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THE DEVELOPMENT AND ON-ROAD PERFORMANCE AND DURABILITY OF THE FOUR-WAY EMISSION CONTROL SCRT™ SYSTEM

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ABSTRACT

The progressive tightening of the Heavy Duty Diesel emissions legislation worldwide necessitates the development of pollution control systems capable of enabling engines to meet the incoming legislative requirements. It is clear that to maximise the benefit to the environment, as well as to meet the very stringent future standards (especially the US 2010 limits), systems capable of high simultaneous conversions of all four major pollutants, carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx) and Particulate Matter (PM), are required.

Very high conversions of CO, HC and PM are achieved using catalyst-based Diesel Particulate Filter (DPF) systems, such as the Continuously Regenerating Technology, CRT®, system. High NOx conversions can be obtained using Selective Catalytic Reduction (SCR) systems, in which ammonia (generated from urea) is used to selectively reduce the NOx. This paper summarises the key steps in the development of the four-way SCRT system, which comprises the CRT system followed by an SCR system. Engine bench results obtained during the development of this system are presented and discussed.

However, the key to real-world emissions benefit is the actual on-road performance of such systems. It is well established that the CRT system provides very high and durable conversions of CO, HC and PM, so the focus of this current work was to demonstrate the NOx conversion capability and durability of the SCRT system. The SCRT unit was installed on a long-haul truck powered by a 15 litre Cummins engine. On-road NOx emissions performance was measured using NOx sensors located upstream and downstream of the SCRT unit. Over an 850 km evaluation route, the average on-road NOx conversion obtained was up to 82%, even when the urea injection quantity was set to give a maximum NOx conversion of around 85%. The durability of the system has also been assessed. Over the course of 150,000 km, no reduction in the NOx conversion efficiency of the system was observed.

The results presented in this paper demonstrate that the SCRT system provides very high on-road NOx conversion, and that the system has excellent durability within real-world applications.

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INTRODUCTION

The progressive tightening of the emissions standards for Heavy Duty Diesel vehicles throughout the world presents challenges for the engine development and emission control communities. In both Europe and North America the major challenges are in PM and NOx control for the legislation to be introduced in 2005 (Euro IV), 2007 (US '07), 2008 (Euro V), and 2010 (US '10). Table 1 summarises the evolution of the emissions standards in Europe, and Table 2 outlines the US regulations.

Table 1: Emissions Legislation Limits in Europe (ESC Test Cycle; g $kW^{-1}hr^{-1}$)

Year	HC	CO	NOx	PM
2000 (Euro III)	0.66	2.1	5.0	0.10
2005 (Euro IV)	0.46	1.5	3.5	0.02
2008 (Euro V)	0.25	1.5	2.0	0.02

It is clear that major reductions in both PM and NOx emissions are required in the near future, so systems capable of reducing both of these key pollutants need to be developed and demonstrated.

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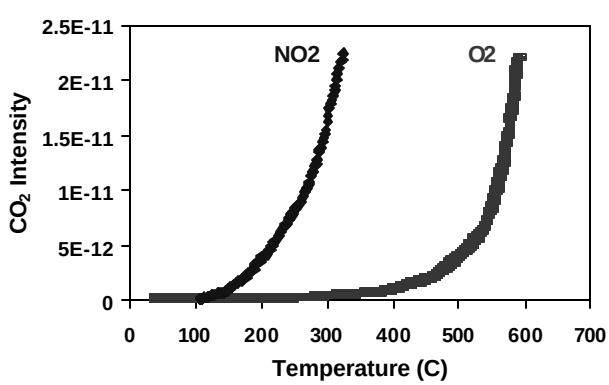
Table 2: Emissions Legislation Limits in the US (SET Test Cycle and US HDT Cycle; g $bhp^{-1}hr^{-1}$). (Note that 1 g $bhp^{-1}hr^{-1}$ = 1.341 g $kW^{-1}hr^{-1}$)

Year	HC	CO	NOx	PM
1998	1.3	15.5	4.0	0.10
2004	0.5	15.5	2.5	0.10
2007	0.14	15.5	1.2	0.01
2010	0.14	15.5	0.2	0.01

One system which has shown great promise in controlling PM emissions is the Continuously Regenerating Trap (CRT®, developed and patented by Johnson Matthey [1]). There are currently over 50,000 CRT systems in operation throughout the world, and the long-term field durability of the system has been clearly demonstrated [2]. Indeed, systems have been shown to provide very high levels of CO, HC and PM reduction even after over 500,000 km (and six years) of field operation [3].

The CRT system comprises an oxidation catalyst followed by a wall-flow Diesel Particulate Filter (DPF). The DPF traps the PM and the oxidation catalyst oxidises a portion of the engine-out NO to generate NO_2. This NO_2 combusts the PM at a much lower temperature (around 250°C) than does oxygen (around 550°C), as shown in Figure 1.

Figure 1: Temperatures Required for PM Combustion in NO_2 and O_2



This low temperature combustion of PM by NO_2 enables the passive operation (with continuous PM removal) of the CRT system on a wide range of HDD applications (eg buses, trucks, garbage trucks) and is the basis of the CRT. The CRT system has been used very successfully in the retrofit market over a wide range of operating duty cycles, since most HDD applications have duty cycles which are sufficiently warm to guarantee continuous regeneration of the CRT system.

The oxidation catalyst used within the CRT system is optimised to generate appropriate levels of NO_2 to enable continuous, passive PM regeneration. This catalyst is also very effective at oxidising CO (into CO_2) and HC (into CO_2 and H_2O), so the system provides very high conversions of PM, HC and CO. However, when the NO_2 generated by the oxidation catalyst reacts with carbon it is converted back into NO, so very little NOx conversion is observed over the CRT system.

As discussed above, high conversions of NOx are also required within the pollution control systems of the future. The most effective on-board NOx reduction strategy for HDD vehicles is Selective Catalytic Reduction (SCR) [4], so this was the approach used to control NOx emissions in this work. SCR systems reduce NOx via reaction with ammonia; this reaction is highly selective even in environments containing excess oxygen, such as the exhaust of Diesel vehicles. The SCR reaction can proceed via three different reaction processes:

$$4\,NH_3 + 4\,NO + O_2 \rightarrow 4\,N_2 + 6\,H_2O \quad (1)$$

$$2\,NH_3 + NO + NO_2 \rightarrow 2\,N_2 + 3\,H_2O \quad (2)$$

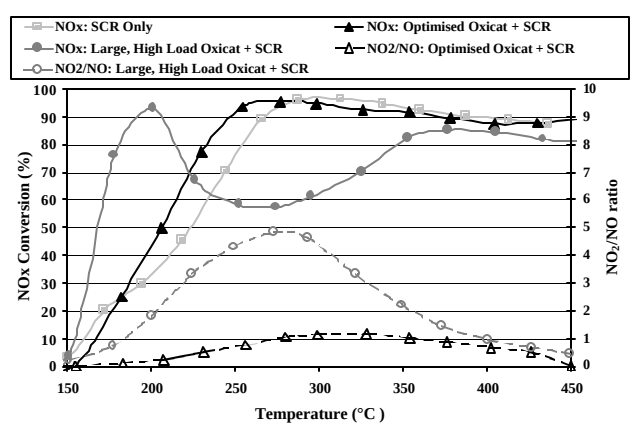
$$8\,NH_3 + 6\,NO_2 \rightarrow 4\,N_2 + 6\,H_2O \quad (3)$$

Reaction (1) is a fast reaction, while Reaction (2) is very fast [5, 6] – this low temperature promotion of the SCR reaction is an important phenomenon, as will be shown later. However, Reaction (3) is very slow. Therefore, care needs to be taken when deliberately generating NO_2 to promote the low temperature SCR reaction via Reaction (2), since if too much NO_2 is generated (ie more than the 50:50 level required for the stoichiometric completion of Reaction (2)), the NOx conversion can be significantly reduced, since the direct reaction between NO_2 and ammonia (Reaction (3)) is very slow.

These effects are demonstrated in Figure 2, which shows the NOx conversion profile of three systems:

(a) SCR only,
(b) large, highly loaded oxidation catalyst in front of SCR,
(c) optimally sized and loaded oxidation catalyst in front of SCR

Figure 2: Impact of NO_2 Generation on SCR Catalyst Performance



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It can be seen that there is a very dramatic promotion of the low temperature NOx conversion of the SCR system when the large, highly loaded oxicat is placed upstream of the SCR catalyst. For example, the NOx conversion at 175°C increases from 20% over the SCR catalyst to over 75% when the oxicat is installed. However, the activity of the system with the large, highly loaded oxicat then decreases strongly across the 200-350°C temperature range. This is because the oxicat in this system generates far too much NO_2 in this temperature range. As shown in Figure 2, the NO_2/NO ratio increases above the optimum 1:1 ratio at 180°C, and does not come back below this optimum ratio until the temperature reaches 400°C. Therefore, within this range, the NO_2/NO ratio is too high, which explains the poor NOx conversion performance. Figure 2 also shows that this large dip in NOx conversion can be removed by optimising the size and active metal loading of the oxicat to limit its NO_2 production such that the NO_2/NO ratio is always at or below the optimum 1:1 level ("Optimised Oxicat"). A significant improvement in low temperature NOx conversion is still seen with respect to the performance of the SCR catalyst alone, but, of course, the enhancement is not as dramatic as when using the larger, more highly loaded oxicat. Nevertheless, an increase of 20-25% NOx conversion is seen at most temperatures in the low temperature range when using this optimised oxicat system. These data demonstrate the importance of optimising the NO_2 generation of the upstream oxicat when developing SCR systems based around this principle of low temperature promotion.

DEVELOPMENT OF FOUR-WAY SYSTEMS TO CONTROL VEHICLE EMISSIONS

It is clear that in order to meet the very challenging future legislation, systems capable of controlling all four major pollutants, NOx, PM, CO and HC must be developed. Such systems have already been demonstrated on the engine bench, and this paper summarises the key results from this earlier work.

The first system to be demonstrated comprised a CRT system upstream of an SCR system [5]. This system enables several synergies to be developed, since the CRT system generates some NO_2 which is not reacted with carbon in the downstream filter. As shown above, this leads to a significant improvement in the low temperature performance of the SCR system. In addition, the CRT system removes CO and HC, which leads to a further enhancement of the low temperature SCR activity, since both of these species inhibit the SCR reactions.

The in-line SCRT system used in this initial demonstration is shown schematically in Figure 3, and comprises a CRT catalyst of 8.5 litres volume, a DPF of 17 litres, a total SCR catalyst volume of 17 litres and an 8.5 litre ammonia slip (clean-up) catalyst. Therefore, the total system volume was 51 litres, and this system was characterised on a 12 litre HDD engine.

Very high conversions of all four pollutants were measured over three different versions of this system (using 3 different SCR catalyst formulations), as summarised in Table 3. It can be seen that the CO and HC emissions of these systems approach zero, due to the high oxidation activity of the CRT catalyst. The PM emissions are strongly controlled by the DPF, and the SCR system provides NOx conversions in the 75-85% range. Therefore, this system provides excellent four way emissions control.

Figure 3: The In-Line SCRT System

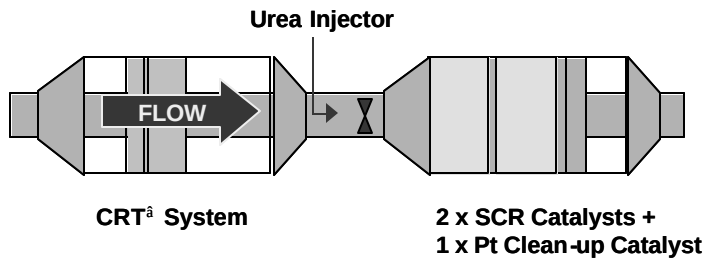
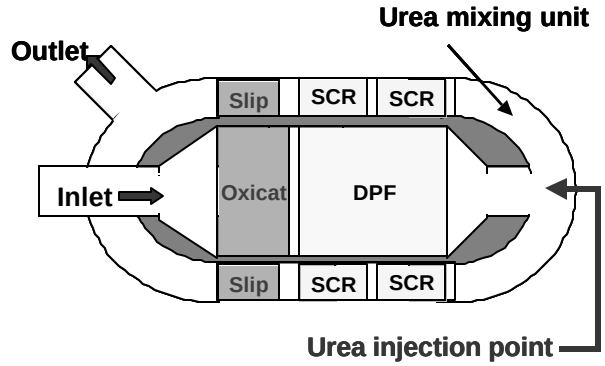


Table 3: ESC Emissions of the In-Line SCRT System Tested on a 12 litre Engine

Technology	HC	CO	NOx	PM
Engine Baseline	0.162	0.989	7.018	0.163
SCRT1	0.004	0.005	1.312	0.010
SCRT2	0.005	0.008	1.592	0.008
SCRT3	0.003	0.000	1.061	0.007
2005 Limits	***0.460***	***1.500***	***3.500***	***0.020***
Proposed 2008 Limits	***0.250***	***1.500***	***2.000***	***0.020***

This in-line system is quite long, and could present packaging issues in some applications. Therefore, the system was further developed into a much shorter system, without compromising system performance. This was done by locating the SCR catalysts and the ammonia slip catalyst on annular catalysts around the CRT system, to create the Compact SCRT system [7]. This system is shown schematically in Figure 4. The oxicat volume was 8.5 litres, and the filter had a volume of 34.5 litres. Each annular catalyst was 9.5 litres in volume, so the total catalyst plus filter volume was approximately 71.5 litres.

Figure 4: The Compact SCRT System



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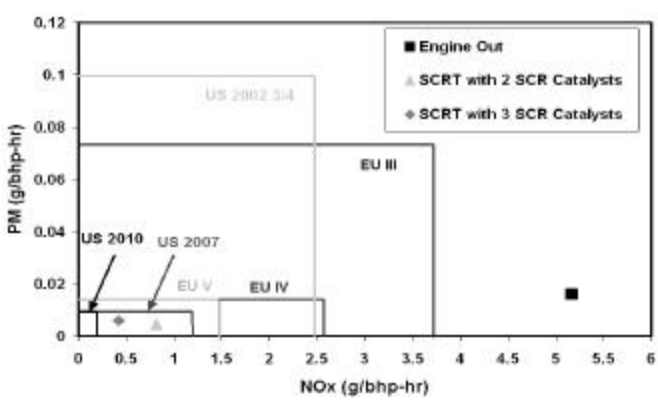
The performance of the system was initially measured over the ESC test cycle. The urea injection strategy was carefully calibrated to provide very high NOx conversion with very little ammonia slip. The urea was injected to provide an ammonia-to-NOx (ANR) ratio of 0.95, so the maximum possible NOx conversion in these experiments was 95%. Two Compact SCRT Systems were tested: one containing two annular SCR catalysts followed by an annular ammonia slip catalyst, and the other containing three annular SCR catalysts followed by an ammonia slip catalyst located downstream of the compact unit. In both cases the emissions measurements were made after the ammonia slip catalyst. The ESC emissions of these two compact systems are summarised in Table 4.

Table 4: Emissions of the Compact SCRT System over the ESC (g kW^{-1} hr^{-1})

System	HC	CO	NOx	PM
Engine Out	0.123	0.324	6.926	0.022
2 SCR Catalysts	0.002	0.000	1.097	0.006
3 SCR Catalysts	0.002	0.000	0.562	0.008
Euro V Limits	*0.460*	*1.500*	*2.000*	*0.020*

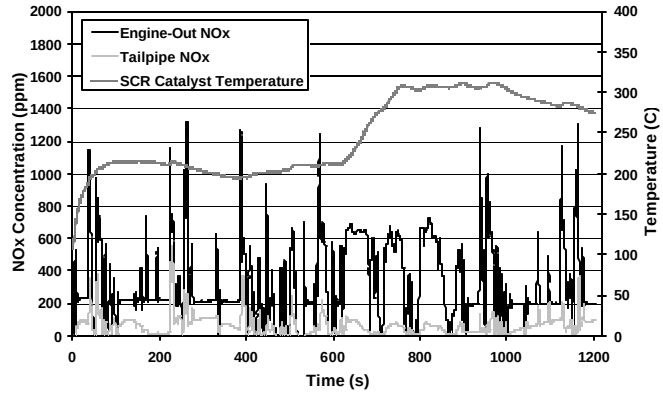
It can be seen that the system with the lower catalyst volume (the one containing only 2 annular SCR catalysts) is very comfortably inside the Euro V emission legislation for all four pollutants. Indeed, the NOx emissions of the system are approximately half the proposed Euro V NOx standard of 2 g kW^{-1} hr^{-1}. When the additional SCR catalyst is added to the system, the NOx emissions are reduced to approximately one quarter of the proposed Euro V NOx level. As expected, the addition of the third SCR catalyst does not lead to any significant changes in the other emissions, which all remain far below the Euro V legislated levels. These systems are also inside the US 2007 regulated levels, and the system containing the 3 SCR catalysts approaches the US 2010 emissions limits, as shown in Figure 5.

Figure 5: ESC Emissions of the Compact SCRT System



This Compact SCRT system was also tested over the US Heavy Duty Transient cycle, and Figure 6 shows the second-by-second NOx traces obtained during the hot start part of the cycle. Very high NOx conversion (83%) was obtained over this hot start cycle.

Figure 6: NOx Emissions and SCR Catalyst Temperature During a Hot Start US Heavy Duty Transient Test



The weighted (cold start + hot start) emissions levels and conversions of the system are summarised in Table 5.

Table 5: Weighted Emissions From the Compact SCRT System in the US Heavy Duty Transient Test (g $bhp^{-1}hr^{-1}$)

System	HC	CO	NOx
Engine Out	0.199	0.899	5.040
Tailpipe	0.008	0.050	1.079
Conversion	96%	94%	79%

Once again, therefore, very high pollutant conversions are observed using this Compact SCRT design.

Field Trial of the SCRT System

Following on from these very promising engine bench demonstrations of the four-way SCRT systems, it was decided to run a field trial to assess the in-field performance and durability of the system. An in-line SCRT system was selected for this trial, which was run on a Class 8 truck containing a Cummins ISX, 15 litre, 425 hp engine. The dimensions and volume of the components of the pollution control system are summarised in Table 6 below.

The CRT and SCR components were integrated onto the truck as shown schematically in Figure 7. The CRT was located upstream of the SCR system, which was installed in an oval can with two flow paths. Two SCR catalysts and one clean-up catalyst were installed within each flow path.

The vehicle used in this work is shown in Figure 8, in which the SCR muffler unit can be clearly seen at the base of the vertical stack. The CRT unit is located underneath the body of

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the truck, and cannot be seen. This truck is used to haul freight from the mid-west to the west coast. Each round trip comprises 5,000 miles and takes approximately 110 hours.

Table 6: Characteristics of the SCRT System Used in the Field Trial

Component	Dimensions	Volume
CRT DOC	12” x 6”	11.0 litres
CRT Filter	12” x 15”	27.5 litres
SCR Catalyst	4 off 9.5”x 6”	27.8 litres
Clean-Up Catalyst	2 off 9.5”x 4”	9.2 litres

Figure 7: Schematic Representation of the SCRT Installation on the Field Trial Vehicle

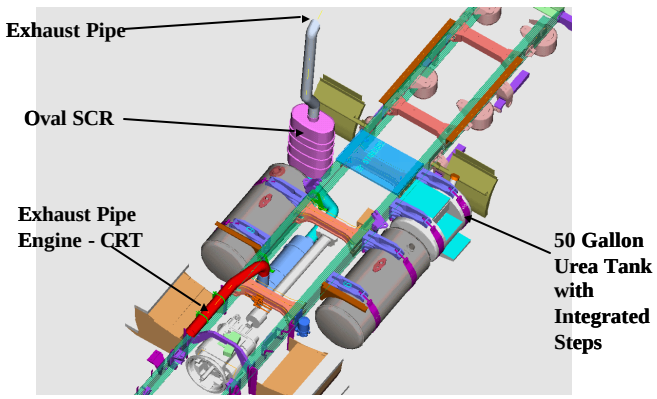

Figure 8: Photograph of the Tractor Unit of the Truck with the SCRT System

Urea was injected using a Bosch Urea Dosing System (UDS), and the required quantity of urea at each engine operating point was determined by mapping the engine prior to the field trial. A very conservative urea injection strategy was used, such that the Ammonia-to-NOx Ratio (ANR) was only 0.85, which means that the maximum possible NOx conversion was 85%. In addition, urea was not injected until the temperature reached 250°C, to be absolutely sure that deposits due to the partial decomposition of urea would not be formed during this field trial. (At low temperatures the partial decomposition of urea can produce undesirable species such as cyanuric acid.) In addition, NGK NOx sensors were installed on the vehicle to monitor both the engine-out and tailpipe NOx levels, to provide an on-road assessment of the NOx conversion obtained by the system.

The temperature profile measured downstream of the SCR unit over the course of a typical freight trip is shown in Figure 9. The temperature of the system is between 325 and 425°C for the majority of the time, with significant excursions into the 500-550°C range.

Figure 9: Temperature Profile Downstream of the SCRT System during a Typical Freight Trip

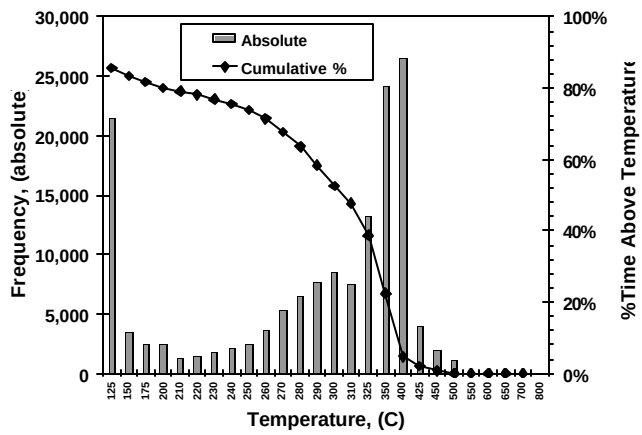

Figure 10 shows the NOx conversion obtained during an on-road system evaluation after approximately one month of the field trial. It can be seen that for the majority of the time the temperature of the SCR system was above the critical level of 250°C at which urea injection was enabled. It is clear that a very high level of NOx conversion is observed over the course of this evaluation trip. Indeed, the average on-road NOx conversion measured over this trip was 80%. This in itself is a highly impressive achievement, but the result is even more outstanding because the ANR was set to a maximum of 0.85, so 85% was the maximum NOx conversion attainable with this system. Taking this into account, the true efficiency of the SCR system is actually around 94%.

The truck was used in normal revenue service, but was periodically removed from service for brief periods of time to assess the performance of the SCRT system. It was felt that the best way to do this in a repeatable manner was to identify a route that could be run reproducibly, such that the truck speed (and therefore the engine-out NOx profile, system temperatures etc) could be well controlled during these system evaluation trips. A route comprising a round-trip of 850 km was

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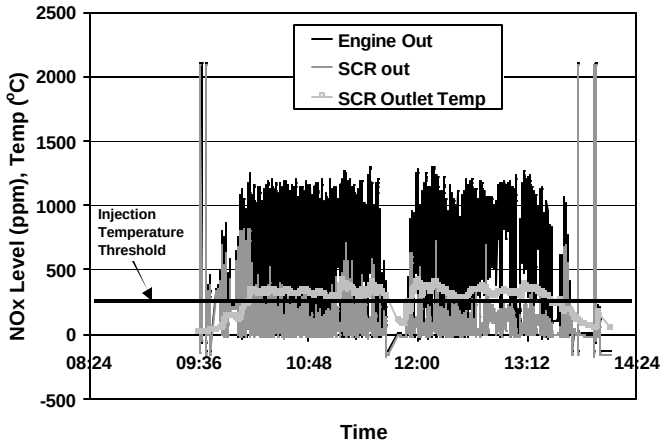
developed, and measurements made over the course of these runs were used to assess the efficiency of the system.

Figure 10: On-Road NOx Conversion Obtained Over the SCRT System After One Month of the Field Trial



After each evaluation trip the truck was placed back into revenue service and continued to accumulate mileage at a high rate. Figure 11 shows the engine-out and tailpipe NOx levels over the evaluation route after 6 further months of mileage accumulation on the truck. The system performance is again exceptional, attaining the 80% NOx conversion level. So the true on-road NOx conversion efficiency of the SCR system has remained at an outstanding 94%. Therefore, the system did not lose any NOx conversion activity over the initial 6 month period of the field trial.

Figure 11: On-Road NOx Conversion Obtained Over the SCRT System After Seven Months of the Field Trial

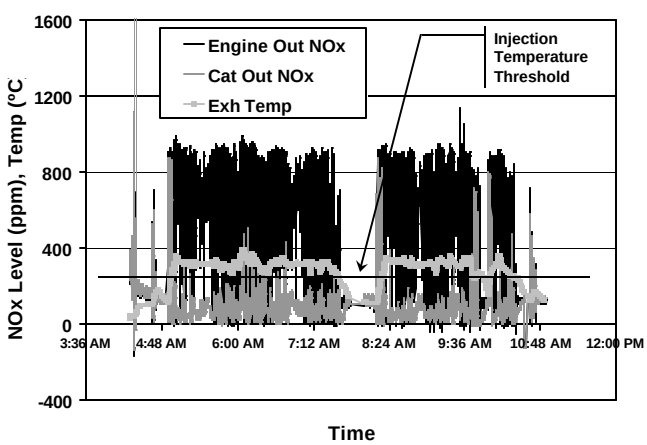
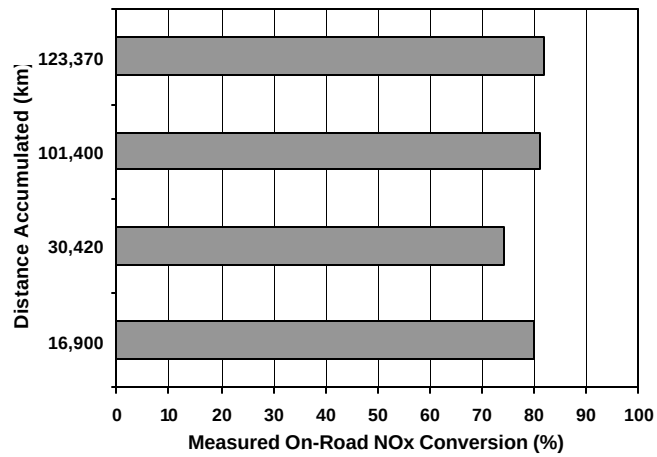


Figure 12 shows the average on-road NOx conversion over this 850 km evaluation cycle as a function of the mileage accumulated by the truck. It is clear that throughout the 125,000 km of this field trial, very high on-road NOx conversion levels were attained and maintained. At the 125,000 km point, the measured on-road NOx conversion was 82%, which corresponds to a true system efficiency of 96% (considering that the ANR was set at 0.85). This is clearly an outstanding achievement. In addition, no reduction in system NOx conversion performance was observed over the course of the 125,000 km. Furthermore, the CRT system functioned without any operational issues over the course of the field trial, as expected from the high on-road temperatures within this duty cycle. These observations attest to the excellent on-road durability and poison resistance of the SCRT catalyst system.

Figure 12: On-Road NOx Conversion as a Function of Mileage Accumulated During the SCRT Field Trial



CONCLUSIONS

Systems to provide excellent four-way emission control have been developed. By combining CRT filter technology with SCR technology to form an SCRT system, very high simultaneous conversions of CO, HC, NOx and PM have been obtained. Different packaging options have been demonstrated, such that the SCRT system can be packaged in a number of ways. The in-line SCRT system comprises a CRT system upstream of an SCR system in a linear configuration, while the Compact SCRT system comprises an annular SCR system located around the CRT system. These two configurations give equivalent conversion performance, and can meet different packaging requirements. The SCRT system can meet the Euro V and US 2007 emissions legislation on current engines.

The in-field performance and durability of the in-line SCRT system has been assessed in a field trial on a vehicle powered by a Cummins 15 litre, 425 hp engine. During this field trial the CRT system worked without any issues, and the SCR system gave up to 82% NOx conversion. This is a remarkable result, particularly since the urea dosing strategy was set to provide a maximum ammonia-to-NOx ratio of 0.85, which would lead to a maximum NOx conversion of 85%. Therefore, a NOx conversion of 82% corresponds to a true SCR NOx efficiency of 96%.

No change in the performance of the system was observed over the 125,000 km of the field trial, which clearly demonstrates the excellent activity and on-road durability of the SCRT system.

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