

Aftertreatment System Performance of a Fuel Reformer, LNT and SCR System Meeting EPA 2010 Emissions Standards on a Heavy-Duty Vehicle

2010-01-1942

Published
10/05/2010

James Edward McCarthy, Jr., Erik Dykes and Evan Ngan
Eaton Corporation

Vadim O. Strots
Navistar Inc.

Copyright © 2010 SAE International

ABSTRACT

Diesel exhaust aftertreatment systems are required for meeting both EPA 2010 and final Tier 4 emission regulations. This paper addresses aftertreatment system performance of a fuel reformer, lean NO_x trap (LNT) and selective catalytic reduction (SCR) system designed to meet the EPA 2010 emission standards for an on-highway heavy-duty vehicle. The aftertreatment system consists of a fuel dosing system, mixing elements, fuel reformer, LNT, diesel particulate filter (DPF), and SCR for meeting NO_x and particulate emissions. System performance was characterized in an engine dynamometer test cell, using a development, 13L, heavy-duty engine. The catalyst performance was evaluated using degreened catalysts. Test results show that system performance met the EPA 2010 emission standards under a range of test conditions that were reflective of actual vehicle operation. Catalyst performance was characterized under multiple testing conditions including the 13-mode Supplemental Emission Test, heavy-duty Federal Test Protocol and twelve steady state engine-operating conditions. Testing results were confirmed by operating the aftertreatment system on a test vehicle over 7000 miles on various test cycles including highway, city and severe service cycles. LNT regeneration, LNT desulfation and DPF regeneration were demonstrated in these test cycles while maintaining repeatable and consistent aftertreatment temperature control. EPA 2010 emission standards were met having low fuel usages for LNT regeneration ranging between 1.0 and 1.5%.

I. INTRODUCTION

The Environmental Protection Agency (EPA) issued emission legislation for diesel engine vehicles. EPA year 2010 emission regulations are currently required for on-highway vehicles while meeting final Tier 4 emission standards for off-highway vehicles will be required in 2014. The feasibility of a fuel reformer, lean NO_x trap (LNT) and selective catalytic reduction (SCR) aftertreatment system to meet final Tier 4 emissions standard of 0.4 g/kW-hr NO_x and EPA 2010 emissions standard of 0.2 g/bhp-hr has been addressed [1, 2]. The 0.4 g/kW-hr NO_x standard is applicable for engines having rated power levels above 56 kW. This paper addresses the demonstration of an aftertreatment system meeting EPA 2010 emission regulations on a heavy-duty engine platform. Aftertreatment results are provided for typical dynamometer and vehicle test cycles.

The aftertreatment system consists of a fuel dosing system, mixing elements, fuel reformer, LNT, diesel particulate filter (DPF), and SCR catalyst arranged in series. A sample configuration of this system is shown in [Figure 1](#). Similar systems using LNT and SCR technology without a fuel reformer are cited in literature [3, 4]. A fuel reformer is utilized to generate hydrogen (H₂) and carbon monoxide (CO) using injected diesel fuel. These reductants are used to regenerate and desulfate the LNT catalyst. NO_x emissions are reduced using the combination of the LNT and SCR catalysts. During LNT regeneration, ammonia (NH₃) is intentionally released from the LNT and stored on the downstream SCR catalyst to further reduce NO_x that passed through the LNT catalyst. This approach converts the drawbacks of the single leg LNT approach (low conversion during regeneration and

NH₃ slip) into an advantage while remaining independent of any urea infrastructure since diesel fuel is the only reductant [1, 5, 6, 7, 8, 9]. The DPF is regenerated using the fuel reformer similar to diesel oxidation catalyst by injecting fuel under lean exhaust operating conditions.

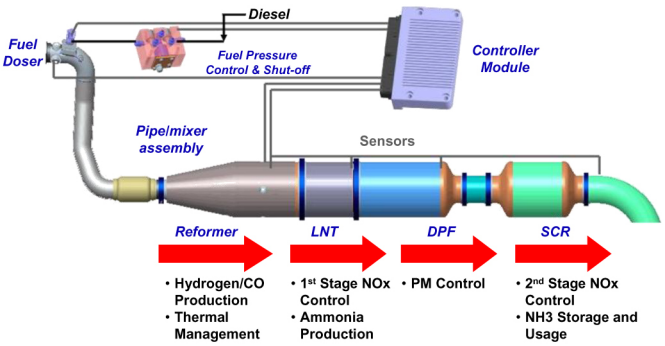


Figure 1. Aftertreatment system layout

The aftertreatment system described was demonstrated for a 13L heavy-duty diesel engine both on a dynamometer test and a vehicle. Multiple systems were procured to accommodate two engine calibrations where each system met EPA 2010 emission regulations. Dynamometer test results are reported over key individual operating modes such as the 13-mode test cycle, heavy-duty federal test protocol (HD-FTP) and severe service duty cycles. Vehicle test results are reported over key individual operating conditions such as highway, city and severe service cycles. The key operating modes for the aftertreatment system were demonstrated on these cycles which include LNT regeneration, DPF regeneration and LNT desulfation.

II. EXPERIMENTAL CONFIGURATION AND PROCEDURE

The experimental configuration and procedure section includes a description of the base engine and specific test cycles. The system design and operation covers a description of the heavy-duty diesel engine, aftertreatment sizing, fuel reformer operation and fuel dosing system. The aftertreatment calibrations used in the test cell and vehicle are described. The system packaging on the vehicle is described followed by instrumentation used to monitor the aftertreatment system. Finally, the dynamometer and vehicle test cycles are described. This section provides an overview of the system sizing and operation while results are provided in the next section.

SYSTEM DESIGN AND OPERATION

A 13L heavy-duty diesel development engine was used for the aftertreatment system dynamometer and vehicle demonstration. The engine was rated at 475 hp with peak torque of 1750 ft-lb and was calibrated for two separate

engine NO_x levels: 1.0 g/bhp-hr and 0.5 g/bhp-hr. As a result, two different aftertreatment systems were sized and procured for the demonstration (Table 1) to meet the EPA 2010 emission NO_x level of 0.2 g/bhp-hr. The fuel reformer was sized to an 11.81" OD × 3.99" long catalyst for both engine calibrations. The thermal mass was sized the same as the fuel reformer. It was positioned downstream of the fuel reformer to thermally isolate the LNT from temperature spikes. A 12" OD × 8" long LNT was used to adsorb the engine out NO_x on the high NO_x engine while a shorter LNT (i.e., 6" long) was used on the low NO_x engine. The 12" OD × 12" long DPF was used to capture soot from the engine exhaust. The last catalyst was the SCR having a size of 12" OD × 8" long for the high NO_x engine and a shorter SCR (i.e., 6" long) for the low NO_x engine.

Table 1. Sizing of the aftertreatment system components to meet EPA 2010 NO_x emissions level of 0.2 g NO_x/bhp-hr

System	Engine out NO _x [g/bhp-hr]	Sizing (inches)	Reformer	Thermal Mass	LNT	DPF	SCR
High NO _x	~ 1.0	Diameter	11.81	11.81	12	12	12
		Length	3.99	3.99	8	12	8
Low NO _x	~ 0.5	Diameter	11.81	11.81	12	12	12
		Length	3.99	3.99	6	12	6

The engine and aftertreatment system were coupled to provide a fuel efficient system. The fuel reformer required a rich exhaust environment to produce reductants. In order to reduce fuel usage, the engine calibration provided lower exhaust oxygen concentrations such that less fuel is needed for the fuel reformer.

The fuel reformer is operated in both lean and rich modes to provide a means to regenerate the LNT and DPF in the aftertreatment system. Its two main functions during regenerations are 1) to consume the residual oxygen in the exhaust gas stream, and 2) to convert remaining reformer fuel to the reductants, H₂ and CO [1, 5, 6, 7, 8, 9, 10, 11]. A typical reformer control is shown in Figure 2. Fuel is injected into the reformer to warm the catalyst to its operating temperature. Engine out oxygen is then reduced via engine control to a lower level (i.e., 3.2% in the example). A higher fueling rate is commanded to consume the remaining oxygen as depicted by the tailpipe oxygen dropping to zero. The higher fuel rate creates a rich condition where reformate is produced, as depicted by the predicted CO and H₂ profiles.

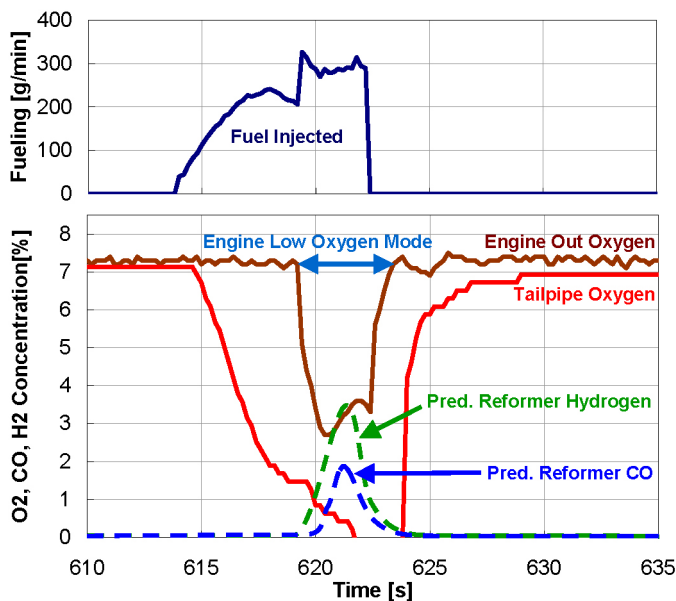


Figure 2. Typical reformer operation [1]

The aftertreatment system required fuel dosers having a flow range of 50 to 1000 grams per minute to meet the heavy-duty aftertreatment fuel flow requirements for all modes of operation. In order to achieve the required fuel flow, the demonstration system used two fuel injectors each having a flow range of 30 to 500 g/min. The fuel dosers are mounted to the exhaust pipe on the vehicle at turbocharger outlet. The fuel dosing system had a drop size distribution that was conducive for fuel vaporization having a Sauter mean diameter ranging between 60 and 70 microns [12]. These drop sizes are smaller than previous fuel dosing systems [13]. The fuel injectors employ a recirculating cooling loop from the fuel tank to an external electrical pump, which funnels diesel fuel to the injectors and back to the fuel tank. The diesel fuel would be provided by the low pressure gear pump already on the engine for serial production. The testing was completed using ultra low sulfur diesel fuel with a maximum sulfur concentration of 15 PPM [14].

AFTERTREATMENT CALIBRATION

The aftertreatment system was calibrated for the heavy-duty engine used in the dynamometer test cell and vehicle. The key control parameters calibrated were the NOx loading on the LNT, level of richness (ϕ , phi) and the reductant to NOx ratio. In this section, the general control strategy is discussed for the dynamometer and vehicle testing.

The parameters used for the dynamometer test cell and vehicle are provided in Table 2. The ϕ control setting is the operation richness level to produce reformat. The total amount of reformat was commanded using the ratio of reductant ($\text{CO} + \text{H}_2$) to LNT NOx storage which sets the rich duration of the reformer. The NOx loading control setting

was estimated to determine the amount of NOx stored on the LNT between regeneration events. The engine out NOx sensor reading was used as the input for the estimation. A complete description of the control strategies are cited in the literature [7, 15, 16].

Table 2. Control settings used to characterize aftertreatment performance

	NOx Loading [grams]	Φ (phi)	Reductant/NOx [mol/mol]
Dynamometer	~5.5	1.3	~7.0
Initial Vehicle	5.5	1.3	7
Final Vehicle	13.5	1.3	4

SYSTEM PACKAGING

Figure 3 shows the ProStar vehicle used for the aftertreatment demonstration which includes the aftertreatment system. The fuel reformer, LNT and DPF are positioned underneath the cab next to the fuel tank while the SCR is position in the vertical stack.

The vehicle was fitted with dual fuel injectors, a custom downpipe, catalyst components, a removable DPF cap for ash cleaning, an aftertreatment control unit and a wiring harness illustrated in Figure 3 (a) and (b). The vehicle packaging was developed using aftertreatment fuel injection and vaporization simulations [17]. The low NOx and high NOx systems were tested on an engine dynamometer while the low NOx system was tested on the vehicle. Additional vehicle packaging options for a 13L heavy-duty diesel engine are cited in the literature [17].

AFTERTREATMENT SYSTEM INSTRUMENTATION

Figure 4 shows the system instrumentation layout used for the aftertreatment system evaluation. The system consists of (a) an in-line fuel doser, (b) downpipe with a mixer, (c) fuel reformer, and (d) thermal mass upstream of (e) LNT, (f) DPF, and (g) SCR. The emission analyzers required to evaluate system performance are shown in Figure 4a. A NOx and linear λ sensor were located at engine outlet. A Horiba MEXA-7100DEGR emission analyzer was located at DPF outlet and a second Horiba MEXA-7100D emission analyzer was located at system outlet Both analyzers measured oxides of nitrogen (NOx), nitric oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbon (THC), methane (CH_4), and oxygen (O_2). An additional NOx and linear λ sensor were installed at tailpipe outlet. The emissions were sampled directly from the exhaust through a heated sample system controlled to 191 °C. System NOx conversion

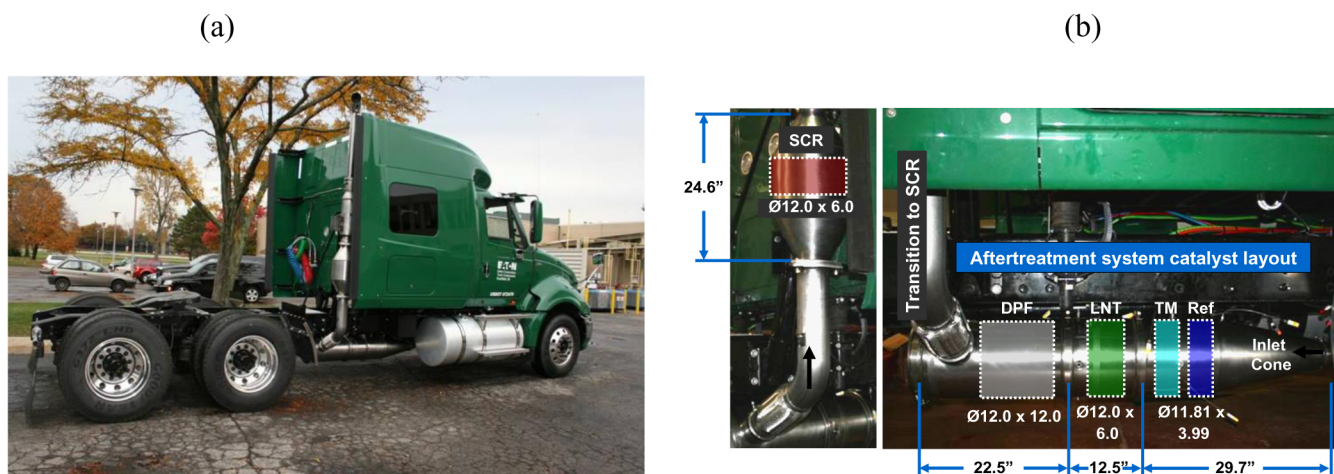


Figure 3. Aftertreatment demonstration vehicle: (a) vehicle view and (b) aftertreatment setup

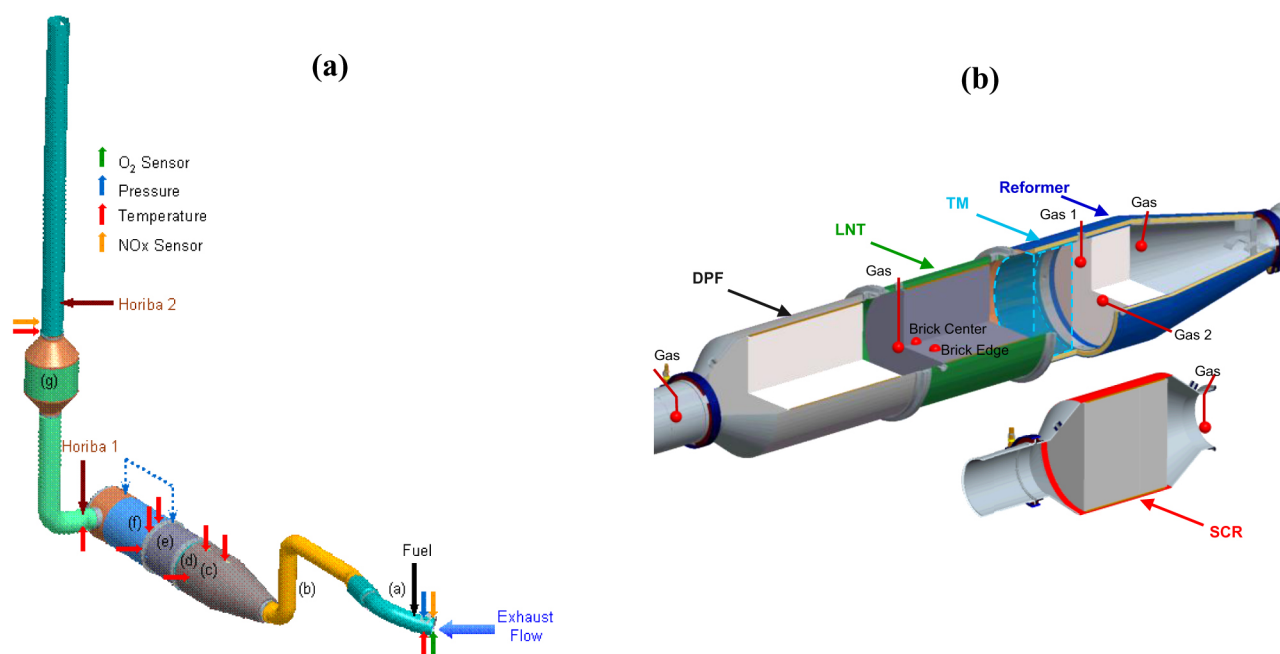


Figure 4. Experimental (a) system layout and (b) detailed thermocouple configuration

efficiency values were calculated using the engine out NOx sensor and the respective NOx measurement from the Horiba analyzers at system outlet. A correlation was established between the Horiba NOx and the NOx sensor during lean operation. Three sensors were used to control and monitor the state of the aftertreatment system. Both engine out and system outlet NOx sensors were used to control the LNT regeneration for the aftertreatment system. A linear λ sensor at engine outlet was used as feedback to control the O₂ concentration during rich mode operation. The instrumentation described was used to evaluate the aftertreatment system performance in the dynamometer lab.

The catalyst brick and exhaust gas temperatures were characterized using nine thermocouples as shown in detail in Figure 4b. Gas thermocouples were located approximately 0.5 inch from the face of each catalyst. Reformer gas thermocouples were arranged 2.6 inches from the centerline at various radial positions. In addition, LNT brick thermocouples were located at a depth of 1.0 inches into the brick. The brick thermocouples were placed at the centerline and outer edge of the LNT. The outer edge thermocouple was placed at 5.2 inches from the center of the brick.

A delta pressure sensor was used to monitor the pressure drop across the DPF and trigger DPF regenerations. The remaining component pressure drop measurements were taken using