REDUCTION OF EMISSIONS FROM OFF-ROAD HEAVY-DUTY DIESEL ENGINES USING CATALYZED DIESEL PARTICULATE FILTER

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Abstract: *Several different techniques and methodologies have been applied to reduce emissions from diesel engines. The main by-products of diesel engine combustion are carbon monoxide, carbon dioxide, total hydrocarbons, oxides of nitrogen, and particulate matter. Diesel particulate matter and oxides of nitrogen are two of the most potentially harmful components of the diesel engine exhaust. Since 1990, the US Environmental Protection Agency (EPA) has been regulating off-road diesel emissions and imposing rules and standards on manufacturers and operators. The objectives of this study was to determine the mechanical durability of Diesel Particulate Filters (DPF) that are retrofitted on off-road heavy duty diesel engines, over prolonged periods of in-field operation and to assess the emission benefits of particulate catalyzed filter. The specific task was to evaluate the exhaust emissions from a Caterpillar 3408 engine on an engine dynamometer. Since the ability of the DPFs in reducing particulate matter (PM) emissions was of a prime concern, it was concluded that the DPFs are very effective in achieving up to 98% reduction.*

Keywords: PARTICULATE MATTER REDUCTION, CATALYZED FILTER, HEAVY-DUTY DIESEL ENGINE EMISSIONS

1. Introduction

Diesel engines are highly robust and reliable machines and can be used for a number of years. Their usual life span is around 10-15 years but can be substantially increased by rebuilding the engines, which takes the life span up to 30 years. Though off-road engines generally operate in large open spaces, improper operation and irregular maintenance cause an increase in the pollution in the surrounding areas. One of the major problems in assessing the damage done by diesel exhaust alone is the difficulty in quantifying the amount of diesel matter in the atmosphere. Like any other internal combustion engine, diesel engines convert the chemical energy contained in the fuels to mechanical power, through combustion. The main by-products of combustion are carbon monoxide (CO), carbon dioxide (CO2), total hydrocarbons (THC), oxides of nitrogen (NOx), and particulate matter (PM). Diesel particulate matter (DPM) and NOx are two of the most potentially harmful components of the diesel engine exhaust.

Extensive research has been conducted over the years, to reduce the risk of air pollution due to diesel engines. There have been significant developments in fuel injection systems, engine combustion chamber designs, injection timing studies, and alternate fuel formulations. The efforts have gone further in trying to control the post-combustion stage, by using after-treatment devices, and reaction catalysts to convert incomplete combustion products into much safer compounds.

2. After-Treatment Solution for Diesel Emissions

Exhaust after-treatment technology has been used since the start of 2000. Devices such as Diesel Particulate Filter (DPF), also known as particulate traps, control emissions by physically capturing particulate matter and by using catalysts to convert the chemical compositions of exhaust matter.

An after-treatment device is a component used to reduce engine exhaust emissions downstream of the combustion chamber. Catalytic converters and particulate traps are examples of after-treatment devices. These devices are currently being used to reduce PM emissions extensively. The filtration devices along with reformulated fuels form an excellent combination in filtering out the particulate matter from the exhaust stream. The three primary types of after-treatment devices are the oxidation catalysts, particulate traps and the continuously regenerating traps. They have also been used to reduce NOx, by using systems such as Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR). In SCR systems, urea solution is added to a catalyst, which reacts with the exhaust to reduce NOx. In EGR, the exhaust gas is fed back to the intake, which in turn contributes to reduction of the combustion temperatures, therefore reducing NOx formation. Reformulated fuels have been researched as an option for reducing emissions. Fuels with high cetane number, low aromatic content, and low sulfur content have known to be beneficial. After-treatment devices require low sulfur fuels for their proper operation and hence some so called synthetic diesel fuels look promising.

The two DPFs used in the current study were the continuously regenerating trap (CRT^{TM}) from Johnson-Matthey and the catalyzed diesel particulate filter (DPX^{TM}) from Engelhard. The CRT^{TM} is a two-stage, passive, catalytic, ceramic wall-flow filter. The DPX^{TM} from Engelhard uses a patented catalytic technology to change the chemical structure of diesel exhaust.

Lean NOx catalysts provide a catalytic reduction of NOx through a lean fuel approach. The system uses hydrocarbons (HC) in the exhaust to reduce the high temperatures, hence reducing NOx formation. Nevertheless, since the system is susceptible to sulfur poisoning and requires a high amount of HC to be generated, it has not gained enough popularity with diesel manufacturers. To supplement the additional HC required either an excess quantity of fuel can be injected directly in the exhaust stream or urea can be used. Ammonia in the form of urea forces catalytic reactions to convert NOx to N2 and water. Khair and McKinnon, have reported that DOCs along with DPFs reduce NOx and PM substantially. 1.1 g/bhp-hr and 0.01 b/bhp-hr emission values, for NOx and PM, respectively, were obtained with 368 parts per million (ppm) sulfur fuel [1].

Diesel Particulate Filters (DPF) were first researched in the late 1970s, when they were characterized by wall flow systems that forced exhaust gases through porous walls of the filter element. The systems had problems with regeneration and performance. The temperatures required to burn soot were too high. The introduction of catalysts in the filters brought the temperatures down to manageable limits [2]. A particulate filter is an after-treatment device with open-pore, wall-flow systems. They are usually designed as foams or loosely sintered structures made of materials such as, ceramic and porous metal. These materials are highly thermal-shock resistant but have a brittle nature. The trapping of particles occurs due to impaction on the filter material, or due to interception and diffusion. The particulate trap affects the tailpipe emissions from a diesel engine due to the presence of catalysts in its filter medium or due to the effect of backpressure created on the engine. Catalytic material is coated on to the walls of the filter medium to aid in the oxidation of hydrocarbons, CO, and in the regeneration process of the DPF. Exhaust gases may react with the catalysts having either a positive or a negative influence on the emissions. Excessively high backpressure is known to reduce the

NOx formation through internal exhaust gas recirculation but increases CO emissions and adversely affects fuel economy.

Commonly used regeneration methods include: passive and active systems, onboard and replaceable filters, and permanent and snap-on filters [3]. Passive systems do not rely on external devices to heat-up the filter and/or direct exhaust flow between two DPFs. They fully rely on self-controlled catalytic mechanisms. Thus, these systems must attain regeneration conditions during normal operation without any additional control systems. Passive regeneration strategies include catalyst-based regeneration using either a catalyst applied to the surfaces of the filter or an upstream oxidation catalyst; fuel-borne catalysts, and NO2 traps, Fig. 1. Active systems include air- intake throttling, post top-dead-center fuel injection, catalyst injection systems, and on-board or off-board fuel burners or electrical heaters.

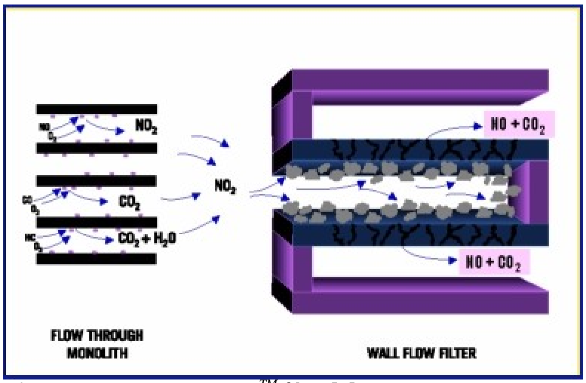

Fig. 1 NO2 reaction in a CRT^{TM} filter [3]

CRT particulate filters usually contain a combination of an oxidation catalyst and an uncatalyzed filter, which requires ultra-low sulfur fuel, Fig. 2. The device is made up of two chambers where the oxidation step is separate from the soot collection/combustion process. The first chamber contains a substrate coated with a proprietary highly active platinum oxidation catalyst, which is designed to oxidize a portion of the NO in the exhaust to NO2, which is the key to the elimination of soot collected by the CRT filter. The catalyst also oxidizes CO and HC into CO2 and H2O. In the second chamber, the exhaust flows through a particulate filter, where gaseous components pass through but soot is trapped on the walls of the filter, where it is destroyed by the NO2 produced by the catalyst in the first chamber. The fuel sulfur level must not exceed 50ppm, but less than 30 ppm is preferable for reliable regeneration (burning of soot). In order to achieve very low levels of PM emissions, the CRT requires fuel with a sulfur level of < 15ppm sulfur [3].

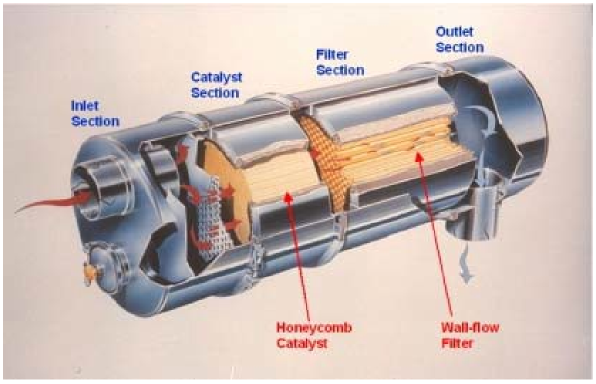

***Fig. 2** Cut-away view of the patented Johnson-Matthey CRT DPF [3]*

3. Diesel Engine Testing Process

University Laboratory conditions for tested engine used a steady state cycle and also employed a transient cycle that was developed using in-field operational data. The temperature readings for intake and exhaust systems are acquired using thermocouples. Torque may be measured through torque sensing devices placed in the driveline of the drive shaft. Modern engines control the fuel rate through an Electronic Control Unit (ECU) that is integral to the engine. The ECU broadcasts speed and percent load (or torque) in addition to information on other engine operating parameters. An ECU protocol adapter was used in this study to obtain speed and torque information. The two objectives of DPF/trap study was to determine the mechanical durability of DPFs that were retrofitted on off-road equipment, over prolonged periods of in-field operation, and to assess the emission benefits of particulate trap retrofit on the same equipment.

The specific objective of this study was to evaluate the exhaust emissions from a Caterpillar 3408 engine on an engine dynamometer. The engine was exercised over ISO 8178 steady state schedule and a transient cycle that was representative of the in-field duty cycle [5]. The engine was operated on a California Air Resources Board (CARB) specification diesel fuel, followed by ultra-low sulfur fuel, named Engine Control Diesel (ECD) without any DPF, and then with a Johnson-Matthey CRT^{TM} and an Engelhard DPX^{TM}, Fig. 3 . Emissions were evaluated at the beginning of the test, and once again after 1400 hours of engine's DPF operation. The test engine was a rebuilt, mechanically controlled, 8-cylinder, Caterpillar 3408, a rear engine taken out of a 657E Scraper. The in-field data was collected from a 657E Scraper with a Caterpillar 3408E electronically controlled rear engine. The engine speed and torque were logged using the Electronic Technician software to record the ECU generated data, using a communication adapter, both supplied by Caterpillar Manufacturer.

***Fig. 3** Picture of the Engelhard DPX used in laboratory testing*

3.1 Test Equipment

The engine dynamometer tests were conducted at University of Wyoming, Department of Engineering Laboratory. All the test equipment and procedures were in compliance with the requirements of US EPA Code of Federal Regulations, CFR 40 Part 86, Subpart D and ISO 8178 [5, 6].

The Caterpillar 3408 (CAT 3408), chosen for this study was 18 liter, V-8 cylinder, mechanically controlled, direct-injection, turbo-charged, after-cooled engine a parallel manifold design, with two intake and exhaust valves per cylinder. It has two full-flow oil filters and a fuel filter. The camshaft is in the center of the "v" with conventional valve lifters, push rods and rocker arms. The in-field data was collected on an electronically controlled rear engine. However, the laboratory testing was performed using a similar mechanically controlled engine, Fig. 4 and Fig. 5. Caterpillar Inc. provided data on both the electronically controlled and mechanical engine that showed that the speed and load values were well within 6% of each other.

The required load is applied on an engine using dynamometers in a laboratory environment Fig. 6. Depending upon the load rating required, the size of the engine, and the application three types of dynamometers were used: the water-brake, eddy-current, and the electric dynamometers.

Fig. 4 *Engine setup with, instrumentation rack, and dynamometer controllers*

Fig. 5 *Gaseous emissions analyzer bench and PM sampling cart*

Fig. 6 *Test engine coupled with GE DC dynamometer*

3.2 Test Fuels

Two fuels were used during testing; CARB Off road diesel, ultra-low sulfur Emission Control Diesel-1 (ECD1). Fuels were analyzed according to the ASTM methods specified in the US EPA CFR 40, Part 86, Subpart D [4]. It has been shown that ultra-low sulfur ECD1 reduces all regulated emissions when compared to CARB Off road diesel [7].

Emission Control Diesel (ECD) fuels are produced from crude oil using a conventional refining process [7]. The original ECD contained less than 15 ppm sulfur, less than 12% aromatics by volume, and a cetane number of greater than 60. The production of ECD required extensive hydro treating which added to the costs. It was shown that the high cetane number and low aromatic levels have a negligible effect on DPF regeneration and conversion efficiency [4]. Hence, a second generation ECD fuel named ECD-1 was formulated, identifying the low sulfur content as the major property required for catalyzed DPF operation. ECD-1 has a maximum sulfur content of 15 ppm but has aromatic and cetane levels that are more typical of currently used diesel fuels. CARB diesel is a blend of one-third volumes from three different fuels, made by companies located in southern California [7].

3.3 Test Conditions

The task of the current study was to generate a transient cycle representative for off-road engine, and evaluate the emissions characteristics of the CAT 3408, by operating it on fuels with different sulfur content. The engine was tested with two different types of DPFs. No modifications were made to the physical or performance characteristics of the engine nor the DPFs. PM was of prime importance and its reduction was kept as the basis for the retrofit evaluation. Also back pressure values on DPF equipped runs were of particular interest. A high backpressure value was considered to be highly significant to the study.

All engine-retrofit configurations were run on both the steady state and transient cycles. The torque and speed set points of the ISO-8178 8-mode cycle and specific weighting factors for each mode, were used to calculate the total weighted emissions [5]. Engine speed and torque remain constant throughout the defined period of each mode. A transient cycle is a test period in which the engine speed and torque are continuously varying according to a predetermined set of values. Engine speed and torque set points were individually determined by mapping the engine on all the test fuels.

3.4 Transient Cycle Characteristics

Before creating a representative duty cycle of actual in-use operation, a few questions needed to be answered on the requirement for transient, in-use emission measurement. Typically, diesel engines are calibrated, by the manufacturer, to meet a certain level of emission standards based upon engine operation at a discrete number of steady state points. However, running an engine on any one particular transient cycle also defeats the purpose. To get a true depiction of in-use, real-time emissions, every engine or piece of equipment must be exercised through engine application driven duty cycle. This duty cycle should be created from the engine’s actual in-field data points, representing the whole range of speeds, loads and activities that the vehicle goes through. Measuring emissions while a vehicle or equipment is in operation gives a picture of the level of emissions control that can be achieved. The alternative to this is laboratory testing. Different advanced technologies have been developed which enable real-time, on-board emissions measurements. This would allow measurement of speed and load conditions on the engine while it is in operation. Such activity would need adherence to newer standards, measurement, and calibration and test procedures.

3.4.1 The need to test under steady state operation

Steady state cycles cover the range of intermediate speeds and loads that may not even be included in a typical transient cycle. Steady state cycles have always been used as bench-marks for emission testing, hence, provide an excellent means of comparison. They provide a high level of consistency in test procedures.

The goal of generating a representative transient duty cycle is to cover the range of all the typical, repeatable activities undergone by a vehicle, engine or equipment and to record their corresponding speed-load data in real-time operation. Under transient operation, it is difficult to optimize the engine parameters for low emissions. Particulates may be formed due to excess fuel injected into the cylinder during speed and load changes and a whole host of engine parameters ranging from turbocharger, in-cylinder temperatures, injection timing, to exhaust system dynamics and after-treatment systems.

The cycle that was developed in this study met the above criteria; hence, it could be used as a common means of measuring emissions from non-road engines. Measurement of emissions was also performed in accordance with the ISO 8178 standards [5]. Emissions were measured at eight combinations of speed and torque settings. The results were then weighed to a single value. As expected, the transient cycle results were not in agreement with the ISO 8178 cycles [5]. Steady state 8-mode cycles were originally developed for certification purposes. There are differences in emissions for different applications and driving patterns, which load the engine in a transient manner.

3.5. Analyzed Test Results

DPFs need high temperatures for regeneration. The first mode of the 8-mode cycle is the R100 mode, which raises the exhaust temperatures to approximately 1000 °F. At high temperatures the DPF enters the regeneration mode. The first retrofit configuration was ECD1 diesel with the CRT trap. It should be noted that sampling times were lengthened for retrofitted engine tests to allow collection of sufficient PM sample.

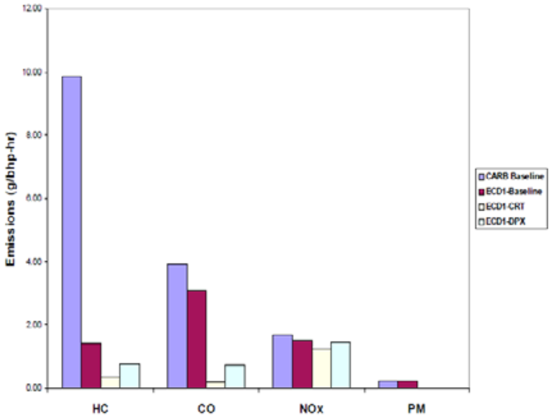

Fig. 7 *Comparison of CARB baseline with ECD1, with and without trap, under 8- mode steady state operation*

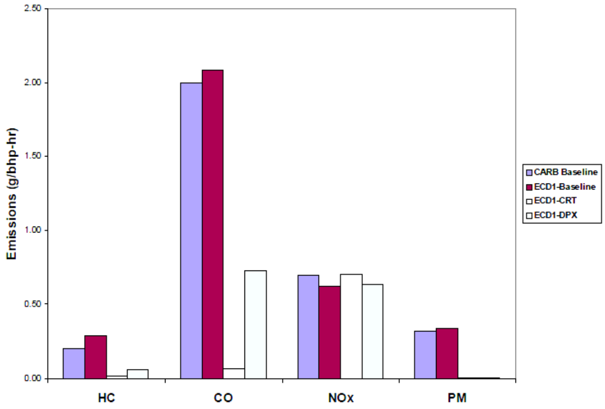

Fig. 8 *Comparison of CARB baseline with ECD1, with and without trap, under transient operation*

Table 1, Fig.7 and Fig. 8 presents the total weighted average emissions for HC, CO, NOx, and PM under steady state operation, in grams per brake-horse power (g/bhp-hr). It also presents the total continuous sampling emissions under transient operation, in g/bhp-hr.

The general formula for calculating percentage difference was:

% Difference = (Reference Value – Actual Value) / (Reference Value) (1)

In Equation (1), the steady state values were taken as reference and the transient values are taken as actual values because they represent “real-world” emissions. There exist large differences in emissions for every configuration tested except for CO. This suggests that the steady state cannot be used as a means of determining “real-world” emissions. CO and PM seem to be reasonable in their percent differences. HC and NOx values are very different between steady state and transient. Except for PM emission, the baseline percentage differences using CARB diesel are more than 50% for HC, CO, and NOx. Similarly, while using ECD1 diesel, the percentage difference was more than 40% for HC, NOx and PM.

Table 1: *Overall weighted emissions for steady state and average continuous emissions for transient cycle.*

Configuration	**8-mode Weighted Average (g/bhp-hr)**	**Transient Cycle (g/bhp-hr)**	**Percent % Difference**	**8-mode Weighted Average (g/bhp-hr)**	**Transient Cycle (g/bhp-hr)**	**Percent % Difference**
	HC			**CO**		
CARB-Baseline	**9.86**	**0.21**	**97.91**	**3.90**	**1.99**	**48.88**
ECD1 Baseline	**1.44**	**0.29**	**79.90**	**3.09**	**2.08**	**32.66**
ECD1 +CRT	**0.35**	**0.02**	**94.11**	**0.19**	**0.06**	**65.41**
ECD1 +DPX	**0.78**	**0.06**	**92.15**	**0.73**	**0.73**	**0.75**
	NO$_X$			**PM**		
CARB-Baseline	**1.70**	**0.70**	**59.03**	**0.25**	**0.32**	**25.50**
ECD1 Baseline	**1.52**	**0.62**	**58.83**	**0.24**	**0.34**	**40.74**
ECD1 +CRT	**1.24**	**0.70**	**43.69**	**0.004**	**0.006**	**51.71**
ECD1 +DPX	**1.46**	**0.63**	**56.54**	**0.006**	**0.005**	**13.78**

It should be noted that since only one engine was tested during this study, any inferences about average emission factors representing the performance of a particular fuel or other after-treatment device would be inappropriate. Nevertheless, this study gives some idea about the effect of fuel and diesel particulate filter/trap used for reduction of exhaust emissions from heavy-duty off-road diesel engine.

4. Diesel Particular Filter/Trap Durability

The following common issues, but not all of them, were observed during in-field operation on off-road engines equipped with DPF: CRT and DPX filters had structural failures due to vibrations; CRT and DPX filters experienced high backpressure. Burning of carbon soot had caused significant burn-through of the ceramic trap element; Engelhard filter elements were broken, Fig. 9. The substrate inside the canning had shifted and was partially broken up so that loose chunks were present. Visual inspection revealed that the substrate had become dislodged from the center-body and allowed to "beat" itself against the outlet cross-members and the housing, resulting in substrate attrition and fracture. The major demise was due to mechanical stress. No sign was evident that the substrate experienced excessive temperatures, local hotspots and/or chemical attack. The trap had not experienced burn through as no soot was observed on the outlet channels. The preliminary finding was that the ceramic contacted the restraining crossbars which first scored, and then cracked the ceramic. The excessive contact between the ceramic and the crossbars may have been due to backpressure or due to vehicle vibration.

Fig. 9 *Filter damage on Engelhard DPX^{TM}*

5. Conclusion

- The diesel engine retrofits fulfill the US EPA off-road emission standard requirements
- Results from the steady state and transient cycles showed significant differences. PM emissions were 14% lower for transient than steady state cycles, and the HC emissions for transient operation were 97% lower than for steady state cycle.
- In most of the test configurations, the 8-mode weighted average emissions were greater than the transient average emissions, though the results were within the standards.
- There was a remarkable reduction in particulate matter, hydrocarbons and carbon monoxide in all the combinations of fuel with filters tested under transient loading. This amounted to a 98% reduction of PM emissions for the low-sulfur fuels+DPF configurations. Brake specific CO emissions were reduced by 96% with the ECD1+CRT setup.
- The duty cycles of off- road construction equipment provide greater shocks and heavier vibrations than are found in on-road vehicles. Advanced manufacturing techniques will be needed to produce a durable commercial product for off-road applications that meets the diesel emission reduction standards same time.

Acknowledgements

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