

Aftertreatment Architecture and Control Methodologies for Future Light Duty Diesel Emission Regulations

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ABSTRACT

Future light duty vehicles in the United States are required to be certified on the FTP-75 cycle to meet Tier 3 or LEV III emission standards [1, 2]. The cold phase of this cycle is heavily weighted and mitigation of emissions during this phase is crucial to meet the low tail pipe emission targets [3, 4]. In this work, a novel aftertreatment architecture and controls to improve Nitrogen Oxides (NO_x) and Hydrocarbon (HC) or Non Methane Organic gases (NMOG) conversion efficiencies at low temperatures is proposed. This includes a passive NO_x & HC adsorber, termed the diesel Cold Start Concept (dCSC™) catalyst, followed by a Selective Catalytic Reduction catalyst on Filter (SCR®) and an under-floor Selective Catalytic Reduction catalyst (SCR). The system utilizes a gaseous ammonia delivery system capable of dosing at two locations to maximize NO_x conversion and minimize parasitic ammonia oxidation and ammonia slip. This aftertreatment system was evaluated on the chassis dynamometer and demonstrated the potential to achieve Tier 3 Bin 30 (T3B30) or SULEV30 emissions on the FTP-75 (Federal Test Procedure) cycle and HWFET (highway fuel economy) test cycles. A similar aftertreatment architecture, consisting of a Diesel Oxidation Catalyst (DOC) instead of a diesel cold start concept catalyst, was also evaluated. This system demonstrated the potential to achieve Tier 3 Bin 125 or ULEV125 emissions on the FTP-75 cycle. The aftertreatment architecture with the diesel cold start concept catalyst in place of the DOC was a key enabler to improve the low temperature NO_x and HC conversions to demonstrate the potential to meet Tier 3 Bin 30 or SULEV30 regulations.

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INTRODUCTION

Lower carbon foot print, improved fuel economy and mitigation of environmental pollutants are the potential driving factors for the Department of Energy (DoE) to engage in supporting a light duty diesel engine program for the United States automotive market. Cummins Inc., Johnson Matthey Inc. and Nissan partnered along with the DoE in the Advance Technology Light Automotive Systems (ATLAS) program [5]. The overall objective of this program was to design, develop, and demonstrate a state-of-the-art light-duty diesel vehicle that can demonstrate the potential to meet the United States Environmental Protection Agency (EPA) Light-Duty T2B2 or T3B30 emission standards and increase fuel efficiency by at least 40% compared with a state-of-the-art port fuel-injected gasoline engine powered vehicle (MY 2010 V8 5.0L 2WD Nissan Titan) [5]. The vehicle was tested at an estimated test weight of 5500 lbs. This paper will delve into both aftertreatment and control technologies that have been researched in this program.

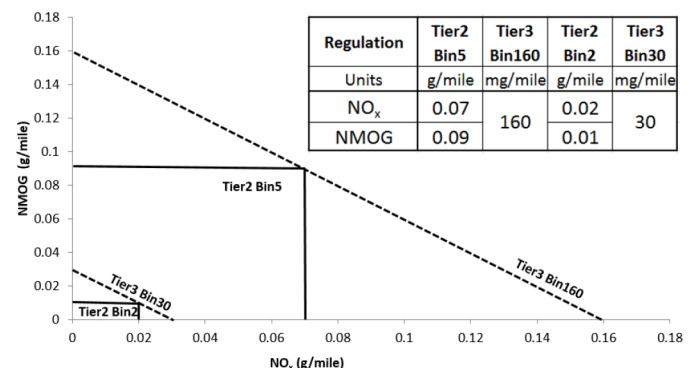


Figure 1. Reduction Trends in Tail Pipe Emission Targets [6, 7]

This paper contains several references to Tier 2 and Tier 3 emission standards and compares Tier 2 and Tier 3 standards for NO_x and NMOG targets for comparable bins as shown in Figure 1. The Tier 3 or LEV III standards modified the Tier 2 or LEV II standards in several

ways: (1) combined NMOG and NO_x standards into one NMOG+ NO_x standard, (2) introduced a more stringent combined NMOG+ NO_x fleet average requirement (3) added several emission standard bins, and (4) increased durability requirements for emission control systems [1, 2].

CHALLENGES WITH THE BASELINE SYSTEM

The baseline for the ATLAS program is a MY 2011 Cummins ISF 2.8L Euro IV, Class III certified engine. Engine out NO_x and NMOG emissions for this engine with no modifications are shown in Table 1 below. In order to meet the T2B2 or T3B30 emission levels, an aftertreatment system capable of at least 99% conversion in NO_x and 99.5% conversion in NMOG is required for the same engine out emissions as the base engine. This task cannot be accomplished by the aftertreatment system alone considering the required emission reduction capabilities as shown by Henry *et al.* [4]. System level optimization is required to improve NO_x and NMOG conversion efficiencies and reduce engine out emissions. Table 1 shows the engine out emissions for the engines that were developed and tested as part of this program, which were previously discussed in detail by Suresh *et al.*, [8].

The aftertreatment development for the program has two stages, at the first stage, the potential to demonstrate T2B5 or Tier 3 Bin 160 emissions will be discussed followed by the potential to demonstrate T2B2 or Tier 3 Bin 30 emissions at the second stage. The aftertreatment architecture and path to T2B5 and T2B2 are described in the following sections.

Table 1. Engine out Emissions over FTP-75

Engine Variant	Engine out emissions		T2 Bin5 (T3 Bin160) Conv %		T2 Bin2 (T3 Bin30) Conv %	
	NO_x	NMOG	NO_x	NMOG	NO_x	NMOG
	g/mile	g/mile	%	%	%	%
Baseline MY 2011 ISF	2.00	1.90	96.5	95.3	99.0	99.5
ATLAS Mule	0.80	0.56	91.3	83.9	97.5	98.2
ATLAS HP+LP EGR	0.40	0.26	82.5	65.4	95.0	96.2

APPROACH TO TIER 2 BIN 5 OR TIER 3 BIN 160 SYSTEM

The MY 2011 2.8L ISF engine was optimized to reduce engine out NO_x ($\text{NO}+\text{NO}_2$) by making improvements to the fuel delivery and air handling systems. The modified engine was referred to as the ATLAS “mule engine”. 60% reduction in engine out NO_x and 70% reduction in engine out NMOG was achieved. Engine out emissions and required conversion efficiencies over the aftertreatment system are shown in Table 1.

Aftertreatment Architecture for T2B5 System

Typical particulate filters used in diesel applications are coated with precious metals (e.g., Pt, and Pd) to facilitate soot oxidation, nitric oxide (NO) oxidation and CO/HC oxidation. However, the particulate filter utilized in this study was coated, instead, with a selective catalytic reduction catalyst or SCR on DPF to facilitate close coupling of the SCR functionality with the engine outlet. This resulted in faster warm up of the catalyst and hence achieved increased NO_x

conversion during cold start conditions. In addition, flow through SCR catalysts were used in the under-floor location for further reduction of NO_x when necessary, such as high engine load excursions and active regeneration of the SCR on DPF catalyst. A state-of-the-art Copper-Zeolite based SCR on DPF catalyst and flow through SCR catalysts were used in this study. SCR catalyst performance at various aging states and temperatures have been discussed previously by Luo *et al.* [9].

A gaseous ammonia delivery system was used to enable low temperature NO_x conversion by allowing delivery of the reductant required for the SCR reaction at significantly lower temperatures compared to urea dosing systems. Unlike urea based systems, the gaseous ammonia delivery system does not require long mixing lengths and long residence times for urea decomposition/hydrolysis reactions and thus enabled close coupling of the SCR on DPF catalyst to the engine for faster warm up. In order to demonstrate the potential to meet T2B5 emission targets, the key enablers were the SCR on DPF catalyst and the gaseous ammonia dosing system. The gaseous ammonia (NH_3) dosing system used has been described by Johannessen *et al.* [10].

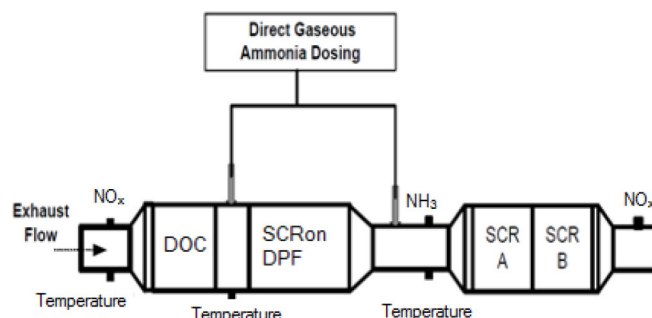


Figure 2. Aftertreatment Architecture for T2B5 System

Figure 2 shows the prime path architecture for the T2B5 system. The prime path for architecture packaging was based on analysis at several conditions. The DOC and SCR on DPF catalysts were close coupled to improve cold start NO_x control and minimize fuel penalty during active regeneration operation. Detailed analysis was performed including modeling work, simulating real world driving conditions and active regeneration conditions to position the flow through SCR at an optimum distance from the SCR on DPF catalyst to maximize its effectiveness under normal driving conditions (non-desoot) and minimize thermal aging. Ammonia was dosed either upstream or downstream of the SCR on DPF catalyst.

Table 2. Information of the Aftertreatment System used for demonstration of T2B5 comparable emissions levels

Catalyst Function	Substrate Type	Catalyst Dimensions	Catalyst Aging
DOC	Cordierite	5.66" x 4"	700 C/ 24 Hours
SCR on DPF	Silicon Carbide	5.66" x 6"	700 C/ 24 Hours
SCR Brick A	Cordierite	4.66" x 3"	650 C/ 24 Hours
SCR Brick B	Cordierite	5.66" x 4"	650 C/ 24 Hours



Documents

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Table 2 shows the final aftertreatment options chosen for targeting T2B5 emission levels. The optimal DOC was selected based on optimizing the HC oxidation while achieving a cycle average 50% NO_2/NO_x split entering the SCR on DPF catalyst to promote the fast SCR reaction. Multiple filter substrates were screened which included cordierite, silicon carbide and mullite from various suppliers. The SCR on DPF filter substrate selection was based on optimal warm up characteristics, lower clean back pressure, optimal soot loaded pressure drop response, ash loading capacity and soot loading capacity. Catalyst sizing was based on packaging volume available in the Nissan Titan truck, the maximum space velocities and the required storage and conversion efficiencies of NO_x , HC and CO. The impact to active and passive PM oxidation rates and subsequently active regeneration frequencies due to the absence of precious metals in the SCR on DPF was not evaluated in detail. The DOC and SCR on DPF catalysts were hydrothermally aged at 700°C for 24 hours in 10% H_2O in air while the flow through SCR catalysts were hydrothermally aged at 650°C for 24 hours in 10% H_2O and air before evaluations. Since the flow through SCR catalysts were located in an under floor location compared to the engine mounted DOC and SCR on DPF catalysts, they get exposed to lower temperatures and hence a milder hydrothermal aging condition was used. A catalyst aging study was performed to assist with the SCR formulation selection by evaluating the degradation of the NO_x conversion after end of useful life equivalent engine aging (accelerated engine aging to 120K miles equivalent).

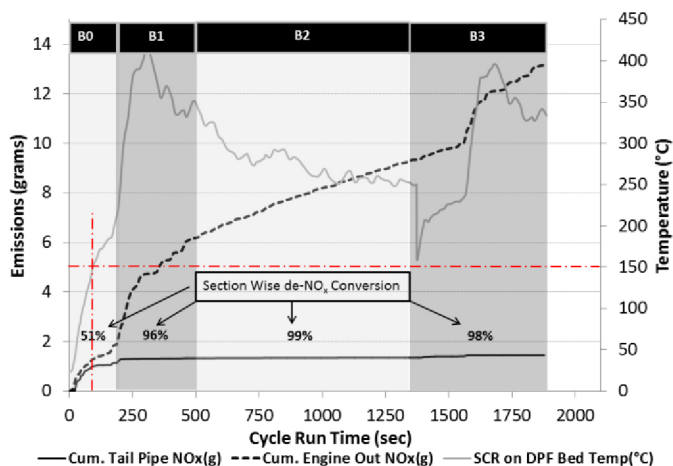


Figure 3. NO_x Emissions, NO_x Conversion Efficiency and SCR on DPF Bed Temperature during FTP-75

To better evaluate the cold start performance of the aftertreatment system during the FTP-75, the entire cycle was divided into 4 sections. Figure 3 shows these sections of the FTP-75 cycle represented as B0, B1, B2 and B3. Bag 1 of the FTP-75 consists of B0 (the first 200 seconds) and B1 (from 200 to 505 seconds), while B2 represents Bag 2 (505-1369 seconds) and B3 represents Bag 3 emissions (505 seconds post 10-minute soak after the end of Bag 2). A closer look at the NO_x conversion over the FTP-75 cycle during the various sections described above clearly shows that the majority of tail pipe NO_x is generated during B0 or the first 200 seconds of the FTP-75 with the aftertreatment architecture shown in Figure 2. Splitting up bag 1 into B0 and B1 facilitated separate design targets

for aftertreatment and engine during cold and warm-up operation. The 10 minute soak portion during the FTP-75 has been omitted in Figure 3 for ease of representation.

Results of SCR Formulation Selection Study

Figure 4 shows the normalized results from the aging study performed with the optimal Cu SCR formulation under FTP-75, HWFET and US06 cycles. The results indicate no significant degradation of performance between a de-greened (4k miles equivalent aged) catalyst versus an aged (120k miles equivalent) catalyst.

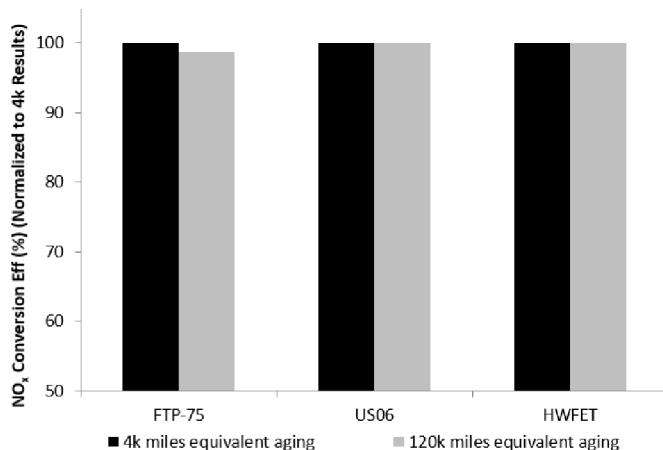


Figure 4. NO_x Conversion over FTP-75, US06 & HWFET after 4k and 120k miles equivalent aging

Emission Results for T2B5 Architecture

The control requirements for the proposed aftertreatment architecture in this paper are to maximize the NO_x conversion efficiency while minimizing the total NH_3 consumption and tail pipe emissions. The control system hardware for the aftertreatment architecture proposed for the T2B5 system includes actuators for NH_3 dosing, sensors to measure NO_x and NH_3 concentrations and sensors for gas temperature measurements as shown in Figure 2. The NH_3 dosing actuators are located at both upstream and downstream of the SCR on DPF catalyst. The NO_x sensors are located at engine out and system out or tail pipe locations and the NH_3 sensor is located downstream of the SCR on DPF catalyst. The gas temperature sensors are located at DOC inlet, outlet and SCR inlet locations.

The base NO_x reduction controller concept used only the upstream NH_3 dosing actuator for delivering NH_3 to both the SCR on DPF and underfloor SCR catalysts under normal operating conditions (non-desoot), while the downstream NH_3 dosing actuator was used only during desoot or active regeneration events to deliver NH_3 to the underfloor SCR catalysts. Since the NO_x conversion capability of the upstream SCR on DPF catalyst is limited or inhibited by parasitic NH_3 oxidation at high temperatures ($>550^\circ\text{C}$), under the high temperature operating conditions in the SCR on DPF catalyst, such as during a desoot event, the NO_x reduction was achieved using the under floor SCR system which is typically at around 450°C during desoot events. The NO_x reduction controller under normal operating conditions has feed-forward and feed-back control loops and utilizes the system