

Performance of a Fuel Reformer, LNT and SCR Aftertreatment System Following 500 LNT Desulfation Events

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ABSTRACT

An advanced exhaust aftertreatment system is characterized following end-of-life catalyst aging to meet final Tier 4 off-highway emission requirements. This system consists of a fuel dosing system, mixing elements, fuel reformer, lean NO_x trap (LNT), diesel particulate filter (DPF), and a selective catalytic reduction (SCR) catalyst. The fuel reformer is used to generate hydrogen (H₂) and carbon monoxide (CO) from 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 paper addresses system durability as the catalysts were aged to 500 desulfation events using an off-highway diesel engine. Catalyst performance was characterized at three engine operating conditions to quantify catalyst durability. The LNT catalyst performance stabilized after 250 desulfation events. The downstream SCR catalyst yielded stable performance across all desulfation events. Results confirm that NO_x conversions required for meeting final Tier 4 off-highway emissions are feasible with catalysts aged to the end of the emissions useful life using this fuel reformer, LNT and SCR based aftertreatment system.

off-highway vehicles will be required in 2014. This paper addresses the feasibility of an aftertreatment system to meet final Tier 4 emissions standard of 0.4 g/kW-hr NO_x [1]. The 0.4 g/kW-hr NO_x standard is applicable for engines having rated power levels above 56 kW.

The aftertreatment system consists of a fuel dosing system, mixing elements, fuel reformer, lean NO_x trap (LNT), diesel particulate filter (DPF), and selective catalytic reduction (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 [2,3]. A fuel reformer is utilized to generate hydrogen (H₂) and carbon monoxide (CO) from 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 [4-8]. A similar system was evaluated following desulfation (DeSO_x) aging to 150 events [4]. The current study evaluates system performance following 500 DeSO_x events.

INTRODUCTION

The Environmental Protection Agency (EPA) issued emission legislation for future diesel engine vehicles. Strict emission standards will be required for on-highway vehicles in 2010 while final Tier 4 emission standards for

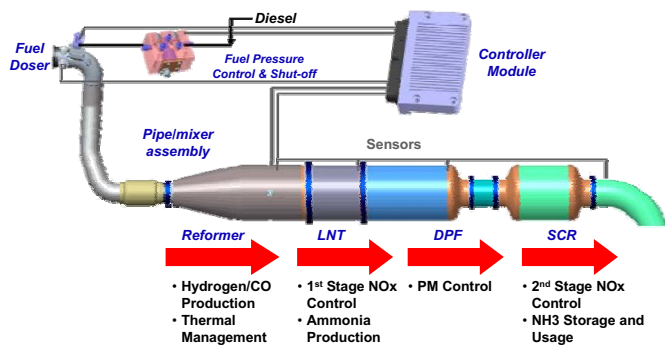


Figure 1: Aftertreatment system layout.

VALUE PROPOSITION - The aftertreatment system shown in Figure 1 was designed to meet the strictest diesel emission standards (final Tier 4 off-highway and 2010 on-highway standards). The system was also designed to be scalable with engine power or size, and to meet customers' reliability standards. The system offers four core values for customers:

- Single fluid system (one dosing system needed)
- Independence from urea solution & infrastructure
- Independence from urea sensors and compliance related penalties
- Flexible, customized and compact packaging

REFORMER OPERATION OVERVIEW - The reformer has two main functions during regenerations, 1) to consume the residual oxygen in the exhaust gas stream, and 2) to convert remaining reformer fuel to the reductants, H_2 and CO . Operation of this reformer is cited in literature [4, 5, 7-9]. Because the reformer requires a uniform fuel distribution at the inlet, the optimization of fuel doser, mixing, and vaporization system from [10] was used in this study. Typical reformer control during a high engine load operation (1800 rpm, 100% load) is shown in Figure 2. Fuel is injected into the reformer to warm the catalyst to its proper operating temperature. Engine out oxygen is then reduced via engine control to a lower oxygen operating mode from 7.2% to 3.2%. A higher fueling rate is commanded to consume the remaining oxygen as depicted by the tailpipe oxygen dropping to zero. This higher rate creates a rich condition where reformate is produced, depicted by the predicted CO and H_2 profiles. The reformate is key to regenerating and desulfating the downstream LNT.

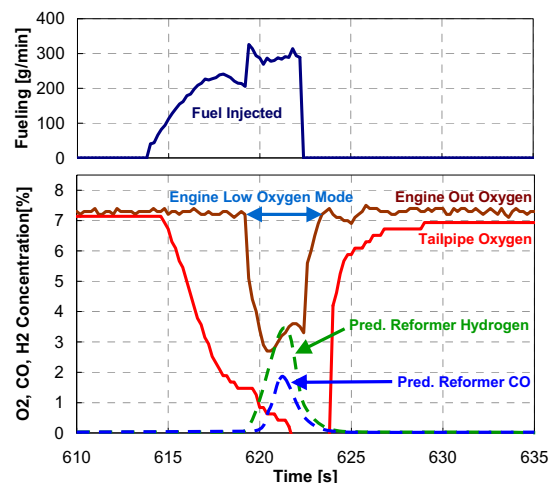


Figure 2: Typical reformer operation (1800 rpm, 100% load).

ACCELERATED AGING PREP - The LNT and SCR catalysts were sized appropriately for an off-highway engine in the 7L displacement range prior to desulfation testing. Hydrothermally aged LNT catalysts were used for preliminary performance characterization to be representative of mid-life catalyst aging. Both the LNT and the SCR were sized to 1.5 times the engine displacement volume. In addition to the sizing, control logic was calibrated and implemented lowering exhaust oxygen concentration (engine in-cylinder) during LNT regeneration/desulfation (i.e., rich mode operation). Lower exhaust oxygen concentrations were desired to minimize fuel usage. The aftertreatment electronic control unit (AT-ECU) triggered the engine electronic control unit (ECU) via J1939 to command a lower engine oxygen mode during LNT regeneration and DeSOx. Prior to the start of the 500 DeSOx events, the LNT and SCR were removed and replaced with fresh catalysts.

ENGINE OPERATING CONDITIONS - Performance was characterized at three engine operating conditions over the 500 DeSOx events: 1800 rpm-50% load, 1800 rpm-75% load, and 1800 rpm-100% load. Engine speed was held constant for the program to accelerate testing. The nomenclature corresponding to the engine operating conditions is 1800-50, 1800-75, and 1800-100, respectively. These three operating conditions are representative of higher duty cycles for off-highway applications. Additionally, previous studies conducted over 13 mode emission test cycles confirmed that these operating conditions are the more difficult modes to meet the emissions standards [5]. This is due to the higher exhaust flow (i.e. 1800 rpm) combined with higher temperature at the 100% load operating condition.

END OF LIFE OVERVIEW - Desulfation events were conducted using an off-highway engine having an emission useful life of 8000 hours. Estimates of the sulfur concentrations in both the fuel and the oil were used to determine the number of DeSOx events and required sulfur loading. In Q4 2000, the EPA estimated

ultra low sulfur diesel (ULSD) fuel sulfur levels to be 7 to 10 ppm [11]. Recent studies by the American Transportation Research Institute revealed that the mean ULSD fuel sulfur level was 6 - 7 ppm at the diesel fuel pump in Q4 2008 [12]. The contribution of sulfur from the oil also needs to be considered. The EPA estimated that the engine oil would contribute between 2 and 7 ppm sulfur based on the fuel consumed by the engine [11]. A conservative value for the total sulfur from fuel and engine oil was estimated to be 12 ppm on a fuel basis.

The total fuel consumed from a fleet of off-highway vehicles was tallied and the required number of DeSOx events was calculated. It was determined that 500 DeSOx events were required to meet the emission useful life requirements for high-duty cycle off-highway applications. This corresponded to a total of 2520 grams of sulfur loaded on the LNT over the life of the system. Prior to each DeSOx event, sulfur was added to the LNT to a level of 0.5 g/L using an LNT volume of 1.5 times engine displacement. This is consistent with a previous DeSOx study [4]. This analysis equates to one DeSOx event every 16 hours over the emissions useful life of an off-highway vehicle. The number of DeSOx events along with the cumulative sulfur addition is shown in Figure 3. Aging would normally have taken 1000 normal (8 hour) working days. Because of the accelerated nature of this program, a total of 84 days were required for this aging (includes weekends).

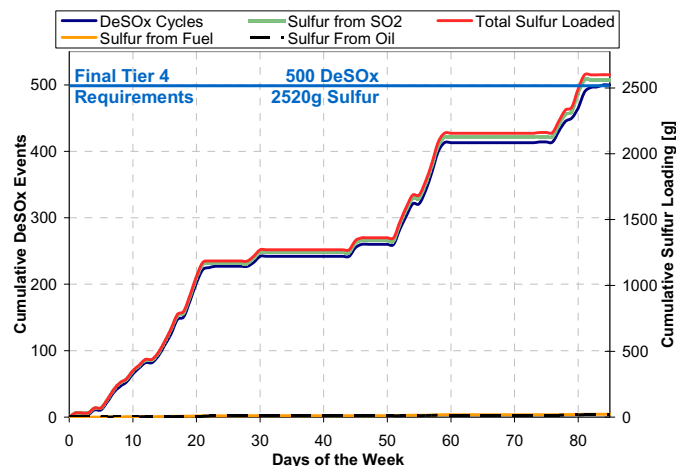


Figure 3: End of life requirements for cumulative desulfations and sulfur loading.

The off-highway emission useful life of 8000 hours is nearly equivalent to the heavy duty on-highway standard of 435,000 miles. Heavy duty on-highway vehicles have a useful life of approximately 1,000,000 miles while off-highway vehicles have a useful life of 20,000 hours. The ratio of the emissions useful life to the vehicle useful life is nearly equivalent for off-highway and heavy duty on-highway vehicles. Medium duty on-highway vehicles have an emission useful life of 185,000 miles. Using the required number of DeSOx events for off-highway and the ratio of the medium duty to heavy duty emission

useful life levels yields an on-highway medium duty emissions useful life of 213 DeSOx events.

Previous studies estimated that the required number of DeSOx events for medium duty on-highway vehicles was 300 events [5]. The study assumed a higher total fuel and oil sulfur level of 16 ppm; however, this was performed prior to more recent fuel estimates. Applying the most recent fuel sulfur levels, only 225 DeSOx events would be required for medium duty on-highway vehicles. This corresponds well with the estimate of 213 events in this study. As a result, 500 DeSOx events are required for off-highway and heavy duty on-highway vehicles to meet emissions useful life. Approximately 213-225 DeSOx events are required for medium duty on-highway vehicles.

EXPERIMENTAL SETUP

Figure 4 shows the experimental system layout used for the 500 DeSOx event aging program. 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. For reference, the specific distances between components are listed:

- 1.3 m between fuel doser and reformer inlet
- 4.6 m between DPF outlet and SCR inlet due to mounting constraints in the test cell

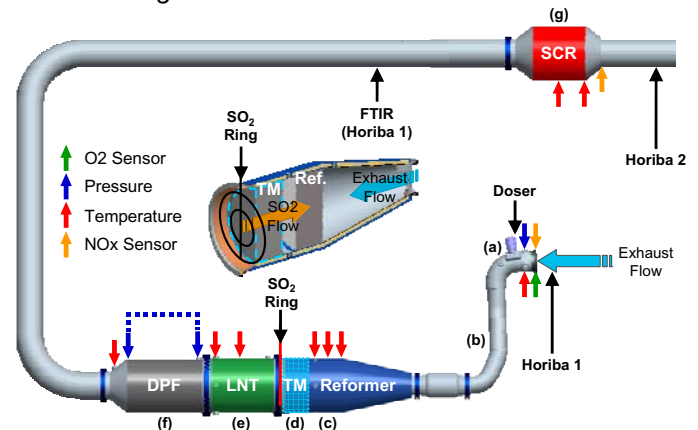


Figure 4: Experimental system layout.

ANALYZER LOCATIONS - Emissions analyzers and sensors were used to characterize performance and monitor diagnostics. NOx and UEGO oxygen sensors were used at engine and SCR outlet for aftertreatment controls and diagnostics. A Horiba Mexa 7170D analyzer (Horiba 1) was also used at engine out to measure NOx, NO₂, total hydrocarbons (HC's), oxygen (O₂), carbon monoxide (CO), and carbon dioxide (CO₂). A correlation was established between the Horiba analyzer at engine out and the NOx sensor at engine out. A Horiba Mexa 6000FT Fourier transform infrared spectroscopy (FTIR) analyzer was used at SCR inlet to measure NOx, NO, NO₂, and ammonia (NH₃). Due to constraints in the test cell, the Horiba 1 was occasionally used at SCR inlet in place of the FTIR.

Mexa 7170DEGR analyzer (Horiba 2) was used at SCR outlet to measure NO_x, NO₂, HC's, O₂, CO, and CO₂.

THERMOCOUPLE LOCATIONS - The catalyst brick and exhaust gas temperatures were characterized using thirteen thermocouples as shown in Figure 5. Gas thermocouples were located approximately 13 mm from the face of each catalyst. Reformer gas thermocouples were arranged 51 mm from the centerline at various circumferential positions. Brick thermocouples were located at a depth of 25 mm into the brick. These were placed at the centerline or outer edge (104 mm from the center) of the brick. The AT-ECU used a select number of thermocouples for feedback control.

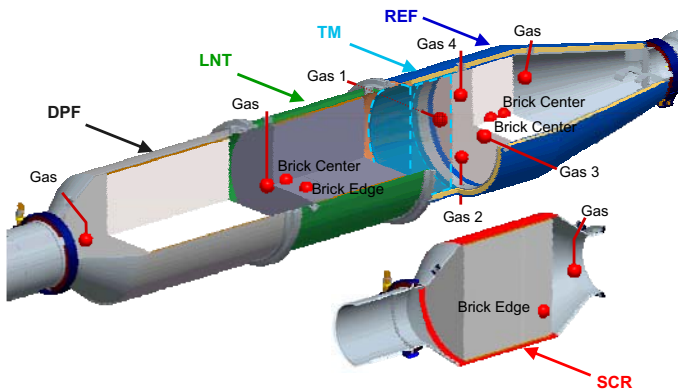


Figure 5: Catalyst thermocouple locations.

TEST PLAN

Testing was conducted using a test cell computer controlled automated program that consisted of four main phases as shown in Figure 6. The testing was accelerated using sulfur dioxide gas (SO₂) as opposed to accelerating aging using a higher sulfur fuel [4].

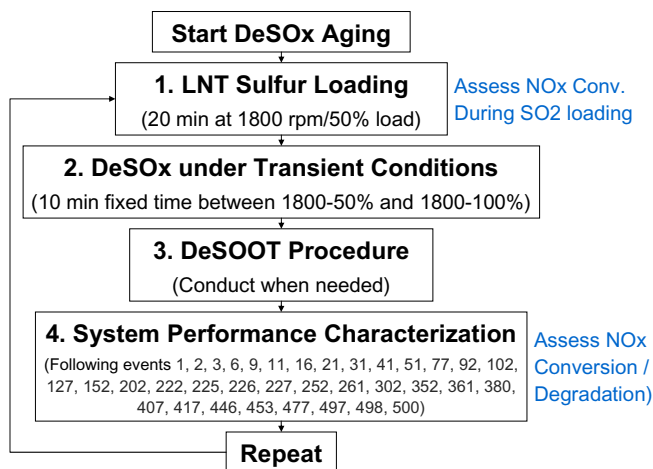


Figure 6: Test protocol overview.

1. **LNT Sulfur Loading** - Sulfur was added to the LNT catalyst at the 1800-50 operating condition.

2. **Transient DeSO_x** - Sulfur stored on the LNT catalyst was removed using DeSO_x events under transient engine operation.
3. **DPF Regeneration (DeSOOT)** - The AT-ECU used pressure sensors across the DPF as one input to assess the filter soot loading and to enable a DeSOOT. DPF regenerations were not needed for this integration of engine and aftertreatment system.
4. **Performance Characterization** - System performance was characterized at 35 intervals over 500 DeSO_x events to resolve system performance at the three engine operating conditions (1800-50, 1800-75 and 1800-100).

AUTOMATED TEST PROGRAM - The test program sequence was automated, as shown in Figure 7, to accelerate testing. This automation also allowed testing to run unattended while diagnostics monitored for system and test cell issues.

The sulfation/ desulfation phase of the program was repeated 500 times while performance was characterized 35 times. The aftertreatment system sensors were in operation throughout all test phases and were used for diagnostics and controls. During the performance characterization portion of the program, emissions analyzers were engaged automatically. The emissions analyzers were used in conjunction with the aftertreatment sensors to monitor performance.

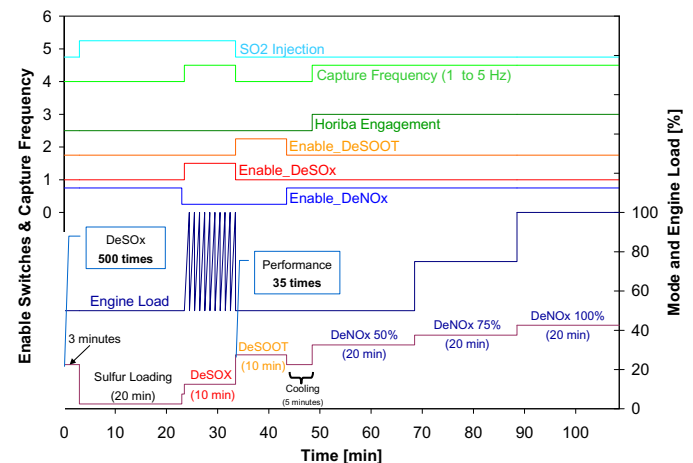


Figure 7: Automated test protocol.

TRANSIENT OPERATION - Sulfur was removed from the LNT with DeSO_x events while the engine was operated under transient conditions. The transient engine operation is shown in Figure 8. Engine load was ramped from 50% to 100% in 58 seconds followed by an immediate drop to 50% load in approximately 2 seconds. This transient engine operation is a difficult condition for catalyst temperature control and was utilized to be representative of transient off-highway vehicle operation.

During catalyst warm-up, the AT-ECU commanded the engine to operate in normal oxygen mode. Once the temperature threshold was met, low oxygen mode was