

Development of Emission Control Systems to Enable High NO_x Conversion on Heavy Duty Diesel Engines

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ABSTRACT

Selective Catalytic Reduction (SCR) systems have been demonstrated as effective solutions for controlling NO_x emissions from Heavy Duty diesel engines. Future HD diesel engines are being designed for higher engine out NO_x to improve fuel economy, while discussions are in progress for tightening NO_x emissions from HD engines post 2020. This will require increasingly higher NO_x conversions across the emission control system and will challenge the current aftertreatment designs. Typical 2010/2013 Heavy Duty systems include a diesel oxidation catalyst (DOC) along with a catalyzed diesel particulate filter (CDPF) in addition to the SCR sub-assembly. For future aftertreatment designs, advanced technologies such as cold start concept (dCSC™) catalyst, SCR coated on filter (SCR-F® hereafter referred to as SCR-DPF) and SCR coated on high porous flow through substrates can be utilized to achieve high NO_x conversions, in combination with improved control strategies.

The objective of this work is to evaluate different advanced emission control system options in order to meet future high NO_x conversions.

First, high performance NO_x control system architecture was designed by using a combination of dCSC catalyst, SCR-DPF filter system and high performance SCR on high porosity substrates. In this architecture, dCSC technology stores NO_x during cold start when system is cold for any SCR reaction and then releases when the system warms up to allow NO_x reduction across the SCR-DPF filter. The SCR-DPF filter enables lower temperature NO_x conversion due to its location closer to the turbo and improved SCR coating. Finally the advance SCR on high porosity substrate provides additional NO_x reduction to achieve overall very high NO_x control.

Second, the impact of different parameters on the system performance was studied. This included, changes in engine out NO_x concentration, early availability of ammonia, different dosing strategies and rapid catalyst warm up during cold start.

Tests were carried out on a HD engine under transient test cycles. The results indicated that NO_x conversion can be significantly improved using the proposed design in combination with early availability of ammonia in the system. In addition, implementation of thermal management improved the NO_x conversion at lower temperature. The results of this work demonstrated that such systems along with improvement in control strategies can provide >95% NO_x conversion under cold FTP transient cycle and will allow diesel engines to meet future emission regulations and fuel economy.

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INTRODUCTION

To meet NO_x emission requirements and regulations for heavy duty diesel engines, selective catalytic reduction (SCR) has been demonstrated to be an effective solution. With increasing demand for improved fuel economy there is a desire to improve the NO_x emission reduction of the SCR system, thus allowing for higher engine out NO_x emissions. Such requirements will challenge the current aftertreatment designs, which consist of DOC, catalyzed soot filter (CSF) and SCR units. One approach is to replace the CSF with a diesel particulate filter coated with SCR (SCR-DPF) while keeping the flow-through SCR downstream. The downstream SCR can also be improved by using a highly porous flow-through substrate coated

with higher washcoat loadings than those typically used on standard substrates today. This design will not only allow for improvement of NO_x conversion at low temperature since the SCR-DPF unit will be closer to turbo out, but also an increased number of SCR active sites can be placed in the overall system without increasing the packing size in a typical 2010/13 system and thus provide high NO_x conversion. For the SCR-DPF technology, high porosity filters are needed to enable the use of the higher catalytic loadings necessary to get good performance and durability. These highly porous filters need to have very good thermo mechanical properties to enable them to survive the active regeneration events over the life of the system. Also, a novel catalyst known as diesel Cold Start Concept (dCSC™)

catalyst was introduced for cold start applications [1]. This Cold Start catalyst stores HC and NO_x at low temperatures with very high storage efficiencies. The NO_x release temperature in a cold start catalyst is designed to be high enough that the released NO_x can be further converted by the downstream catalytic components.

Previous work has demonstrated that SCR-DPF systems have high NO_x conversion capabilities [2,3,4,5]. For the downstream flow through SCR catalysts, work is continuing to demonstrate that high NO_x reduction can be achieved by placing a high amount of active catalytic material on highly porous and high cell density flow through substrates [6,7,8]. In the current study, results are being presented from the evaluation of combinations of a cold start catalyst plus SCR-DPF unit with downstream high porosity SCR catalysts to achieve high NO_x conversions. The performance was evaluated on an engine with high engine out NO_x. First, the NO_x conversion capability of these systems was evaluated during standard transient FTP protocol cycle. Second, different control strategies were evaluated to understand the effect of reductant dosing strategy and thermal management on NO_x conversion.

EXPERIMENTAL

In previous paper [9], it was shown that the best system for high NO_x conversion is a combination of DOC, SCR-DPF, and SCR on high porosity high cell density SCR catalyst. In the current work, two systems were utilized; they consisted of 1) diesel oxidation catalyst (DOC), SCR coated on DPF or SCR-DPF system and a high porosity, high cell density SCR catalyst, and 2) Cold Start Concept catalyst, SCR-DPF system and, a high porosity high cell density SCR catalyst. Cu-zeolite SCR catalyst technology was used in the systems for SCR-DPF technology and high porosity high cell density SCR. The system configurations are shown in Figure 1. The different substrate details and aging conditions are shown in Table 1.

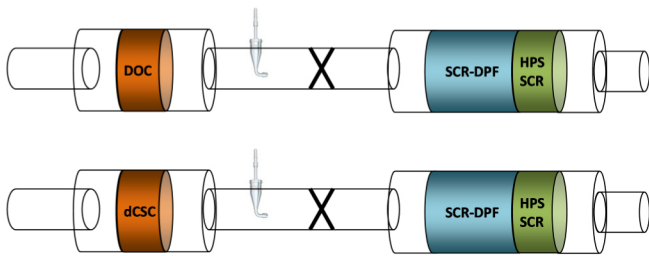


Figure 1. System Configurations

As shown in Table 1, SCR-DPF component used for this study was on a NGK cordierite C650, 300 cells per square inch and with 12 mil wall thickness. The high porosity high cell density flow through substrates (HPS) used for SCR was on NGK cordierite 600 cells per square inch with 4 mil wall thickness. All components were hydrothermally aged at 650°C for 100 hours, prior to testing. There was 10% water present during hydrothermal aging.

Table 1. Catalyst Information

	Substrate	Size (in)	Aging Condition
DOC	NGK-400cpsi/7mil	10.5x4	650°C/100 hours
dCSC	NGK-400cpsi/7mil	10.5x6	650°C/100 hours
SCR-DPF	NGK C650-300cpsi/12mil	10.5x12	650°C/100 hours
SCR	NGK-HPS 600cpsi/4 mil	10.5x6	650°C/100 hours

Testing was conducted using a 2007 model year Cummins ISL diesel engine. Engine details are shown in Table 2. During this study, EGR was adjusted to have 4.0 g/hp-hr engine out NO_x. Urea was delivered and injected into the exhaust by an air assisted Grundfos pump. A six inch static mixer was placed after the injection nozzle and before the SCR-DPF unit to ensure good mixing and uniform urea distribution in the exhaust.

Table 2. Details of Engine

Model	Cummins ISL
Emissions Standard	EPA 2007
Displacement	8.9L
Type	4-stroke
Power	425 Hp
Config/Cylinders	Variable Geometry Turbocharger Inline 6 Cylinder
Controls	Electronic Control Module (ECM)
Certified Emission Level	
NO _x (g/bhp-hr)	1.5
NMHC (g/bhp-hr)	0.14
PM (g/bhp-hr)	0.01
NO _x Emission During Test (EGR Adjusted)	
NO _x (g/hp-hr) during cold FTP	4.0

The dynamometer utilized in this study was 800HP AC motoring dyno from Horiba. Intake air flow was measured with Sierra air flow meter ranging from 0-2400kg/hr with $\pm 1\%$ accuracy in full scale. Engine out emissions were measured using Horiba MEXA 7500D dual bench (CO, HC and NO_x) analyzers with $\pm 1\%$ accuracy across the full scale. System out emissions were also measured using an FTIR (MKS model 2030 HS). DPF backpressure was monitored using pressure transducers, Setra Model 206. Temperatures in the system were measured using K type thermocouples.

Heavy duty transient cycle (FTP) testing was conducted to determine the performance of this system. Cold and hot cycles were used during different parts of the study. The average ANR for urea dosing during transient cycles was 1.2-1.3. It should be noted that during this study soak/cool down time for cold FTP was 3hrs. This was done to reduce the experimental timing. Previous studies had shown that 3hrs of aftertreatment soaking would result in approximately the same inlet temperature as 8hrs soak time for cold FTP, which brings engine coolant and lube oil back to room temperature. There was less than 8°C difference up to 250 second into FTP cycle between two soaking methods. The SCR inlet temperature comparison is shown in Figure 2.

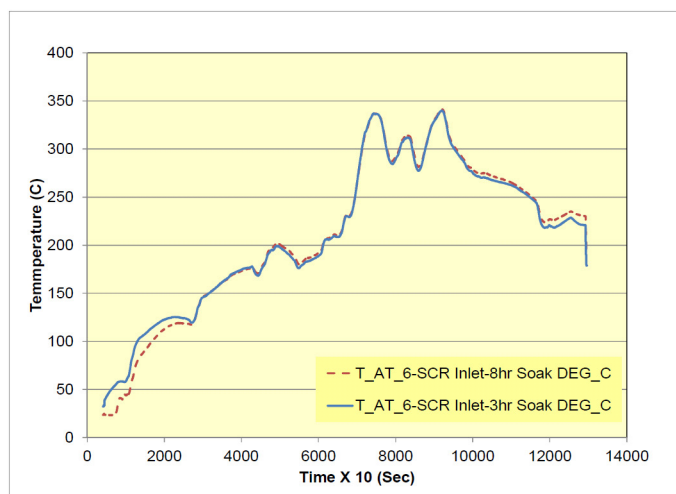
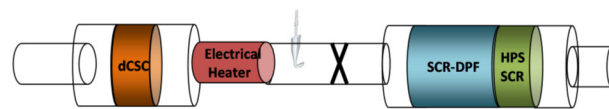


Figure 2. Comparison of SCR Inlet Temperature during Cold FTP between 3hrs and 8hrs Soak Time

A part of this study consisted of applying different reductant and control strategies during the cold transient FTP cycle.

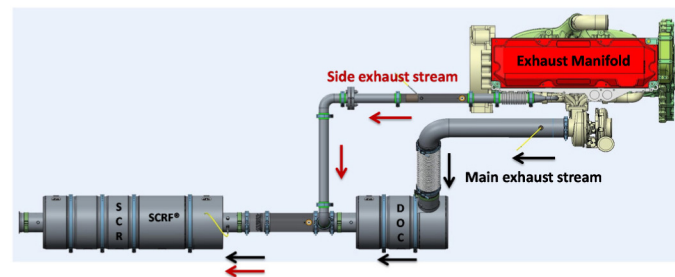
Three options were considered for this study. In one option, effect of dosing NH₃ gas under very cold temperature condition of the cold FTP cycle was evaluated. NH₃ gas was introduced during the cold sections while standard Urea dosing was resumed once the temperature was warm enough to enable Urea dosing. In another option, the impact of pre-stored NH₃ along with standard Urea dosing was evaluated. In the final and third option, an electrical heater was used to warm up the exhaust in the first 400 seconds of the cold FTP and its effect was evaluated under cold FTP along with NH₃ pre-saturation and standard Urea dosing. The maximum power for the

heater was 20KW. The heater was installed after either DOC or Cold Start Concept catalyst and before urea injection and SCR-DPF unit as shown in the schematic



System with Electrical Heater Schematic

A side flow NH₃ doser was designed in order to generate and inject NH₃ gas into the main exhaust for conditions when Urea could not be dosed due to very cold temperatures. The side flow NH₃ doser was connected to engine out turbo and a small amount of hot exhaust flow (approximately 15-25kg/hr) was pulled from the engine into the side flow system. Since flow was diverted from pre-turbo to the side flow doser, exhaust flow temperature was significantly higher than the main exhaust temperature. Urea was injected into the side flow reactor and it was converted into NH₃ gas over a hydrolysis catalyst. The NH₃ created was introduced back into the main exhaust, upstream of the mixer and the SCR-DPF component. The side flow NH₃ doser control was designed to start NH₃ injection into the main exhaust stream from the beginning of the cold FTP cycle, until the SCR-DPF unit inlet temperature reached 215°C. When temperature was greater than 215°C, the main urea dosing system was activated to inject urea into the exhaust, for the remainder of the cycle. Both system injection control strategies were set to maintain an overall ANR of approximately 1.2. The schematic is shown below.



Side NH₃ Doser Schematic

Results and Discussion

In this study, tests were carried out in two sections. In the first section, a high NO_x reduction capable system was designed by combining an SCR-DPF unit and higher performance SCR catalysts. This system included a DOC. The second system was designed by replacing the DOC with the Cold Start Concept catalyst. Engine testing was carried out to demonstrate and compare the performance characteristics of these two systems. In the subsequent section, the two mentioned systems were tested under different conditions to demonstrate how further performance enhancements can be achieved by using different control strategies, especially with respect to cold start testing. The different systems tested in the first section are shown in Table 3.