

Transient On-Road Emission Reduction of an LNT + SCR Aftertreatment System

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ABSTRACT

An LNT + SCR diesel aftertreatment system was developed in order to meet the 2010 US HD EPA on-road, and tier 4 US HD EPA off-road emission standards. This system consists of a fuel reformer (REF), lean NOx trap (LNT), catalyzed diesel particulate filter (DPF), and selective catalytic reduction (SCR) catalyst arranged in series to reduce tailpipe nitrogen oxides (NOx) and particulate matter (PM). This system utilizes a REF to produce hydrogen (H_2), carbon monoxide (CO) and heat to regenerate the LNT, desulfate the LNT, and actively regenerate the DPF. The NOx stored on the LNT is reduced by the H_2 and CO generated in the REF converting it to nitrogen (N_2) and ammonia (NH_3). NH_3 , which is normally an undesired byproduct of LNT regeneration, is stored in the downstream SCR which is utilized to further reduce NOx that passes through the LNT. Engine exhaust PM is filtered and trapped by the DPF reducing the tailpipe PM emissions. The REF is used to periodically generate heat to raise the DPF temperature and oxidize the accumulated soot. This paper addresses the issues resulting from transient operation and control of the above mentioned aftertreatment system. These results were obtained from urban and highway drive cycles using a 2007 compliant medium duty test vehicle equipped with an LNT + SCR aftertreatment system. The system performed LNT regenerations, DPF regenerations, and LNT desulfations as needed under a variety of transient conditions. An average system NOx conversion of 86% was demonstrated for a variety of transient driving conditions.

INTRODUCTION

The aftertreatment system consists of a fuel reformer (REF), lean NOx trap (LNT), catalyzed diesel particulate filter (DPF), and selective catalytic reduction (SCR) catalyst arranged in series to reduce nitrogen oxides (NOx) and particulate matter (PM) for the 2010 on-road and tier

4 off-road emission standards. Similar LNT + SCR systems without a REF have been cited in the literature [1,2]. By utilizing a REF catalyst to generate hydrogen (H_2) and carbon monoxide (CO) from diesel fuel, the LNT can be efficiently regenerated and desulfated. Figure 1 illustrates the configuration used herein. The LNT + SCR aftertreatment system was installed on a MD test vehicle with a 2007 US EPA emission compliant engine. An engine independent aftertreatment control unit was also installed on the vehicle to control the aftertreatment system. Using the developed aftertreatment system and control logic, the system was tested under a variety of transient driving conditions.

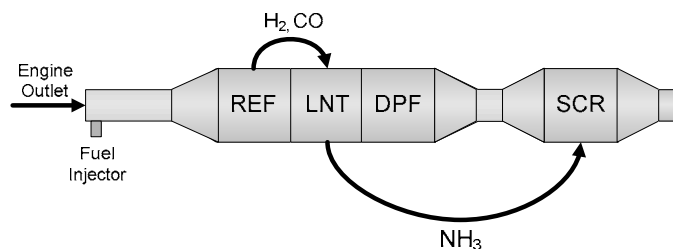


Figure 1: Aftertreatment System Layout

NOx Abatement

The system uses a LNT to trap engine out NOx under lean conditions. The engine out NOx 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 NOx under lean operation, the number of available storage sites decrease, causing the NOx trapping efficiency to decline. To recover the LNT's trapping effectiveness, periodic purging under rich exhaust conditions is required to remove the stored NOx from the LNT and convert it back to nitrogen (N_2). In order to purge the LNT, reductants such as H_2 or CO

must be present to reduce the stored nitrate to N_2 . During LNT regeneration a portion of the stored nitrate is reduced to form ammonia (NH_3). The NH_3 generated is utilized by the downstream SCR catalyst to reduce NOx that slips past the LNT catalyst.

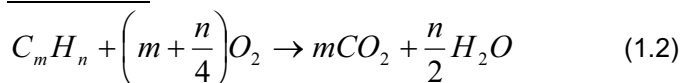
Reformer Operation

A fuel reformer catalyst is used to produce H_2 and CO reformat for LNT regeneration and desulfation. This is accomplished by dosing fuel into the engine exhaust stream using an injector mounted near the engine turbocharger outlet. During LNT regenerations, the REF temperature is first increased to a range where the reforming process will begin. As the REF temperature increases, the fuel conversion efficiency also increases. The REF warm-up is accomplished by injecting fuel into the tailpipe to achieve an overall equivalence ratio (ϕ) that is lean of stoichiometric. ϕ is defined as:

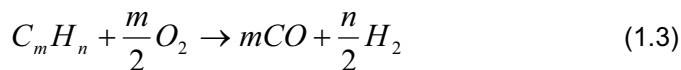
$$\phi = \frac{1}{\lambda} = \frac{AFR_{Stoichiometric}}{AFR_{Actual}} \quad (1.1)$$

The injected fuel and remaining engine outlet oxygen (O_2) will react in the REF producing heat. The fuel rate is adjusted in a manner that the REF catalyst temperature follows a planned trajectory until the desired warm-up target temperature is reached. Once the target warm-up temperature is reached, the fuel rate is increased to obtain an overall rich ϕ , producing H_2 and CO. The rate at which the REF generates CO and H_2 can be controlled by adjusting the ϕ that enters the REF. The REF reaction scheme can be represented by the following four chemical reactions which are consistent with [3,4]:

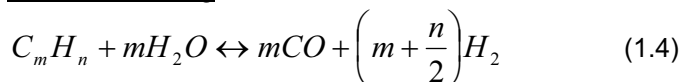
Combustion



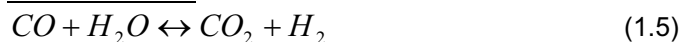
Catalytic Partial Oxidation



Steam Reforming



Water Gas Shift



Rich REF operation used to regenerate the LNT is illustrated in figure 2. The results shown were obtained under steady state engine operation in an engine dynamometer test cell. At 4 sec, the engine intake air is reduced using an electronic throttle control (ETC)

mounted in the intake manifold. This reduction of exhaust O_2 concentration increases the exhaust ϕ . By reducing the exhaust O_2 concentration the fuel penalty associated with running the regeneration is reduced, as all of the O_2 must be consumed in the REF by combustion of injected fuel before any reductant can be produced. During throttling the REF warm-up phase begins with fuel injection at 8.5 sec. The warm-up fuel rate is adjusted based on the current exhaust flow, temperature, and O_2 concentration to achieve a specific heating rate up to a specific target operating temperature. Once the REF warm-up temperature has been reached (18.5 sec), the fuel rate increases to achieve a $\phi > 1$. Constant ϕ is maintained during rich operation by adjusting the fuel flow to compensate for changes in exhaust flow and O_2 concentration. During rich operation the formation of H_2 and CO at the REF outlet is measured using an H-Sense H_2 analyzer, and a Horiba 7100D emission bench respectively. Once the desired amount of reductant has been produced, the fuel injection is terminated and the ETC returns to the open position.

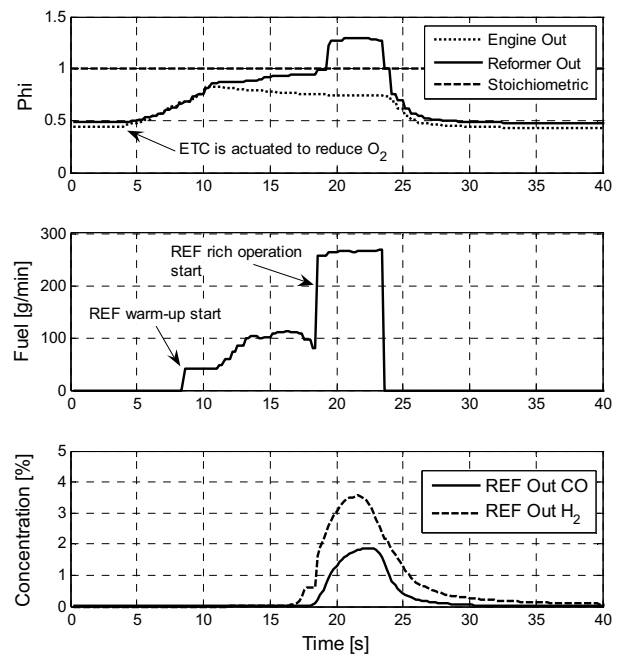


Figure 2: Rich Reformer Operation

EXPERIMENTAL SETUP

The aftertreatment system tested was installed on a 2007 production medium duty test vehicle. This test vehicle was equipped with a 7.6 L 225 hp engine which meets the EPA 2007 NOx and PM emission limits. The stock aftertreatment system and exhaust piping were removed from the vehicle and replaced with a REF + LNT + DPF + SCR system, shown in figure 3. The system consists of a fuel injector (a), downpipe with mixing elements (b), 4.2 L REF (c), 4.2 L thermal mass (d), 10.5 L LNT (e), 14 L catalyzed DPF (f), and a 10.5 L SCR catalyst (g). The

REF, LNT and DPF are mounted in a close coupled configuration. A small section of pipe is installed between the DPF and SCR catalyst to shed temperature during desulfation and DPF regeneration in order to protect the SCR catalyst from high temperature exposure.

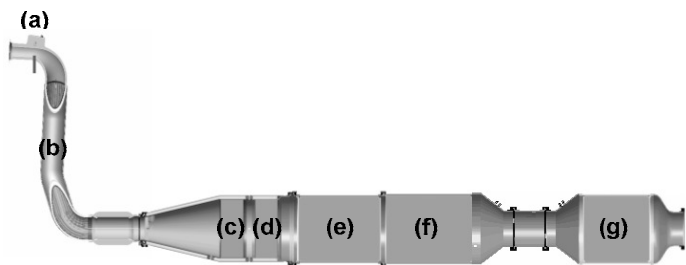


Figure 3: Catalyst Configuration Tested

The downpipe is a double walled insulated pipe mounted directly to the engine turbo outlet to minimize heat loss. An ETC was installed in the engine intake manifold to reduce engine exhaust O₂ concentration on demand. Two Siemens VDO UniNOx sensors were installed in the system to monitor NO_x and ϕ . One sensor was installed upstream of the fuel injector and one downstream of the SCR catalyst. A fast responding linear λ sensor was installed upstream of the fuel injector to be used by the aftertreatment control unit. Eight thermocouples were installed to monitor various catalyst temperatures. The thermocouple locations are listed in table 1. The two LNT substrate thermocouples are inserted 2.5 cm into the outlet face of the LNT. A delta pressure sensor was installed across the DPF to monitor pressure drop across the filter. All of the thermocouples and sensors were wired to the aftertreatment control unit.

TC Number	Location	Orientation	Distance from Catalyst Center [cm]	Type
1	REF Inlet	NA	0	GAS
2	REF Outlet	3 o'clock	3.8	GAS
3	REF Outlet	6 o'clock	3.8	GAS
4	LNT Outlet	NA	0	GAS
5	LNT Out (Center)	NA	0	Substrate
6	LNT Out (Edge)	9 o'clock	10.4	Substrate
7	DPF Outlet	NA	0	GAS
8	SCR Outlet	NA	0	GAS

Table 1: Thermocouple Locations

The LNT + SCR aftertreatment system, (installed on the vehicle) is shown in figure 4. The system is mounted to the vehicle frame using standard exhaust hangers. Rubber isolation mounts were installed to minimize system vibration during vehicle operation.

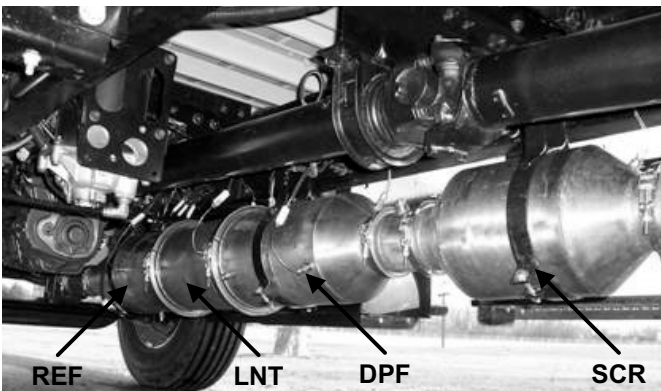


Figure 4: Aftertreatment System Installed On Test Vehicle

CONTROL STRATEGIES

NO_x Trapping and Regeneration

The basic overall LNT control scheme is represented by the flowchart in figure 5. LNT regeneration is triggered based on the current estimated LNT NO_x loading and overall system NO_x conversion efficiency (engine outlet vs. SCR outlet). Once either threshold is exceeded, the controller will request an LNT regeneration. Before the regeneration is started, the controller must first determine the feasibility of regeneration under the current exhaust conditions. To protect the REF, safe-guards have been implemented in the controller to pause regeneration if the exhaust conditions become unfavorable for REF operation. Engine exhaust conditions are continuously monitored to ensure that the exhaust flow, O₂ concentration, and temperature are in the correct range for REF operation.

At low exhaust flows the injected fuel may not properly vaporize and mix within the exhaust stream. This can lead to localized overheating of the REF catalyst caused by overly rich and lean areas across the catalyst. During the rich reforming process, the energy production is balanced between the exothermic combustion reactions, (eq 1.2 – eq 1.3) and endothermic rich reactions (eq 1.4 – eq 1.5). Any locally lean areas will produce heat at a faster rate than the exhaust flow can remove, generating local hotspots. These overheated areas will cause the REF fuel conversion efficiency to drop over time as the catalyst sinters, reducing the overall catalyst surface area.

The controller also pauses fueling if the engine exhaust O₂ concentration becomes too high. Since the aftertreatment controller is not directly integrated with the engine controller, there are conditions where the O₂ cannot be managed by throttling the engine intake. High concentrations of O₂ will lead to faster temperature rises on the REF and higher fuel penalties, because more fuel is required to consume the O₂ to create rich conditions. Because of this, the fuel injection must be paused during rapid unloading transitions such as steep downhills and braking.

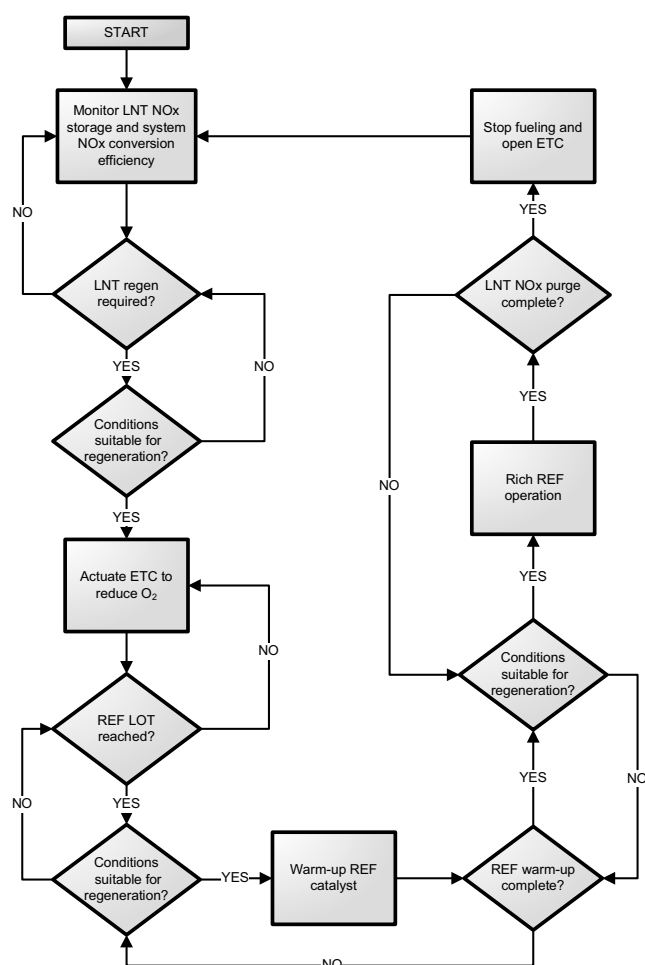


Figure 5: LNT Regeneration Flowchart

Once REF operation is permissible, the LNT regeneration process is started. The ETC is actuated to reduce the exhaust O_2 entering the REF. During throttling, the REF temperature is monitored to ensure that the minimum REF light off temperature (LOT) is reached before fuel injection begins. If the REF is too cool, the injected fuel will pass through the REF unreacted potentially poisoning the downstream SCR catalyst. During periods of high REF hydrocarbon breakthrough, the majority of the HC will enter the SCR unreacted due to the inability of the LNT and DPF to efficiently convert large quantities of HC. A reduction in SCR NOx conversion from hydrocarbon adsorption is well documented in the literature [5,6]. A minimum REF operating temperature of 260°C was set to ensure that the REF would light off properly during fuel injection.

The engine exhaust typically runs richer and thus hotter when the ETC is actuated. This effect was incorporated into a light-off support feature to increase the range of engine operating points that would permit LNT regeneration. By throttling the engine intake, the REF

temperature is increased by the hot exhaust gas flow entering the REF. A sample low temperature light-off scheme is shown in figure 6. A LNT regeneration is requested while the REF temperature is at 240°C . The ETC is actuated to raise the engine out temperature before the fuel injection begins. Once the ETC is actuated, the engine out temperature increases from approximately 225°C to a peak of 350°C . The higher exhaust temperature heats the REF catalyst above 260°C before the fuel injection begins.

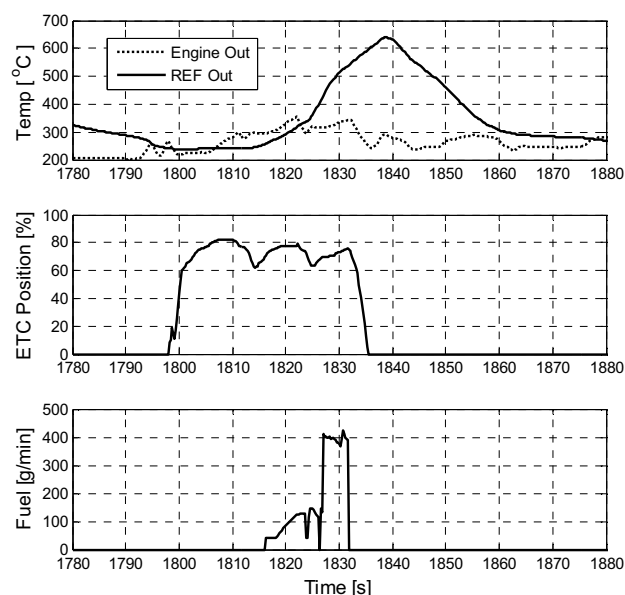


Figure 6: Reformer Light-off Support

Once the REF LOT is reached, the tailpipe fuel injection begins running the REF through the warm-up and rich phases. If the exhaust conditions become unfavorable for REF operation during the regeneration, the fueling will pause until the conditions become favorable again. The REF warm-up is accomplished by running a real-time REF thermal model in the controller. The controller calculates the appropriate fuel injection rate, accounting for variations in exhaust temperature, flow, and O_2 concentration. After the REF warm-up is complete the REF is switched to rich operation targeting a $\phi > 1$. During the rich phase, the real-time REF model is utilized to predict the REF temperature and reductant production. Rich REF operation is continued until the required amount of reductant has been generated (based on model prediction) to purge the stored NOx from the LNT. Once the regeneration is complete, the system will return to the original state monitoring NOx accumulation on the LNT.

DPF Regeneration

Another objective of a diesel aftertreatment system is to reduce PM. This is accomplished by using a DPF filter located between the LNT and SCR catalysts. By placing the DPF between the LNT and SCR, passive DPF regeneration will occur, but periodic active regeneration is