TRIAL OF A NEW EMISSIONS CONTROL SYSTEM FOR BUSES IN LONDON

Duncan Arrowsmith[1], Martin Taylor[2], Ioannis Gekas[3] and Pär Gabrielsson[4]

1. Eminox Ltd, Gainsborough, England; duncan.arrowsmith@eminox.com
2. Eminox Ltd, Gainsborough, England; martin.taylor@eminox.com
3. Haldor Topsøe A/S, Lyngby, Denmark; iog@topsoe.dk
4. Haldor Topsøe A/S, Lyngby, Denmark; pg@topsoe.dk

ABSTRACT

Selective Catalytic Reduction (SCR) is the aftertreatment technology being adopted by the majority of diesel bus and truck manufacturers for meeting Euro IV & V emissions limits. However this leaves the problem of reducing the exhaust emissions from vehicles already in service. 80% of buses in London already have Eminox Continuously Regenerating Trap (CRT®) systems fitted, dramatically reducing hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM). Eminox and Haldor Topsøe have now developed an SCR system to reduce the major remaining regulated pollutant, nitrogen oxides (NO_x), using urea as the reductant.

This paper describes the development and performance of retrofit SCR+CRT systems fitted to buses in London for a demonstration trial. Bus applications are particularly difficult for SCR technology due to highly transient, low temperature duty cycles and vehicle packaging complications. The operating principles of the system, design and development work to overcome the difficult application are described in the paper, together with field trial experience.

Results from chassis dynamometer testing showed 87% NO_x conversion over a real world drive cycle for urban buses, before and after a 12,000 mile field trial. NO_x reduction results from the vehicle in service during the field trial showed similar levels of reduction.

KEYWORDS: NO_x Reduction, SCR, CRT, Retrofit.

1. INTRODUCTION

Increased environmental awareness is leading to more stringent emissions legislation, which in turn is the driving force behind the development of emissions control technology. Euro IV and V emissions legislation, that become effective in Europe in 2005 and 2008 respectively, are forcing the development of exhaust emissions control to be used in conjunction with advanced engine technologies to achieve the needed reduction in NO_x and PM. SCR is the technology being favoured by the majority of diesel bus and truck manufacturers in Europe to meet this legislation. One reason for this is the high NO_x conversion possible when using SCR technology, greater than 75% NO_x reduction is achievable compared to typically up to 50% NO_x conversion when using Exhaust Gas Re-circulation (EGR) technology [1]. Another reason is that SCR is a proven technology, with long experience from stationary applications. SCR systems also do not suffer the problems associated with Lean NO_x Traps (LNT); fuel consumption penalty or high sensitivity to sulphur [2].

However, these regulations do not affect the large number of Euro II and III vehicles in service. Mandatory and voluntary schemes are either in place or are being introduced, instigated by local authorities within Europe to retrofit emissions control technologies to existing vehicles. Transport for London (TfL) has mandated that all buses in service in London will have to meet Euro II emissions legislation and be fitted with a Diesel Particulate Filter (DPF) by 2005.

In 2003, 85% of the 6,300 buses running scheduled services in Greater London were fitted with DPF's, of which more than 90% were Eminox CRT systems [3].

2. DEMONSTRATION OVERVIEW

A demonstration project was set up to retrofit SCR technology to an existing city bus already fitted with a CRT. To verify the performance of the combined SCR+CRT system one vehicle was tested on a chassis dynamometer over a test cycle representative of city bus operation, before and after a 12,000 mile, 5 month monitored field trial. Three vehicles were fitted with SCR+CRT systems and put into service for the field trial. The project was partly funded by the Energy Saving Trust (EST), a non-profit making company set up by the UK government; one of its objectives is to create a market for clean vehicles, which will deliver local and global environmental benefits.

2.1 Vehicle Type

The vehicle used for the field trial was the Dennis Dart bus with a 3.9 litre Cummins ISBe _135 engine. Figure 1 shows one of the vehicles used for the trial. The vehicle was chosen due to the large numbers in service; there are around 1500 such vehicles operating in the London area alone and therefore there is a large potential market for a retrofit product. This engine satisfies Euro III emission requirements and generates a max power of 133hp at 2500rpm. Although the space available on the vehicle is very tight it was identified that there was enough room in the engine bay to accommodate the SCR+CRT system and ancillaries without having to move any major vehicle components.

Figure 1.

2.2 Field Trial Location

The field trial was conducted from Alperton Depot near Wembley in North West London. Vehicles operating from this depot experience a mixture of both inner London and suburban routes. These routes are in heavy traffic, with low average speeds and long periods at idle, giving a highly transient, low temperature duty cycle. This type of duty cycle is challenging for both CRT and SCR systems, as they are both temperature-constrained technologies.

3. SCR AND CRT TECHNOLOGY OVERVIEW

3.1 Continuously Regenerating Trap (CRT)

The CRT comprises an oxidation catalyst, upstream of a wall flow filter. The catalyst oxidises some of the NO to NO_2 and also oxidises HC and CO, whilst the filter collects the PM. The NO_2 is then used to combust the soot in the collected PM, enabling the filter to continuously regenerate in service. The performance of the CRT is well known [4] and is proven to reduce more than 85% of HC, CO and PM in most applications. The ability of the CRT to regenerate passively in service even on low temperature duty cycles has meant that it has become the leading PM-reduction technology for city buses [3].

3.2 Selective Catalytic Reduction (SCR)

SCR is a method of reducing nitrogen oxides (NO_x) in diesel exhaust and works by introducing a reducing agent into the exhaust to convert the NO_x to harmless nitrogen and water, over an SCR catalyst. SCR technology has been used in stationary applications since the 70’s and more recently it has been adapted for mobile applications. The NO_x reduction performance on mobile applications has been proven over legislative cycles to give up to 92% reduction [5,6].

The reactions to convert NO_x to nitrogen and water over the SCR catalyst require ammonia (NH_3). The two main reactions are shown below; Equation 1 is a fast reaction and dominant when there is no NO_2 present, Equation 2 is a very fast reaction and is dominant with NO_2:NO ratios around 1:1 [7].

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

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O \quad (2)$$

Due to the toxicity and handling problems when using anhydrous or aqueous ammonia, the reductant chosen by the majority of the industry is urea. Urea is commonly used in the fertiliser and food processing industries and is non-toxic and commercially available. A eutectic solution of urea in water (32.5% by weight) is used, giving a freezing point of -11ºC with the added advantage of equal concentrations during the liquid and solid phases meaning that the correct concentration of urea is dosed into the exhaust even if there is partial freezing of the urea solution. Once the urea solution has been dosed into the exhaust it decomposes and hydrolyses to ammonia.

It is critical to the NO_x conversion performance of the SCR system that the correct amount of urea is injected for the amount of NO_x present in the exhaust. The amount of NO_x in the exhaust can be determined using two different methods;

1. Mapping the engine on a dynamometer to determine the amount of NO_x produced by the engine at each engine condition (different speeds and loads) and then measuring or taking signals from the CAN bus for speed and load when the vehicle is in service.

2. Using a NO_x sensor to determine the amount of NO_x in the exhaust.

Once the NO_x has been determined the correct amount of urea to reduce the NO_x can be calculated. After the urea in water solution has been injected into the exhaust it needs to be uniformly mixed with the exhaust gas to ensure good NO_x reduction performance over the SCR catalyst.

Ammonia slip, (unused ammonia exhausted to atmosphere) also needs to be avoided. This can be done by an appropriate control strategy and accurate control of the dosing system or by using an oxidation catalyst downstream of the SCR catalyst to oxidise the ammonia.

The operation of the system is temperature limited due to the rate of hydrolysis of urea at low temperatures. During the demonstration project urea was only injected when the SCR catalyst temperature was above 200ºC.

4. SYSTEM DESIGN

The system is a sensor-based system comprising a CRT, SCR catalyst, dosing unit, Electronic Control Unit (ECU), urea tank, and temperature, NO_x and Mass AirFlow (MAF) sensors. For the purpose of the trial the system also has a data logger with GPS (Global Positioning System) and GSM (Global System for Mobile communication) capabilities allowing us to remotely track and monitor the vehicles and the NO_x reduction performance of the SCR system in service. The reductant being used is urea in water solution, NO_xCare (formerly marketed as AdBlue). A schematic of the system is shown in Figure 4.

4.1 CRT / SCR Unit

Figure 2 shows the CRT+SCR system before fitting to the vehicle and Figure 3 shows the complete system on the vehicle except for the urea tank, which is situated behind the driver side rear wheels.

Figure 2

Figure 3

The following design factors were particularly important:

- Space envelope including ground clearance and departure angle.
- Mixing of the urea/water solution in the exhaust.

- Backpressure of the complete system.
- Thermal insulation of pipe work and SCR+CRT system.
- Temperature effects on other systems in the engine bay.
- Additional weight on the chassis.
- Positioning of the dosing unit (relative to other system components / vibration / temperature).
- Urea tank (size, material and position).

4.2 Dosing System

The retrofit SCR+CRT system can be schematically seen in Figure 4. The dosing system is sensor-based, using in total four sensors, a NO_x sensor upstream of the SCR catalyst, a mass airflow sensor installed on the engine intake and two temperature sensors, one upstream and one downstream of the SCR catalyst. The information from the sensors is continuously processed by the Electronic Control Unit (ECU). The ECU uses real-time kinetic model calculations and an advanced injection strategy to calculate the appropriate urea injection rate that will give a high NO_x conversion and at the same time minimize ammonia slip for the given conditions.

The calculated injection rate is transmitted to a digital dosing metering pump, which outputs the requested amount with great precision [8]. The urea from the pump is mixed with pressurized air in a series of valves and the urea/air mixture is injected in the exhaust pipe through an atomisation nozzle. The injected urea decomposes and hydrolyses in the hot exhaust, forming ammonia, which in turn reacts with the NO_x over the SCR catalyst to form nitrogen and water.

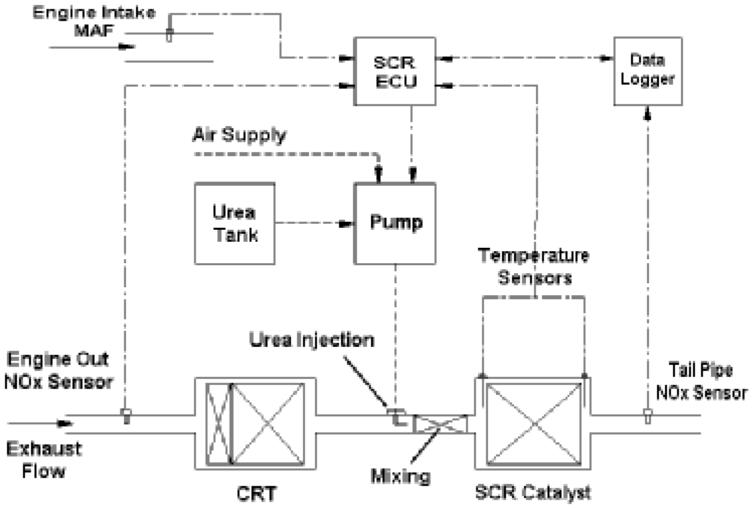

Figure 4

For the purpose of the trial, to be able to measure the NO_x reduction in service an additional NO_x sensor was installed downstream of the SCR catalyst. The data logger is connected to the dosing system ECU via a CAN link and can then record data from the sensors, including the additional NO_x sensor. Recording NO_x data from both downstream and upstream NO_x sensors together with airflow measurements enables the NO_x conversion of the system in service to be calculated.

4.3 Previous Experience

This type of SCR system has been successfully installed in a variety of applications (without CRT's) so far including city buses, long haul trucks, delivery trucks and off-road machines with diesel engine sizes ranging from 4 up to 16 litres and of different manufacturers. Several thousand hours have been accumulated and the SCR technology has been demonstrated to be very robust and durable.

There have been more than 22,000 CRT's fitted to city buses over the last eight years, however this is one of the first field trials of a combined SCR+CRT system on a city bus.

5. CHASSIS DYNAMOMETER TESTING

The chassis dynamometer testing was carried out at Millbrook Proving Ground over the Millbrook London Transport Bus (MLTB) cycle. The MLTB cycle is a drive cycle developed by Millbrook Proving Ground under the sponsorship of London Transport, to allow assessment of various emissions reduction technologies over a cycle representative of a real world urban bus duty cycle [9]. The cycle was developed from recordings of vehicle speed on buses between Brixton (outer London) to Trafalgar Square (city centre) and is split into two phases to represent inner and outer London. The cycle is 38 minutes long with an average speed of 14km/h and for 31% of the time the vehicle is stationary.

The testing was carried out at ambient temperature and the emissions were measured using a full flow Constant Volume Sample (CVS) system using the Critical Flow Venturi (CFV) operation principle.

5.1 Test Procedure

Testing was carried out on one of the three buses fitted with the SCR+CRT system at the start of the field trial, and the same bus was tested at the end of the field trial, after 12,000 miles and 5 months. During the field trial one of the urea pumps experienced an electrical problem, this has been resolved and the pump is now back on the vehicle. However the pump for the second Millbrook test was a temporary replacement, not the same as the original test. All other system components remained constant throughout the field trial.

The test procedure included testing the vehicle with the Original Equipment Manufacturer's (OEM) silencer. By fitting and testing the OEM silencer we were able to obtain baseline engine-out emissions to give us a benchmark against which to measure any reduction in pollutants. With the OEM silencer fitted we ran the vehicle over a warm-up phase, followed by the MLTB cycle. A repeat test was carried out to ensure accuracy.

Measurements over the cycle were made of hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxides (NO_x). The particulate matter was collected using a gravimetric filter method. A Fourier Transform Infra-Red (FTIR) detector was used to measure ammonia (NH_3) slip, taking a raw sample of exhaust gas direct from the tailpipe. The test procedure was then repeated with the SCR+CRT system operational, taking the same measurements with the addition of the main pollutants being measured engine-out as well as tailpipe. This testing was carried out with two different SCR calibrations, to enable the optimum SCR performance with minimum ammonia slip to be determined.

5.2 Results and Discussion

Figure 5 shows the performance of the SCR+CRT system during the initial Millbrook test. The results show substantial reduction in the four main regulated pollutants; greater than 85% reduction was achieved in all four pollutants (HC, CO, PM and NO_x) when considering SCR calibration 2.

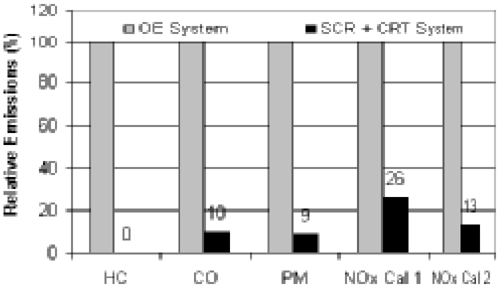

Figure 5

Distance	**Emissions Reduction (%)**		
(miles)	**HC**	**CO**	**PM**
0	100%	90%	91%
12,000	100%	89%	88%

Table 1

Distance	**Calibration**	**NO_x Reduction**	**Ammonia Slip (ppm)**		**Urea Consumption**	
(miles)		**(%)**	**Average**	**Peak**	**(l/100km)**	**(% of Fuel)**
0	1	76	1	7	-	-
12,000	1	77	3	14	2.21	5.9
0	2	87	3	15	-	-
12,000	2	87	5	19	3.06	8.2

Table 2

Table 1 shows the performance of the SCR+CRT system in comparison to the OEM system for both the initial and final testing. As would be expected greater than 85% reduction in HC, CO and PM was achieved at the beginning and end of the field trial. The majority of this reduction occurs over the CRT. The hydrocarbons were reduced to ambient levels, better than would normally be expected from the CRT as a result of further oxidation of the hydrocarbons over the SCR catalyst.

The NO_x reduction performance of the system with both calibrations, before and after the field trial is shown in Table 2. The results show that there was no degradation of the SCR catalyst performance over the field trial. The table also shows that the ammonia slip was kept to acceptable levels, not exceeding an average slip of 5ppm and a maximum peak of 19ppm for any of the test cycles. The urea consumption was between 6 and 8% of the fuel used over the test cycle.

Figures 6 and 7 show time histories for engine-out NO_x, tailpipe NO_x and ammonia slip over the MLTB cycle before and after the field trial. Using SCR calibration 2, there is a dramatic NO_x reduction over the cycle. The NO_x reduction presented in the figures (90%), is slightly higher than the 87% reported in Table 2. This is due to the comparison of engine-out emissions to tailpipe emissions instead of OEM silencer to SCR+CRT system emissions. The SCR+CRT system will have a higher backpressure than the OEM system and therefore the engine will produce slightly more NO_x.

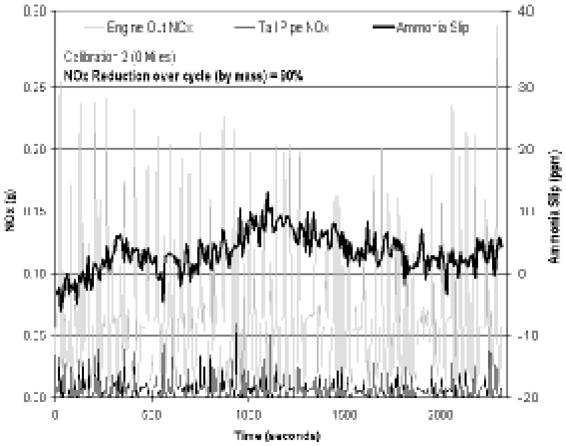

Figure 6

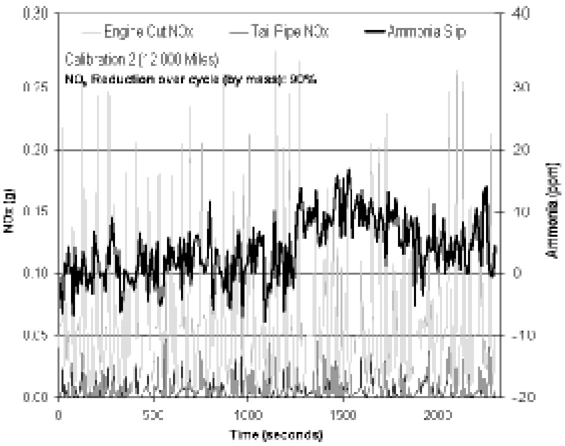

Figure 7

6. FIELD TRIAL EXPERIENCE

The field trial was run from the First Group Alperton Depot in London. Details of the three vehicles are shown below, with distance covered up to 16th February 2004;

- Bus No. 1, went into service 15/09/03 and has covered 12,000 miles.
- Bus No. 2, went into service 17/11/03 and has covered 6,000 miles.
- Bus No. 3, went into service 06/12/03 and has covered 8,000 miles.

A urea dispensing station was installed in the depot. This consisted of an Intermediate Bulk Container (IBC) and dispensing pump with trigger-operated nozzle. The container holds 917 litres of urea (NO_xCare). During the trial, the 25 litre urea tanks fitted to the vehicles were filled when required by staff at the depot. The IBC was able to support all three buses during the field trial period without being re-filled.

6.1 Results from data logging in service

During the field trial, the vehicles were monitored on a regular basis via the Internet. The channels recorded by the data logger were: dosing system error codes, urea tank level, exhaust backpressure, injection pressure, MAF, engine out NO_x, tailpipe NO_x and temperature before and after the SCR catalyst. This system therefore allowed the monitoring of the NO_x reduction being achieved in service. The data logger records a snapshot of the signals every minute, which complicates the processing of the data, however allows the overall trends to be seen.

Figure 8 shows the NO_x reduction in service for bus No. 1 shortly after it went into service, from data recorded over a six hour period on 1st November 2003. An average NO_x reduction of 77% was achieved, lower than the 90% achieved at Millbrook (Fig 6). This is due to the temperature at the SCR catalyst whilst the bus is in service. When testing at Millbrook the vehicle was warmed up before the cycle was started and the catalyst temperature did not drop below 200ºC throughout the whole cycle. It can be seen in Figure 8 that the temperature is below 200ºC at the beginning of the plot, after start up and on two further occasions during the six hours. When the temperature at the SCR catalyst drops below 200ºC there is no urea injection and therefore no NO_x conversion, which in turn reduces the average NO_x reduction.

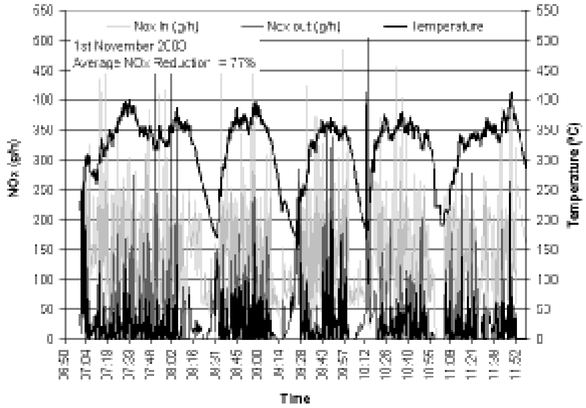

Figure 8

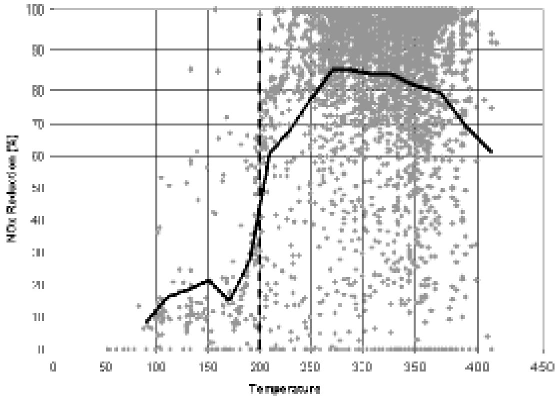

Figure 9

Figure 9 shows NO_x conversion vs. SCR catalyst temperature for the same period as Figure 8, the line on the graph represents the average NO_x conversion at a given temperature. The scatter of points is mainly the result of the data collection and processing, as the tailpipe NO_x sensor is for demonstration purposes only and is not part of the standard SCR kit as such the time mark, snapshot that the data logger records for the engine-out and tailpipe NO_x sensors may vary by 1-2 seconds, also there is a delay in the system due to the exhaust flow between the sensors. As a result some negative values of NO_x conversion were calculated but are plotted in Figure 9 as zero. The graph shows that above 200ºC the mean NO_x reduction rises rapidly to over 80%. There is some conversion below 200ºC even when not injecting, due to stored ammonia on the SCR catalyst.

6.2 Discussion

The results from chassis dynamometer testing and from monitoring of the NO_x reduction during the field trial, have successfully demonstrated the performance of a retrofit SCR+CRT system fitted to a city bus. The high levels of NO_x reduction prove that the difficulties of using urea as the reductant; temperature limitations, decomposition and hydrolysis of urea before the SCR catalyst, have been overcome.

The sensor-based system has allowed retrofit of the system to vehicles without any engine mapping being required, by detecting the amount of NO_x in the exhaust and calculating the correct amount of urea to inject. This has the additional advantage that the system is not sensitive to variations in engine emissions performance or condition of the engine

7. CONCLUSIONS

- A retrofit SCR+CRT system was successfully developed and fitted to a Dennis Dart Euro III London Bus.
- Greater than 85% reduction in CO, HC and PM and 87% NO_x reduction were achieved over the MLTB cycle when comparing to the OEM silencer.
- The ammonia slip was within acceptable limits for all tests, not exceeding an average slip of 5ppm and a maximum peak of 19ppm for any of the test cycles.

- The consumption of urea in water solution for the testing was between 6 and 8% of the amount of fuel used.
- There was no degradation in emissions performance from either the CRT or the SCR over the period of the field trial.
- NO_x reduction in service was slightly lower than measured over the MLTB cycle due to lower SCR catalyst temperatures. However the percentage NO_x reduction in service was typically in the high seventies.

8. ACKNOWLEDGEMENTS

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