

NO_x Performance of an LNT+SCR System Designed to Meet EPA 2010 Emissions: Results of Engine Dynamometer Emission Tests

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ABSTRACT

The paper covers the NO_x performance evaluation of an LNT + SCR system designed to meet the 2010 on-highway heavy-duty (HD) US EPA emission standards. The system combines a fuel reformer catalyst (REF), lean NO_x trap (LNT), diesel particulate filter (DPF), and selective catalytic reduction (SCR) in series, to reduce engine-out NO_x and PM. System NO_x reduction performance was verified in an engine dynamometer test cell, using a 2007 7.6L medium-duty engine. System NO_x performance was characterized using fresh LNT and SCR along with hydrothermal aged LNT and fresh SCR. Test results show levels consistent with EPA 2010 limits under various test conditions. Catalysts performance was characterized at eight steady engine-operating conditions (A100, B50, B75, A75, B100, C100, C75, C50, across a 13-mode Supplemental Emission Test (SET), and an on-highway Heavy Duty Federal Test Procedure (HD-FTP). System level NO_x conversion ranged from 84 to 99%, SCR contributing between 8 – 25% of total system NO_x conversion. System fuel consumption ranged from 2.3 to 4.7%.

INTRODUCTION

A combined lean NO_x trap (LNT) and selective catalytic reduction (SCR) technology with a diesel particulate filter (DPF) was used to reduce Oxides of Nitrogen (NO_x) and Particulate Matter emissions for on-highway diesel applications. A sample configuration is shown in Figure 1. The system consist of a fuel dosing system, mixing elements, fuel reformer catalyst (REF), thermal mass (TM), lean NO_x trap (LNT), diesel particulate filter (DPF), and a selective catalytic reduction (SCR) in series to reduce NO_x and particulate emissions. Similar LNT + SCR systems which use a diesel oxidation catalyst (DOC) instead of a fuel reformer catalyst have been cited in the literature [1, 2]. The engine out NO_x is reduced using a two-step process. First the NO_x, which enters the LNT, is stored on an alkali (e.g. K), or alkaline earth metal (e.g. Ba) storage site in the catalyst washcoat. As the LNT accumulates NO_x under lean

operation, the NO_x trapping efficiency will slowly drop as the number of available storage sites decrease. During rich operation, injected diesel fuel is converted to hydrogen (H₂) and carbon monoxide (CO) across the REF. The generated H₂ and CO is used to regenerate NO_x stored on the LNT. During the LNT regenerating process NO_x is converted to nitrogen (N₂) and ammonia (NH₃) on the LNT; the produced NH₃ is then stored on the SCR and used for additional NO_x reduction. Soot reduction is achieved with a DPF, which traps soot during normal operation, and subsequently burns off the soot by periodic high temperature operation. This high temperature operation is provided during a lean exhaust environment where diesel fuel is injected into the exhaust stream using in-exhaust post injection. The fuel reacts with the exhaust oxygen promoted by the REF to create an exothermic reaction. The increased temperature oxidizes the soot retained in the DPF. The TM was installed in the system downstream of the REF to dampen the high temperature spikes produced during rich operation.

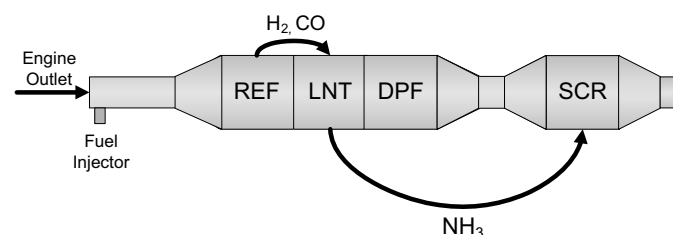


Figure 1: (Aftertreatment System Layout)

Reformer Operation

Figure 2 shows an example of a typical REF operating event. The engine out oxygen is reduced using an air intake throttle valve. The oxygen is reduced from approximately 10.5% to 4.5%. Fuel is injected into the REF to warm the catalysts to their proper operating temperatures. Once the REF temperature has reached the proper operating temperature a higher rate of fuel is

is similar to that of McCarthy et al [6]. It was not the intent of this study to optimize the LNT + SCR system control settings. The control settings used were based on previous test results which showed overall good NO_x performance. The LNT + SCR system fuel consumption shown throughout this study were calculated using aftertreatment system fuel consumed divided by engine fuel consumption. The aftertreatment fuel consumption shown are for LNT NO_x regeneration only and do not include DPF regeneration or LNT desulfation. Typical DPF regeneration and LNT desulfation fuel consumptions are 1.0% and 0.2%, respectively [3].

All engine dynamometer testing was completed on a 7.6L medium-duty engine, with a power rating of 225 hp and a maximum torque output of 560 lb.-ft. All testing was completed at Eaton Corporation's Innovation Center located in Southfield, Michigan.

The testing was completed using ultra low sulfur diesel with a maximum sulfur concentration of 15 PPM, which is consistent with sulfur requirement [7]. System performance was characterized at A100, B50, B75, A75, B100, C100, C75, C50, a 13-mode SET, and the hot cycle of the HD-FTP. The A, B, and C represent specific speeds and 50, 75, and 100 denote engine load percentage at each speed as specified by the SET emission test.

System Configuration

The system configuration used during validation is illustrated in Figure 3. The system consists of a fuel doser (a), down-pipe (b), flexible coupling (c), REF (d), TM (e), LNT (f), DPF (g), SCR (h), and Horiba Bench #1 and #2.

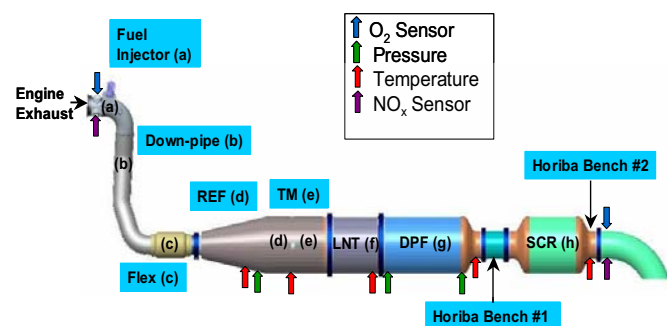


Figure 3: Eaton Aftertreatment System Configuration

The system hardware installed in the test cell is shown in Figures 4 and 5. Figure 4 shows the fuel doser, down-pipe assembly, and flexible coupling. The down-pipe assembly is a double-walled insulated pipe mounted to engine out to minimize heat loss to the REF. The flexible coupling was installed upstream of the REF to minimize system vibration during operation.

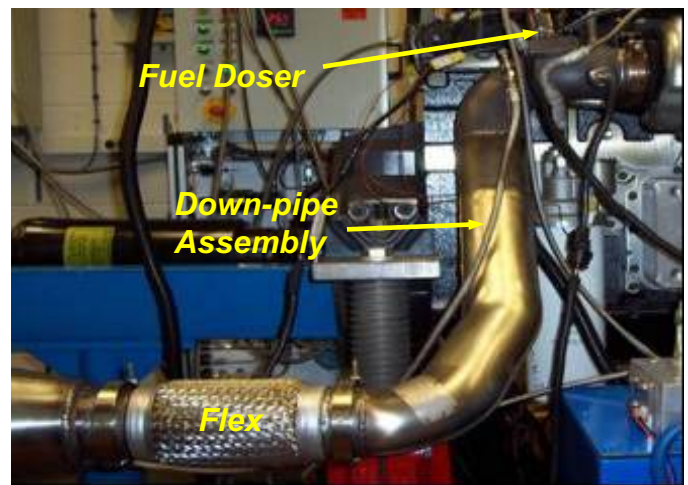


Figure 4: Fuel doser, down-pipe assembly, and flexible coupling

Figure 5 shows the remainder of system downstream of the flexible coupling including the REF, LNT, DPF, and SCR. The transition pipes before and after the SCR are where the gaseous emissions were measured during system performance evaluation. The transition pipe between the DPF and SCR was also used to shed temperature during LNT desulfation and DPF regeneration in order to protect the SCR from high temperature exposure.



Figure 5: System Configuration (Reformer Inlet to SCR Out)

Emission Analyzer Configuration

Figure 3 shows the standard analyzer configuration used to evaluate system performance. A NO_x and linear λ sensor were located at engine out. A Horiba MEXA-7100DEGR emission analyzer measuring oxides of nitrogen (NO_x), nitric oxide (NO), carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbon (THC), methane (CH₄), and oxygen (O₂) was located at DPF out. The

NO_x and NO emissions were measured continuously using two separate analyzers. A second Horiba MEXA-7100D emission analyzer was located at system out and measured oxides of nitrogen (NO_x), nitric oxide (NO), carbon monoxide (CO), carbon dioxide (CO₂), total hydrocarbon (THC), methane (CH₄), and oxygen (O₂). NO_x and NO emissions were measured continuously using two separate analyzers. An additional NO_x and linear λ sensor were installed at system out. The emissions were sampled directly from the exhaust through a heated sample system controlled to 191 °C. A set of span gases were used daily to verify analyzer calibration. A correlation was established between the Horiba NO_x and the NO_x sensor during lean operation. System NO_x conversion efficiency was calculated using the NO_x sensor located at engine out and the NO_x measurement from the Horiba Mexa7100D at system out. LNT NO_x conversion efficiency was calculated using the NO_x sensor located at engine out and the NO_x measurement from the Horiba Mexa7100D at DPF out. SCR contribution was calculated by subtracting LNT efficiency from system efficiency. A delta pressure sensor was installed across the DPF to monitor pressure drop across the filter.

Thermocouple Locations (Reformer, LNT, DPF, and SCR)

Eight thermocouples were added to the aftertreatment system to control and monitor the status of the catalysts temperatures during operation. The eight thermocouples are shown in table 2. There were six thermocouples measuring gas temperature and two measuring catalyst substrate temperature. The orientation of the catalysts thermocouples are viewed looking down the exhaust flow path. The substrate temperatures were located a distance of 1" into the outlet face of the catalyst brick.

Table 2: Catalysts Thermocouple Layout

Location	Orientation	Distance from Center [cm]	Type
REF In	12 o'clock	0	Gas
REF Out	3 o'clock	3.8	Gas
REF Out	6 o'clock	3.8	Gas
LNT Out (center)	NA	0	Substrate
LNT Out (edge)	9 o'clock	10.4	Substrate
LNT Out	12 o'clock	0	Gas
DPF Out	12 o'clock	0	Gas
SCR Out	12 o'clock	0	Gas

TEST PLAN AND DESCRIPTION

This study was completed to characterize full system NO_x performance of the LNT + SCR system. System performance was characterized by running eight steady

state engine-operating points; A100, B50, B75, A75, B100, C100, C75, C50, a SET, and a hot HD-FTP. A fresh LNT and SCR along with a hydrothermally aged LNT and a fresh SCR were tested through the full test matrix as shown in Table 3. The eight steady state test points were chosen to characterize system performance across a range of temperature conditions of the MD engine. Each steady state operating point was operated for a duration of 20 minutes to allow multiple NO_x regeneration events to occur to ensure a stabilization of steady state operation. The number of NO_x regeneration events for each steady state point varied depending on the engine out NO_x level.

Table 3: System Performance Test Matrix

Sequence	Test Mode
1	A100
2	B50
3	B75
5	A75
6	DPF Regeneration
7	B100
8	C100
9	C75
10	C50
11	DPF Regeneration
12	B50
13	SET
14	B50
15	SET
16	DPF Regeneration
17	B50
18	Hot HD-FTP

In addition to the eight steady state engine operating points, a SET was completed. A B50 steady state test was completed prior to running each SET to purge the LNT of stored NO_x. The LNT NO_x purge was completed to establish a baseline condition for the LNT before SET system evaluation.

The discrete mode cycle (DMC) 13-mode SET was utilized. The DMC SET is equivalent to the European Stationary Cycle (ESC). The SET consisted of 13 engine operating modes including idle. The engine map is divided into three engine speed areas referred to as A, B, and C speed. The following description explains how each of the 13 mode points was derived. The high speed n_{hi} is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs (i.e. above the rated speed) on the power curve is defined as n_{hi} .

The low speed n_{lo} is determined by calculating 50% of the declared maximum net power. The lowest speed where this power value occurs (i.e. below the rated speed) on the power curve is defined as n_{lo} .