

An Approach to Controlling N₂O Emission on HDD On-Road Applications

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ABSTRACT

Control of N₂O emissions is a significant challenge for manufacturers of HDD On-Road engines and vehicles due to requirements for NO_x control and Green House Gas (GHG) Phases I & II requirements. OEMs continually strive to improve BSFE which often results in increased engine out NO_x (EO NO_x) emissions. Consequently, the necessity for higher NO_x conversions results in increased N₂O emissions over traditional SCR and SCR+ASC catalysts systems [1]. This study explores methods to improve NO_x conversion while reducing the SCR contribution of N₂O across the exhaust after treatment systems. For example, combinations of two traditional SCR catalysts, one Iron based and another Copper based, can be utilized at various proportions by volume to optimize their SCR efficiency while minimizing the N₂O emissions. Results show that a proper combination of catalysts volume can significantly reduce N₂O levels while simultaneously reaching the highest levels of NO_x performance achieved in the study. The results highlight the traditional expected tradeoff between N₂O emissions and NO_x performance across an ATS system while providing design guidance to manage this tradeoff and, equally importantly, confidence that solutions exist to meet ever tighter emission requirements.

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INTRODUCTION

The introduction of Phase II GHG requirements along with the CARB proposals reaching as low as 20 mg/bhp-hr NO_x has furthered the challenges faced by OEMs and their suppliers of Heavy Duty On-Road engine diesel aftertreatment components and systems [2, 3]. As OEM's strive for improved fuel and fluid economy there is a greater tendency for these GHG and CARB requirements to be in direct conflict.

Firstly, maximizing fuel economy often entails running the engine in a more efficient manner resulting in higher engine out NO_x. Therefore, in order to stay within the NO_x emissions limits, traditional systems requiring UREA decomposition to NH₃ for the reduction of NO_x across a Copper-zeolite based SCR catalyst must be designed with greater catalyst volume and/or managed with a more aggressive delivery of UREA.

Secondly, higher UREA dosing rates increase fluid consumption and, via the Ammonium Nitrate decomposition path or parasitic NH₃ oxidation, yield higher N₂O emissions across the commonly used Copper based SCR catalyst [4, 5]. N₂O is then directly translated into CO₂ by a factor of 298 thereby negatively impacting reported CO₂ emissions [6].

A first consideration toward reducing N₂O make would be to change the SCR technology. Iron and Vanadia SCR's are known to form lower levels of N₂O at NO₂/NO_x levels ≤ 0.5 on a molar ratio compared to Copper SCR [7]. However, relative to Iron SCR's, Copper shows improved performance at lower temperatures and

equivalent or better thermal durability. While several studies have shown good thermal durability of Vanadia based SCR's relative to Copper [8, 9], V-SCR is not included in this study due to its lower market acceptance for On Road HDD applications requiring periodic active filter regeneration [10].

Considering the pros and cons of Iron and Copper, a mix of Iron and Copper SCR can provide a good balance of NO_x control with low N₂O selectivity. Kamasamudram et. al. investigated a blend of catalysts at a fixed volume ratio and demonstrated the potential [7].

A specific study was performed to elucidate the benefits of combining an Iron zeolite SCR with a Copper zeolite SCR at various volume ratios on a standard heavy duty engine modified to mimic high efficiency operation which, subsequently, results in elevated EO NO_x levels. The volume ratios of the various SCR types was varied and their impact on NO_x and N₂O over the standard HDD FTP and RMC cycles has been summarized. It is noted that while N₂O emissions is not required to be reported over the RMC, this info is included for completeness. Additionally, the contribution to overall NO_x and N₂O system performance of a standard Copper based ASC situated behind each Fe/Cu combination will be investigated and summarized.

EXPERIMENTAL SETUP

Engine Setup and Instrumentation

All testing was performed on a 2010 Cummins 6.7L ISB engine as described in [Table 1](#).



Table 1. 2010 Cummins ISB Engine Specifications.

325 HP @ 2400 RPM
2 (Engine Out & Tailpipe) NOx sensors
2 Resistance Temperature Detectors
1 Delta Pressure sensor

The engine operating conditions were de-rated to reduce exhaust temperatures and the EGR was turned off during testing on the HDD FTP and RMC cycles to increase EO NOx levels to those expected from a higher efficiency engine slated for a Class 8 Line Haul vehicle. Specifically, the de-rating consisted of a 30% reduction in torque over the FTP and a 10%-30% reduction over the RMC depending on the mode. The combination of these changes resulted in a substantial increase in NOx and a reduction in CO₂ as shown in [Table 2](#).

Table 2. Emissions and CO₂: Stock Cummins engine and after modifications.

		Stock	Modified
HOT FTP (g/bhp-hr)	EO NO _x	1.85	6
	CO ₂	643	590
RMC (g/bhp-hr)	EO NO _x	1.95	5
	CO ₂	556	540

The system architecture consisted of a Diesel oxidation catalyst (DOC) at 27g/ft³ precious metal loading (pgm), a catalyzed diesel particulate filter (CDPF) at 3g/ft³ pgm, selective catalytic reduction catalysts (SCR) and an ammonia slip catalyst (ASC) at 3g/ft³ pgm all positioned in series. Two standard emission benches (Horiba Mexa-7500-DEGR - dual bench with 2 ovens) were used and two FTIRs (MultiGas™ 2030 HS) were used. An example of the system layout is shown in [Figure 1](#). The systems evaluated with corresponding catalyst geometry and volume are shown in [Table 3](#); the volume ratios of Fe to Cu included the following: 100Fe, 25Fe/75Cu, 50Fe/50Cu and 100Cu, whereas the number in front of the elemental name refer to the percent by volume of SCR catalyst.

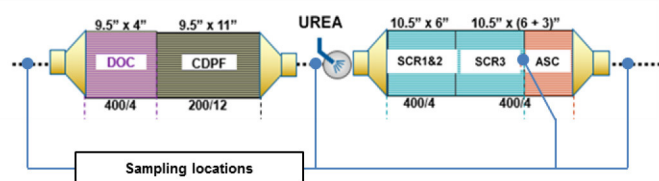


Figure 1. Catalyst configuration used for testing on Cummins ISB engine

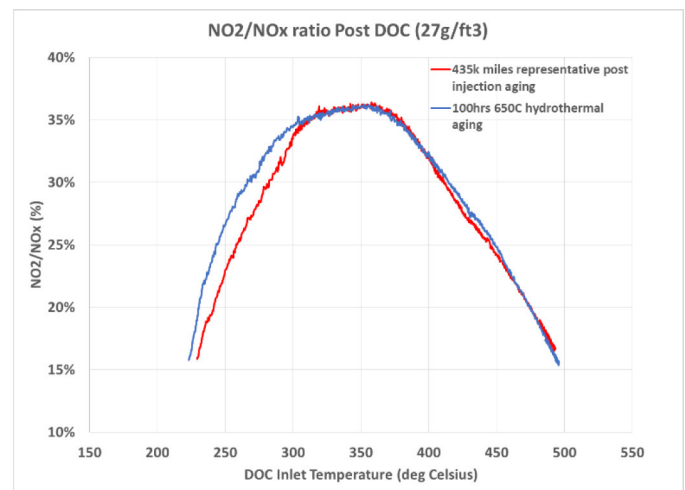
Table 3. Description of SCR systems tested.

System	Fe/Cu ratio	SCR1 type	SCR1 geometry	SCR2 type	SCR2 geometry	SCR3 type	SCR3 geometry
1	100Fe	Fe	10.5" x 6"	-	-	Fe	10.5" x 6"
2	25Fe/75Cu	Fe	10.5" x 3"	Cu	10.5" x 3"	Cu	10.5" x 6"
3	50Fe/50Cu	Fe	10.5" x 6"	-	-	Cu	10.5" x 6"
4	100Cu	Cu	10.5" x 6"	-	-	Cu	10.5" x 6"

Note: 10.5" x 6" = 8.5 liters

Aging and Urea Dosing Control

Two aging protocols were applied in this study. The first aging performed on all catalyst technology types consisted of 100 hrs at 650°C hydrothermal aging performed in an oven with 10% water in air. This aging was shown to yield similar NO₂/NO_x levels post DOC as an exhaust system dyno aged with diesel fuel injection in exhaust (DPF Regeneration) to represent 435,000 miles durability (see [Figure 2](#)).

Figure 2. NO₂/NO_x ratio post DOC during a temperature ramp on the Cummins ISB engine

The second aging protocol used was performed on engine bench using a proprietary cycle that targeted, via post injection, a typical regeneration and consequently maximum inlet temperature to the SCR of 650°C over a total time of 2.5 hours. Two systems consisting of the 100Cu SCR and the 50Fe/50Cu SCR were aged on this protocol in the full configuration as shown in [Figure 1](#). The N₂O performance results were evaluated on the hot FTP cycle to provide an indication of behavior at a milder degreasing condition.

In order to reduce variability associated with the urea dosing controls, during the test cycle, urea was dosed at fixed Ammonia to NO_x ratios (ANR). The two ammonia to NO_x ratios (ANR) used were 1.1 and 1.2 for the cycle when exhaust gases were greater than 180°C at the SCR inlet.

Test Sequence

The test sequence used for the catalyst evaluation on the hot FTP and RMC is shown in [Table 4](#).

Table 4. Evaluation Test Sequence for hot FTP's and RMC's

Step	Condition
1	DPF Regeneration (15 min. 650°C SCR in)
2	20 min @ 270°C
3	2 FTP's
4	2 RMC's

Table 5. Cold FTP Evaluation Test Sequence

Step	Condition
1	DPF Regeneration (15 min. 650°C SCR in)
2	20 min @ 270°C
3	2 FTP's
4	Minimum 12 hour soak
5	Cold FTP

During the regeneration, hydrocarbons were delivered via in exhaust injection upstream of the DOC to raise the temperature pre SCR to 650°C for 15 minutes. The purpose of the regenerations was to remove soot from the filter, sulfur from the SCR and ASC and to remove any residual NH₃ that may have been stored on the SCR from the previous test condition and ultimately to bring the system to a consistent and repeatable starting operating condition. Following the regeneration, a 20 minute warmup at 270°C was run at the selected ANR to condition the SCR with NH₃. Immediately after the warmup, the procedure was to run 2xFTP cycles and then 2xRMC cycles. The first of the FTP or RMC cycles was treated as a preparation cycle to establish a consistent NH₃ storage condition for the SCR catalysts. The 2nd run (in some cases a 3rd was performed) was used to evaluate component and system performance. In addition to the hot FTP's, cold FTP's were run. The sequence for this testing is shown in Table 5. Preceding the cold FTP was a filter regeneration followed by the warmup and two back-to-back FTP's and a soak of sufficient time to bring the entire exhaust to ambient temperature conditions. The cold FTP along with the hot FTP were then combined to get a full cycle performance using the 1/7 cold FTP + 6/7 hot FTP weighting approach.

RESULTS

Figure 3 provides an illustration of the consistency of the flow and temperature conditions for the FTP. Similar behavior is noted for the RMC testing.

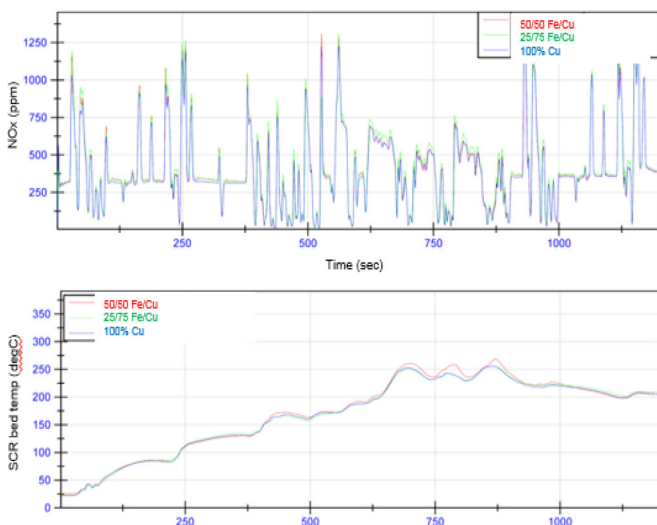


Figure 3. Cold FTP engine out NO_x emissions (ppm) and SCR bed temperatures (deg C)

Cold/Hot/Weighted FTP at 1.1 ANR

Figures 4 and 5 show the NO_x and N₂O performance respectively for the 4 configurations evaluated over the cold and hot FTP's as well as their cycle weighted values. Included in the weighted emission bars is the percent difference compared to the 100Cu system. These percent difference bars relative to the 100Cu system will be used throughout the results. The hot FTP cycle average NO₂/NO_x ratio post CDPF on a molar basis is noted as 34%.

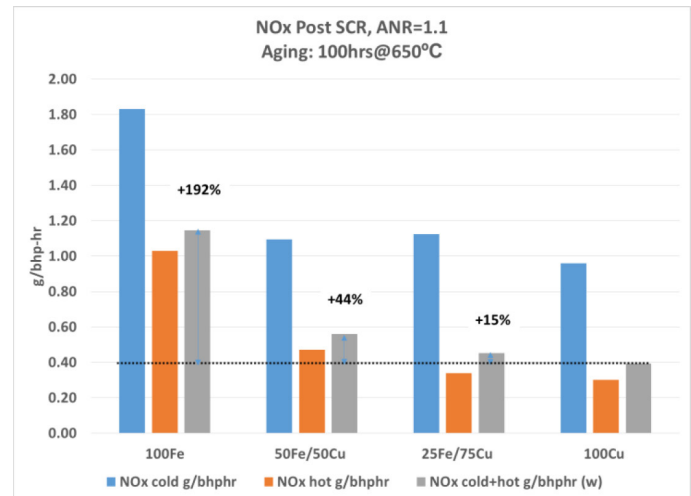


Figure 4. Cold/Hot/Weighted NO_x post last SCR (g/bhp-hr) at ANR=1.1

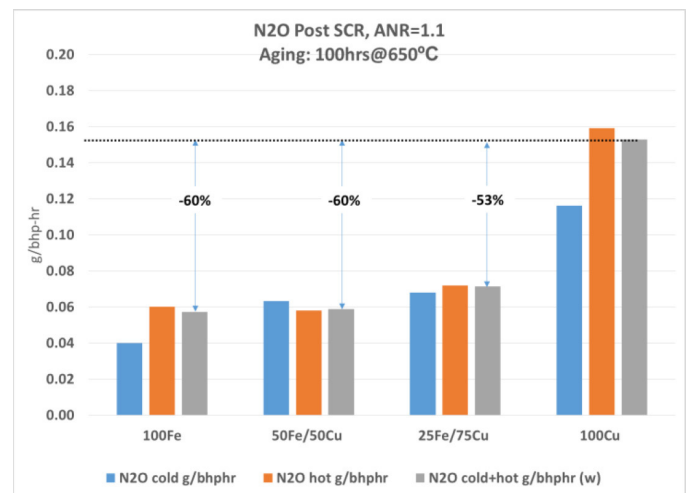


Figure 5. Cold/Hot/Weighted N₂O post last SCR (g/bhp-hr) at ANR=1.1

In Figure 4, the results show that the Fe only system yields significantly higher NO_x during the cold and hot FTP compared to the remaining systems containing Cu. When comparing only the systems that include some proportion of Cu SCR, the NO_x emissions decrease with the proportion of Cu SCR in the hot FTP and weighted FTP cycle. The figure shows a sharp increase in the weighted NO_x emissions at the 100Fe system corresponding to a 192% increase in NO_x emissions compared to the 100Cu system.