between