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INVESTIGATION OF THE FEASIBILITY OF ACHIEVING EURO V HEAVY-DUTY EMISSIONS LIMITS WITH ADVANCED EMISSION CONTROL SYSTEMS

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ABSTRACT

European Directive 99/96/EC sets heavy-duty diesel engine gaseous and particulate matter limit values for 2005 (Euro IV) and 2008 (Euro V). The NOx limit values for 2008 are required to be the subject of a technical review by the European Commission to confirm that the technologies required will be proven. This review has to be published before the end of 2002.

This project has been carried out to investigate the feasibility of achieving the Euro V emission limits of 2.0 g/kWh NOx and 0.02/0.03 g/kWh particulate matter for introduction in 2008 using emission control technologies already developed by members of the Association for Emissions Control by Catalyst but without a programme to optimise their performance as a combined system.

A modern heavy-duty diesel engine was equipped with an integrated catalyst based diesel particulate filter (to remove particulate matter including ultra-fine particulates), a urea-based selective catalytic reduction system (for a high level of NOx reduction) and a clean-up catalyst (to eliminate any ammonia slip). The emission control system was tuned to meet an engineering target of around 1.0 g/kWh NOx (i.e. 50% of the Euro V limit value), with very low particulate matter levels below 0.01g/kWh, and then aged for 1000 hours over an accelerated durability test cycle. The ageing test was designed to simulate real world driving conditions including exposure to higher levels of fuel sulphur than those promulgated in the European Union for 2008, to establish the emission deterioration factors and to demonstrate stable emission levels.

This paper reports the results of the emission measurements before and after the ageing test, with regulated emissions at below 50% of the proposed 2008 limit values after 1000 hours, and also reports unregulated emissions and the observations made during the ageing procedure. Engine-out and exhaust-out emissions of unregulated emissions of aldehydes, ammonia, nitrous oxide and nitro-polyaromatic hydrocarbons were measured and excellent levels of control established.

1 INTRODUCTION

The development of exhaust emissions limits and test cycles for heavy-duty diesel engines in Europe is summarised in Figure 1. The 2005 (Euro IV) emissions standards set carbon monoxide (CO), hydrocarbon (HC) and nitrogen oxides (NOx) limit values that can probably be achieved by engine improvements, but in that case the particulate (PM) limit is likely to necessitate diesel particulate filters (DPFs). An alternative strategy for Euro IV would be to re-optimise the base engine for minimum particulates and to use a selective catalytic reduction (SCR) to control NOx [1]. In 2008 (Euro V), the NOx limit is expected to necessitate the further introduction of SCR catalysts, but the limit is subject to a European Commission review of its feasibility by the end of 2002. A further development that could impact future emissions legislation is the ongoing development of a new test cycle, which is intended to replace existing cycles (WHDC - "Worldwide Harmonised Diesel Cycle") [2].

Figure 1: European Heavy-Duty Diesel Exhaust Emissions Standards

	Test-Cycles	**HC g/kWh**	**CO g/kWh**	**NOx g/kWh**	**PM g/kWh**	**ELR-Light Absorption (m^{-1})**
2000 (EU III)	ESC	0.66	2.1	5.0	0.1	0.8
	ETC	0.78	5.45		0.16	
2005 (EU IV)	ESC	0.46	1.5	3.5	0.02	0.5
	ETC	0.55	4.0		0.03	
2008 (EU V)	ESC	0.25	1.5	2.0	0.02	0.5
	ETC	0.40	3.0		0.03	

Fuel Sulphur Content
<350ppm (EU III)
< 50ppm (EU IV/V)

ESC = European Steady State Cycle
ETC = European Transient Cycle
ELR = European Load Response Test

Of great significance for the potential introduction of exhaust catalysts on heavy-duty engines is the move to lower sulphur diesel fuel. A reduction in diesel fuel sulphur content to less than 50ppm is mandated in Europe by 2005 (Euro IV) and a further reduction to less than 10ppm sulphur has been proposed to be phased in from 2005 and probably will be mandatory by 2008 or 2009 (Euro V) [3].

With this background of legislation on emissions and fuels, members of the Association for Emissions Control by Catalyst (AECC) are developing SCR technology as well as DPFs and other emission control technologies for heavy-duty engines. Recent publications [4-13] have demonstrated that such technology has the potential to reach the future emission limits. Field tests on trucks and buses fitted with exhaust emission control technologies have been reported [5,11,14,15].

2 OBJECTIVE

The purpose of the project reported in this paper was to demonstrate the capabilities of a combined catalyst based-DPF (CB-DPF) system, urea based SCR, and a clean-up oxidation catalyst to meet the 2008 (Euro V) emission limits when fitted to a Euro III production engine.

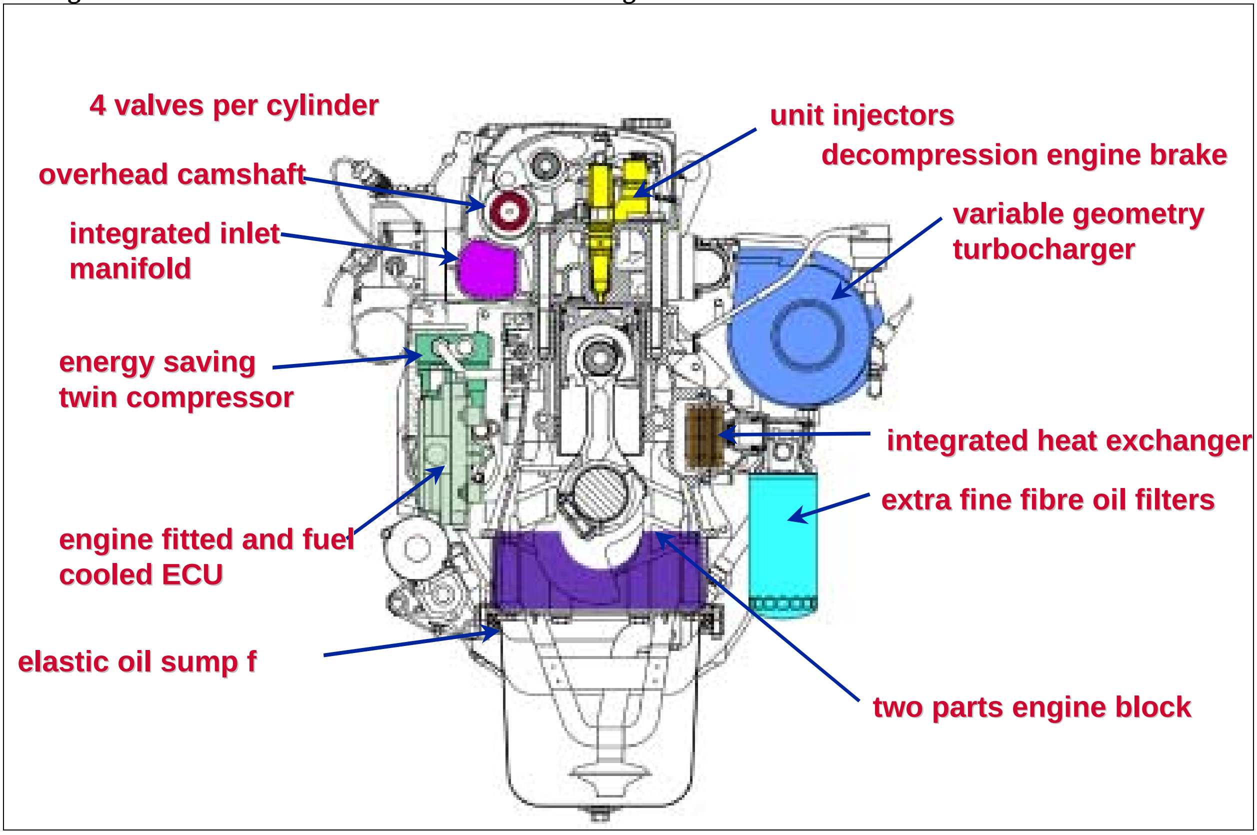
The emissions targets were set at 50% of the 2008 (Euro V) legislated levels (1.0 g/kWh NOx and 0.01-0.015 g/kWh PM) in the fresh condition. No action was taken to improve the fuel consumption of the chosen engine. A key point of this project was to subject the exhaust emission control technologies to an ageing test representative of heavy-duty operation on the road and to quantify the emissions deterioration after severe ageing.

3 TEST ENGINE AND EMISSION CONTROL SYSTEM

Engine

The engine selected for this project was the IVECO Cursor 8 [16] in Euro III specification. This is a 7.8 litre, 6 cylinder engine rated at 295 kW, and 1280 Nm maximum torque. A cross-section with the main features highlighted is shown in Figure 2.

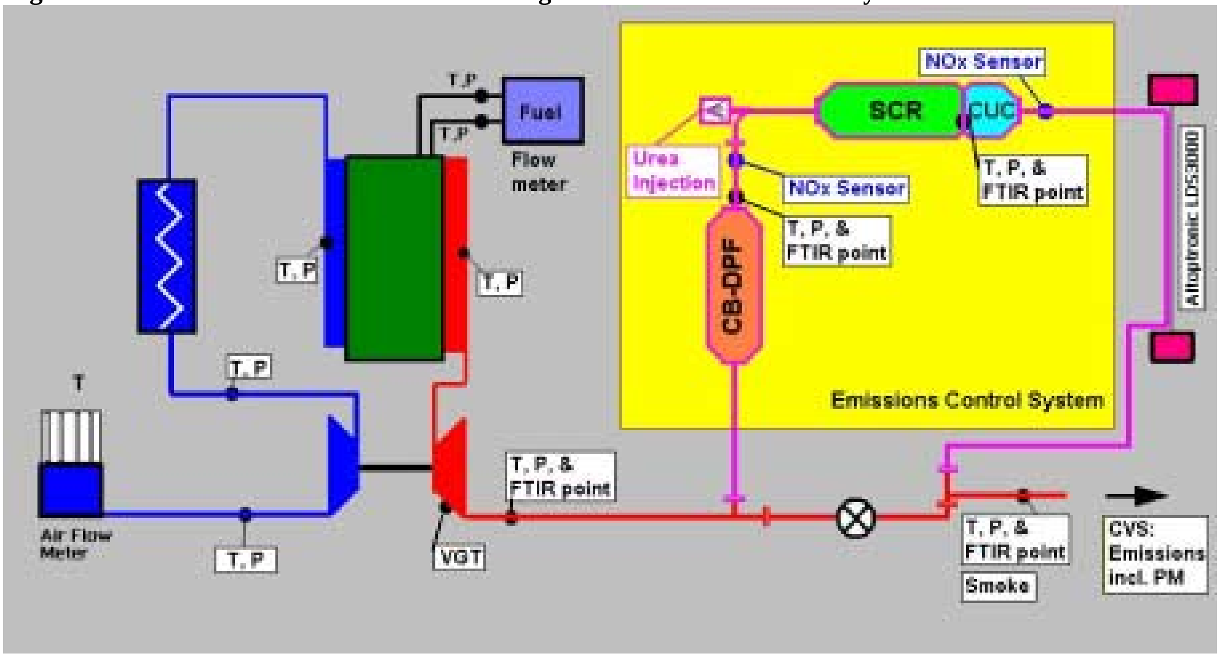
Figure 2: Cross-Section of IVECO Cursor 8 Engine Euro III



Testbed Installation

The arrangement of the catalysts and the measuring locations is shown schematically in Figure 3.

Figure 3: Schematic of the Testbed with Engine and Emission Control System



The base engine was tested with the standard exhaust backpressure (6kPa at rated power) whereas the exhaust emission control technologies caused an increase in backpressure (to 20kPa at rated power) leading to a penalty in fuel consumption of up to 2%.

The conversion efficiencies have been calculated with the baseline result using the standard Euro III exhaust backpressure. In order to check this approach the exhaust backpressure was increased to the same level as that through the catalysts and there was a 2% reduction in NOx over the ESC test and less than 1% over the ETC test, other emissions being unchanged.

The measuring techniques used were as follows:

- Constant volume sampling (CVS) and two stage dilution tunnel
- Horiba Mexa-7200D for gaseous emissions
- Monitoring of NOx by NGK NOx sensors
- Fourier Transform Infra Red (FTIR) for NOx species and aldehyde emissions
- Altoptronic Laser Spectrometer (LDS3000) for ammonia measurement
- Scanning Mobility Particle Sizer (SMPS) for particle size and number
- High performance liquid chromatography with fluorescence for nitro polycyclic aromatic hydrocarbons

Particle size data were collected using twin Scanning Mobility Particle Sizer (SMPS) instruments. SMPS systems comprise an impactor (which removes large particles from the aerosol), a charge neutraliser, which reduces the charge on the particles to a defined distribution, an electrostatic classifier responsible for separating the particles, and a Condensation Particle Counter (CPC), which counts them.

Fuel

The fuel used for ESC and ETC emission tests was selected as reflecting the anticipated EU fuel quality for 2008 (Euro V), with a sulphur content of less than 10ppm. It is known that the efficiency and durability of CB-DPF and other catalyst systems can be sensitive to fuel sulphur [17]. Consequently for the ageing test, fuels with a higher sulphur content were selected in order to increase the severity of the test and to reflect fuel qualities in markets outside the EU.

Figure 4: Test Fuels

			Ageing Test	
		Emissions Tests	**(900h)**	**(100h)**
Sulphur	ppm (wt)	8	40	250
Cetane Number		55	54	54
Density	kg/dm^3	0.829	0.833	0.836
T10	°C	205	218	224
T50	°C	257	275	276
T90	°C	334	328	332
T95	°C	349	341	353
Total Aromatics (IP391)	% (wt)	18.0	22.5	25.8

Lubricant

The lubricant was Shell Rimula Ultra 5W/30, a standard lubricant used in the Euro III engine. Analysis of fresh and used oil samples showed a sulphur level of about 0.3% and a phosphorus level of about 0.1% by weight (by ASTM D5185).

Urea

Aqueous urea is a non-hazardous, non-explosive, non-toxic liquid, which has been released as a food-additive and has the lowest water polluting classification. The urea in water solution used in this project was supplied by NorskHydro and had a urea content of 32.5 ±0.5%. The specification was in accordance with the draft DIN standard 70 070.

4 CALIBRATION

With the project target of around 1.0 g/kWh NOx and with the SCR system designed to reduce NOx by about 80%, the engine-out level could not be much above 5.0 g/kWh so that no change was made to the calibration of the Euro III base engine.

The urea dosing strategy was calibrated to meet the project NOx target. To eliminate ammonia slip a special ammonia oxidation catalyst or “clean-up catalyst” (CUC) was fitted downstream of the SCR as shown in Figure 3.

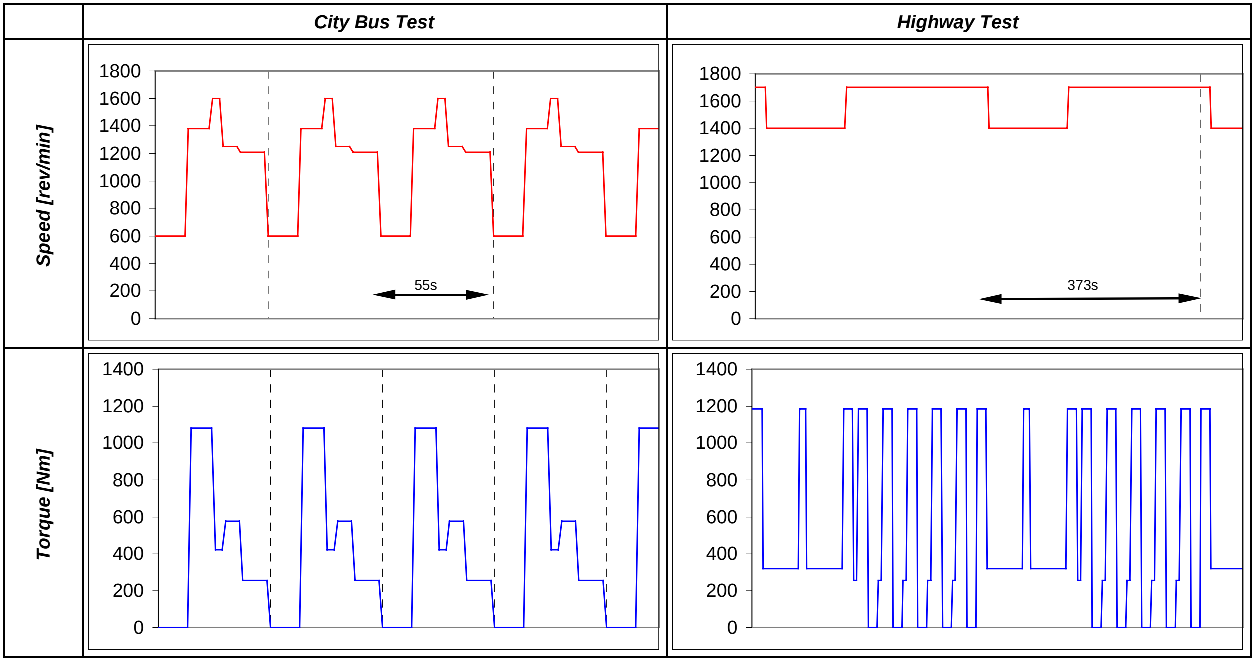
The consumption of urea solution for this calibration was about 4.8% of the diesel fuel consumption on a mass basis over the ESC and ETC tests.

Measurements by laser spectrometer confirmed that ammonia levels in the ESC and ETC tests were reduced to below 10ppm by the clean-up catalyst.

5 AGEING TEST CYCLE

There is no universally accepted method for ageing heavy-duty engine catalysts, consequently a suitable test procedure was devised for this project. The test cycle, proposed by IVECO, was based on on-road data from trucks and buses and consisted of a total of 8h made up of 1h of city driving and 7h of highway driving. The elements of the cycle are shown in Figure 5. The cycle was repeated continuously 125 times making up 1000h in all.

Figure 5: Ageing Cycle



Both parts of the cycle involved rapid changes in load and speed, which resulted in swings in exhaust temperature from 250°C at idle to 550°C at full load in the exhaust manifold. The temperature at the CB-DPF inlet was in the range 330°C-380°C, exhaust temperatures were therefore continuously above the regeneration temperature.

The severity of the test for the catalysts was significantly increased by simulating two incidents reflecting use of higher sulphur fuels, each corresponding to 50h on 250ppm sulphur fuel (at 150-200h and 650-700h), with the remaining 900h on 40ppm sulphur fuel. Compared with a 1000h test on 10ppm sulphur fuel, this increased the test severity by an estimated factor of 6. For an on-highway application, 1000h engine ageing on the testbed was designed to be representative of about 250,000 km of real-world driving.

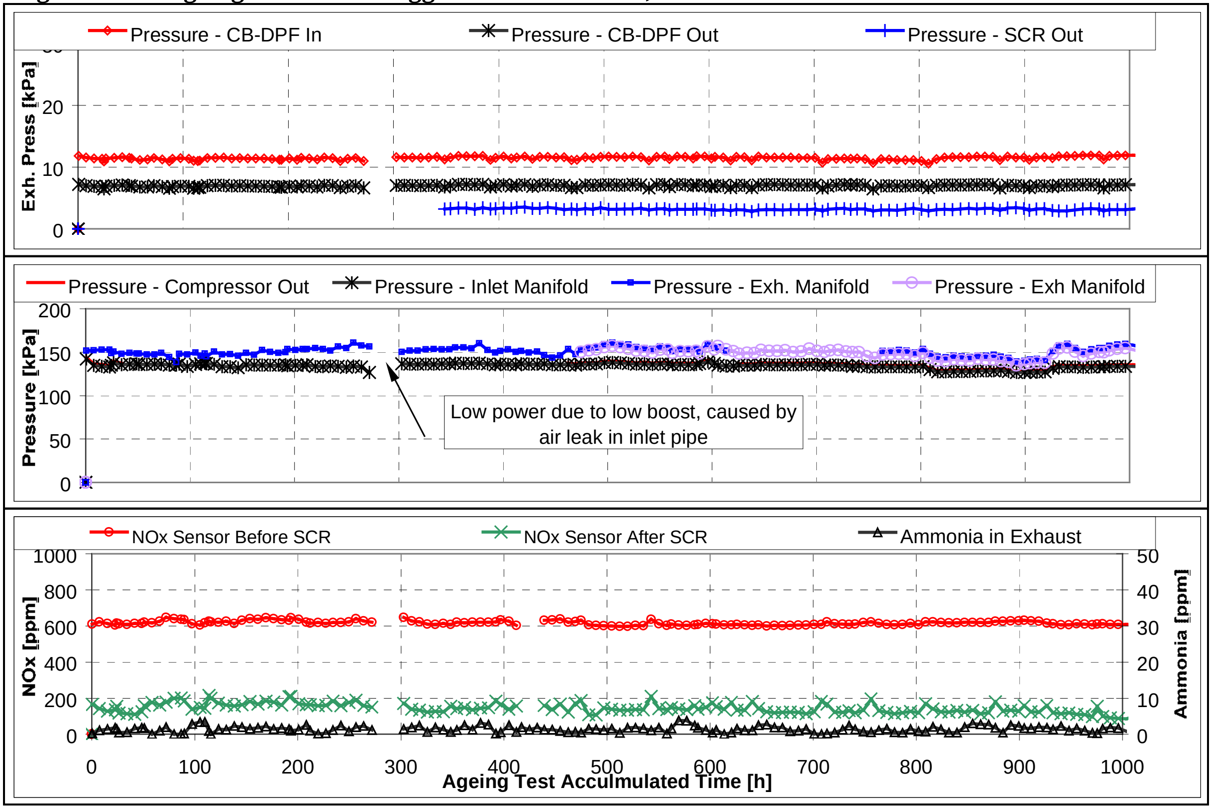
The fluctuating loads and speeds in the ageing cycle were separated out into modes at which the engine was sufficiently stable for checks on parameters to be made at regular intervals (approximately 8 measurements/h). An example of the output from one mode (1380 rev/min, full load) is shown in Figure 6 and 7. It is clear that the temperatures and pressures experienced by the catalysts were more or less unchanged throughout the 1000h.

Calculation shows that sulphur and ash in lubricating oils make a significant contribution to ash formation on the catalysts and there was evidence of soft ash deposits on the front face of the CB-DPF. However the ash build-up was not sufficient to cause an increase in the exhaust backpressure over the ageing test.

The NOx sensors on either side of the SCR continued to operate reliably throughout the ageing test.

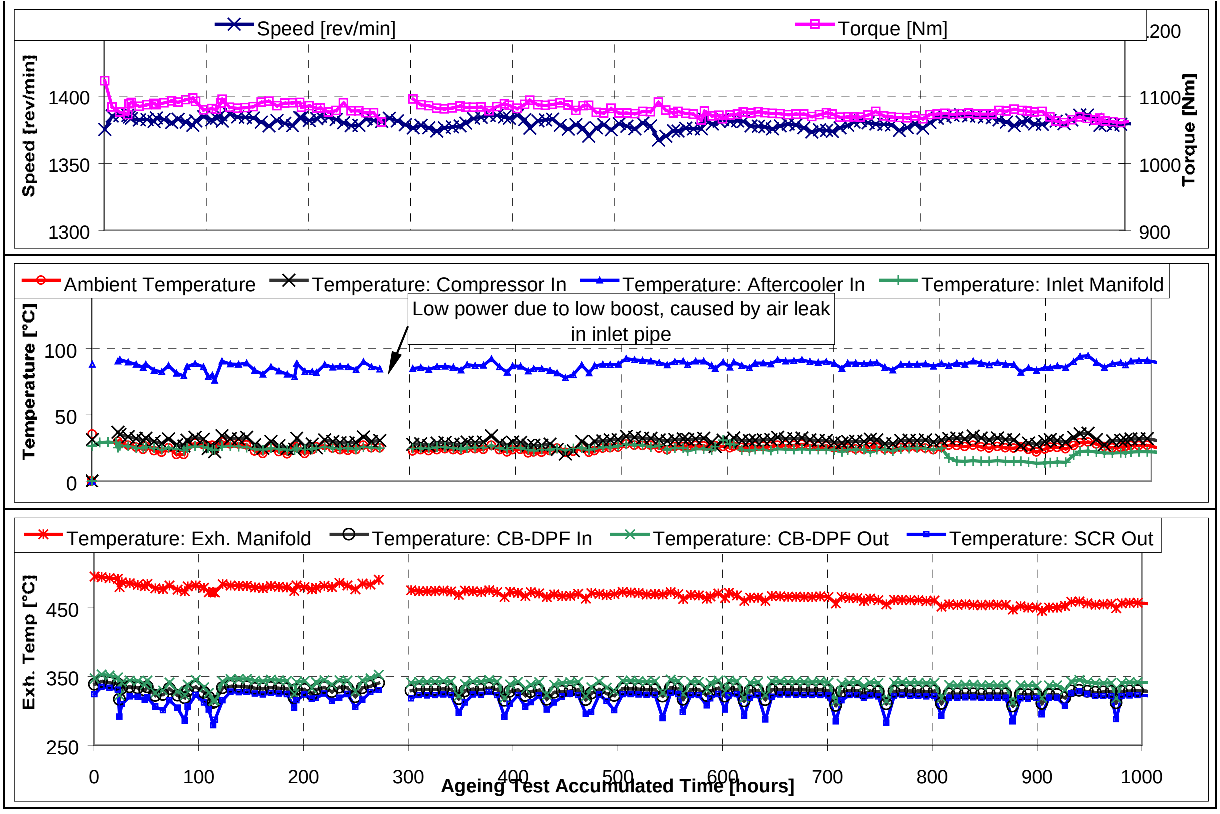
The average consumption of urea solution over the 1000h was 4.4% of the diesel fuel consumption on a mass basis.

Figure 6: Ageing Test: Data Logged at 1380 rev/min, 100% Load



Low power due to low boost, caused by air leak in inlet pipe

Figure 7: Ageing Test: Data Logged at 1380 rev/min, 100% Load



Low power due to low boost, caused by air leak in inlet pipe

6 RESULTS AT EURO V EMISSION LEVELS

The NOx emissions measured over the ETC test before and after ageing are shown in Figures 8 and 9. The NOx levels from the base engine and with the emission control system remained very stable throughout the 1000h test.

Figure 8: ETC Tests at 0h: NOx Engine Out versus Catalysts Out

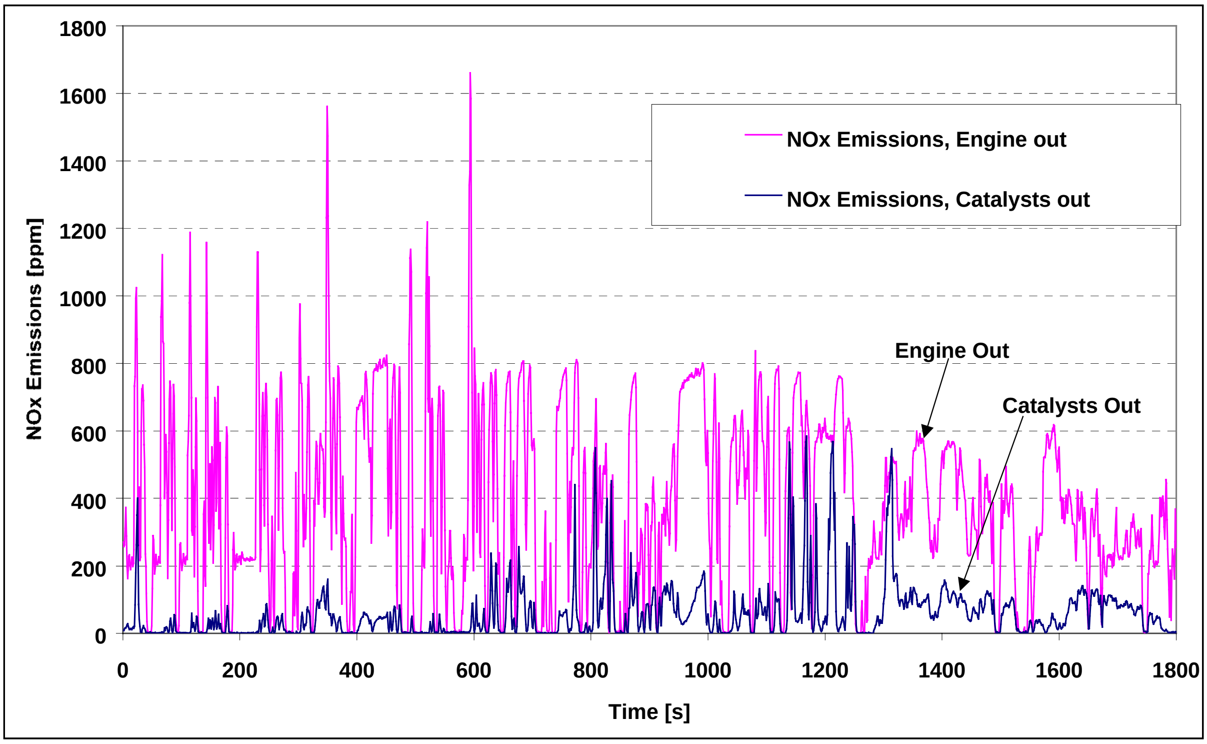
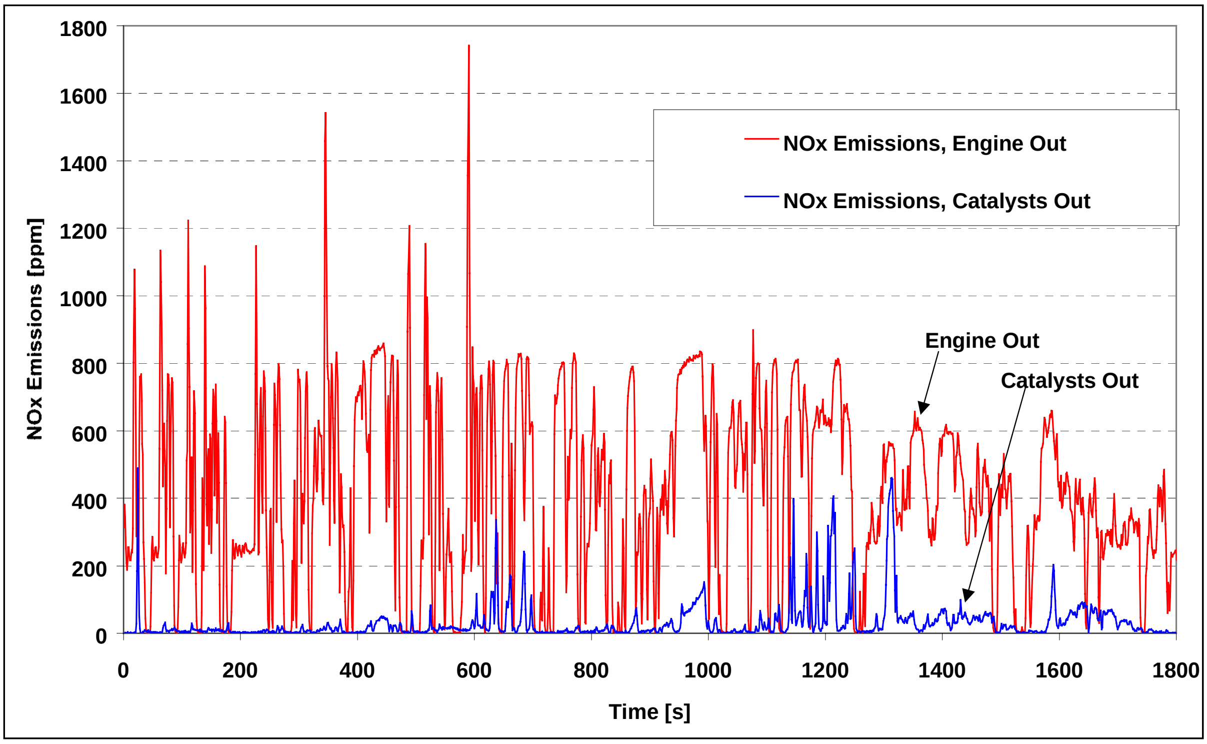


Figure 9: ETC Tests at 1000h: NOx Engine Out versus Catalysts Out



Over the ESC and ETC tests, NOx emissions for catalysts out were below 1 g/kWh after 1000h ageing, giving a margin of more than 50% below the Euro V limit. Particulate emissions were also reduced to less than 50% of the Euro V limits.

The results, summarised in Figure 10, demonstrate that the heavy-duty Euro V emission limits can be comfortably achieved using an integrated emission control system, with no deterioration over the 1000h of engine ageing.

Figure 10: Summary of Emissions Test Results

ETC [g/kWh]	2008 (Euro V) Limits	Before Ageing Test		Conversion Efficiency [%]	After Ageing Test		Conversion Efficiency [%]
		Engine Out	Catalysts Out		Engine Out	Catalysts Out	
HC	0.4	0.31	0.07	77	0.29	0.07	76
CO	3	0.8	0.03	96	0.78	0.01	99
NOx	2	5.89	1.06	82	5.83	0.85	85
PM	0.03	0.066	0.01	85	0.064	0.011	83

ESC [g/kWh]	2008 (Euro V) Limits	Before Ageing Test		Conversion Efficiency [%]	After Ageing Test		Conversion Efficiency [%]
		Engine Out	Catalysts Out		Engine Out	Catalysts Out	
HC	0.25	0.22	0.04	82	0.2	0.05	75
CO	1.5	0.5	0.03	94	0.53	0.01	98
NOx	2	5.27	0.89	83	5.28	0.8	85
PM	0.02	0.07	0.016	77	0.064	0.007	89

7 REVIEW OF EXHAUST EMISSIONS BEYOND EURO V

7.1 Particle Size and Number

The particle size range was measured by the SMPS instruments, which cover the nucleation mode (typically a mode located below 50nm) and the accumulation mode (modes at 50nm or above).

The nucleation mode is comprised of a tiny solid nucleus, typically consisting of sulphate of about 1nm diameter, which grows into the measurable range by the condensation of low volatility hydrocarbons. However, the nucleation mode may also include spontaneously condensed species of very low volatility [18].

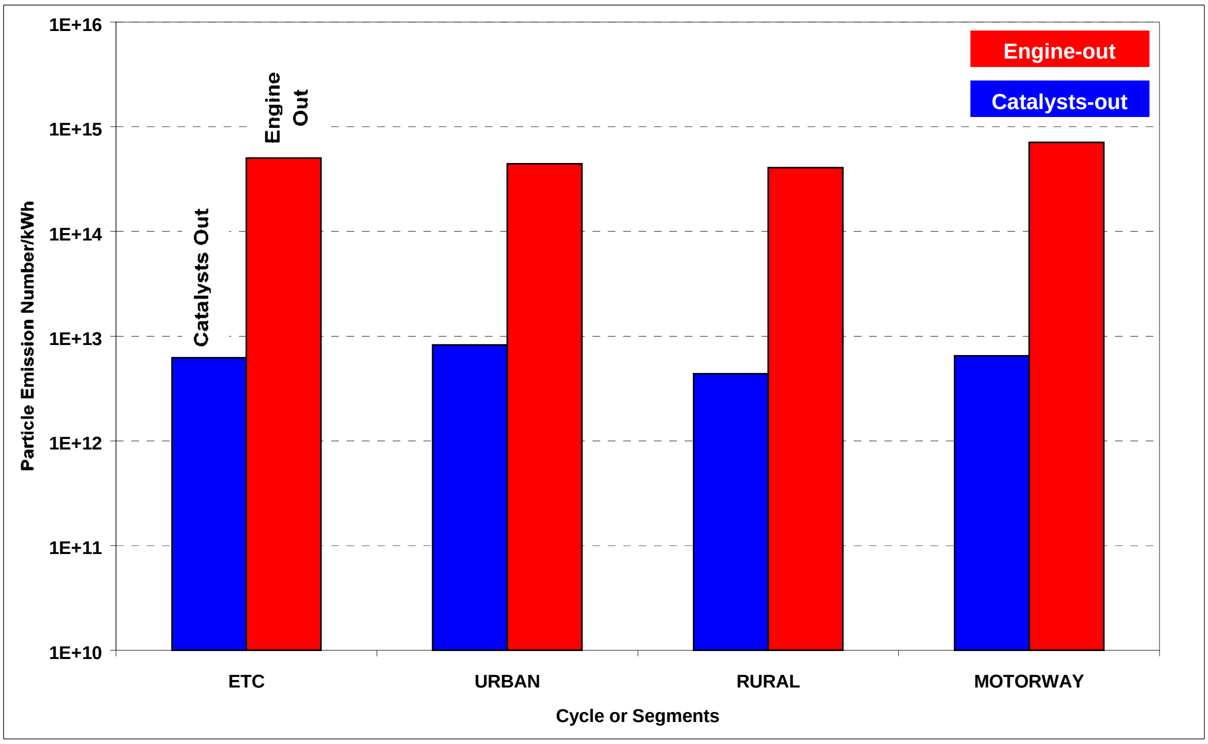
The accumulation mode consists of many accumulated carbonaceous spheres and condensed hydrocarbons together with anionic and cationic materials plus those materials derived from physical wear.

These two modes typically overlap in the 30 to 60nm region.

Comparative particle size distribution data demonstrate that the catalysts achieve a particle number reduction of approximately 2 orders of magnitude.

Integrated particle number data from ETCs (Figure 11) collected before ageing, confirm that this reduction (equivalent to about 99%) applies to all parts of the cycle.

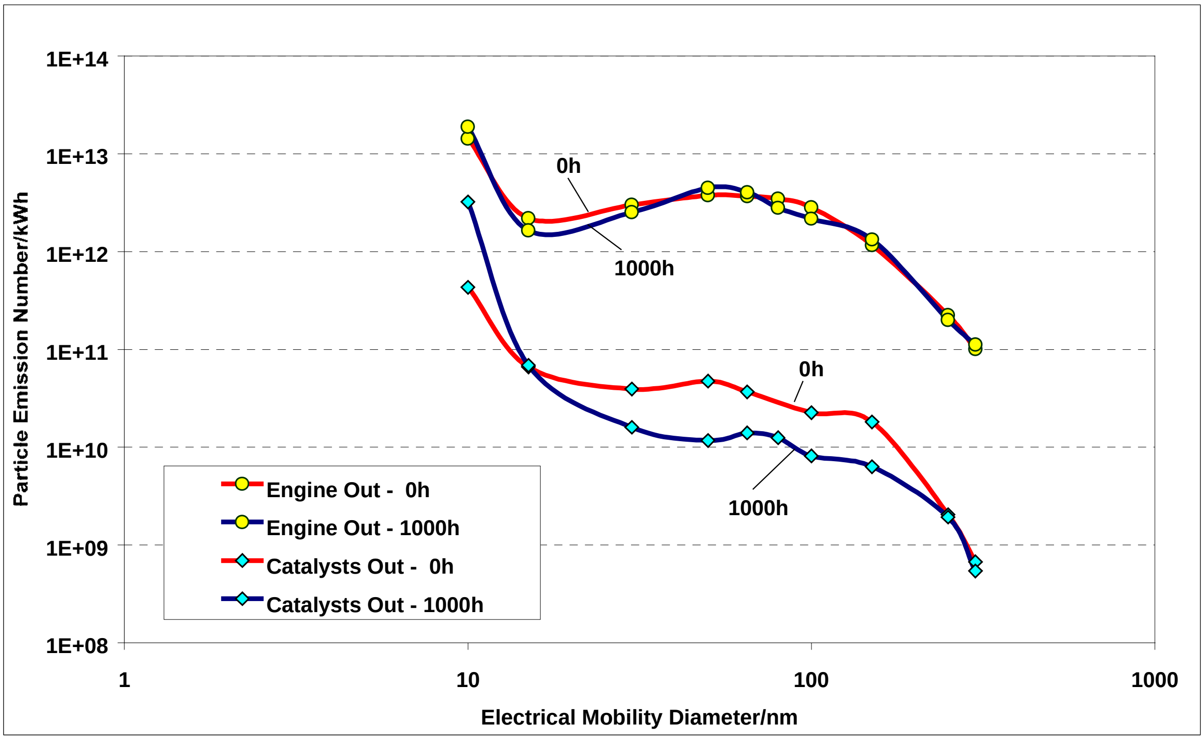
Figure 11: ETC Tests at 0h: Particle Number Emissions from Size Distribution



Comparisons between engine-out and post-catalysts particle size distributions at 0h and 1000h show similar magnitude reductions in particle numbers in the range 30nm to 300nm (Figure 12). The lower post-catalysts levels of these particles observed at 1000h were consistent with reductions in both carbonaceous material and particulate mass relative to the pre-ageing measurements.

After ageing, reductions in particles smaller than 30nm are still considerable (equivalent to about 50%) but are lower than those observed pre-ageing. This effect may be the consequence of both a reduction in accumulation mode levels and an increase in sulphate levels promoting nucleation.

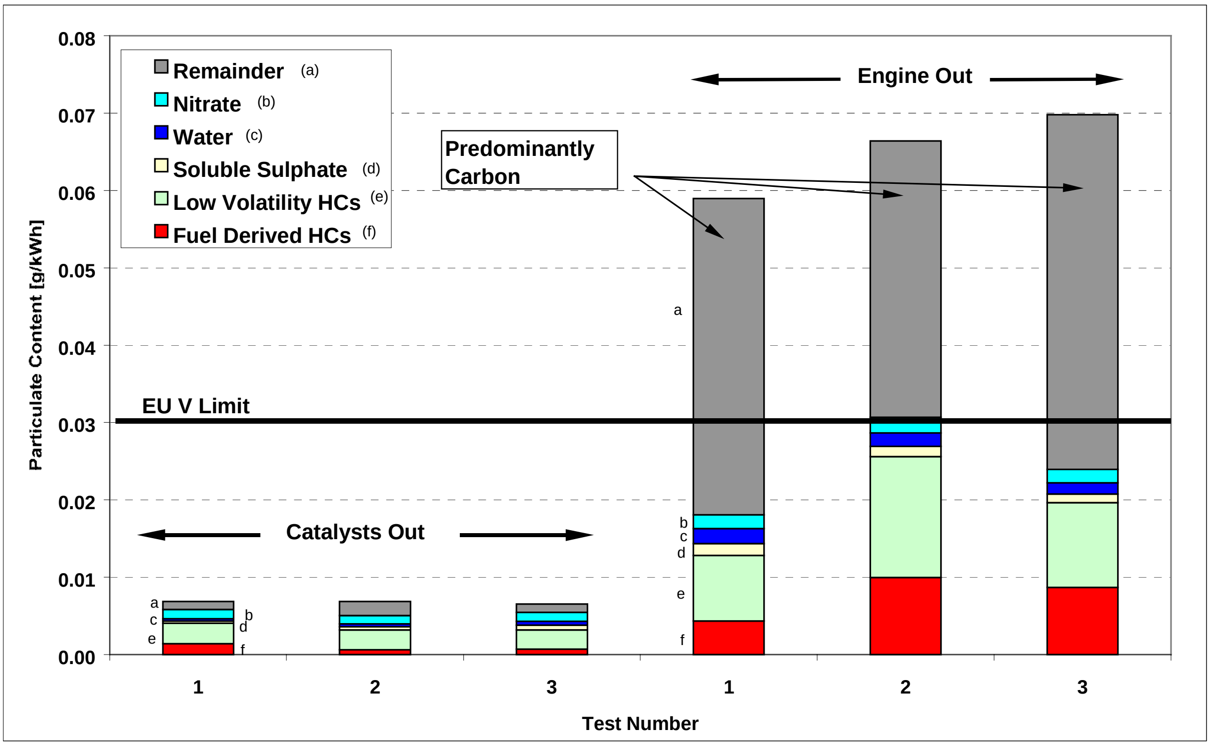
Figure 12: ETC Tests: Number Weighted Particle Size Distribution Data



7.2 Sulphate Conditioning

Analyses of the particulate from pre-ageing ETC tests showed that the catalysts reduced the carbon to very low levels below the detection limits (Figure 13). At this stage, the engine had been run on low sulphur fuels only (8ppm and 40ppm), and the sulphate levels in the particulate were low.

Figure 13: ETC Tests at 0h: Effect of Catalysts on Particulate



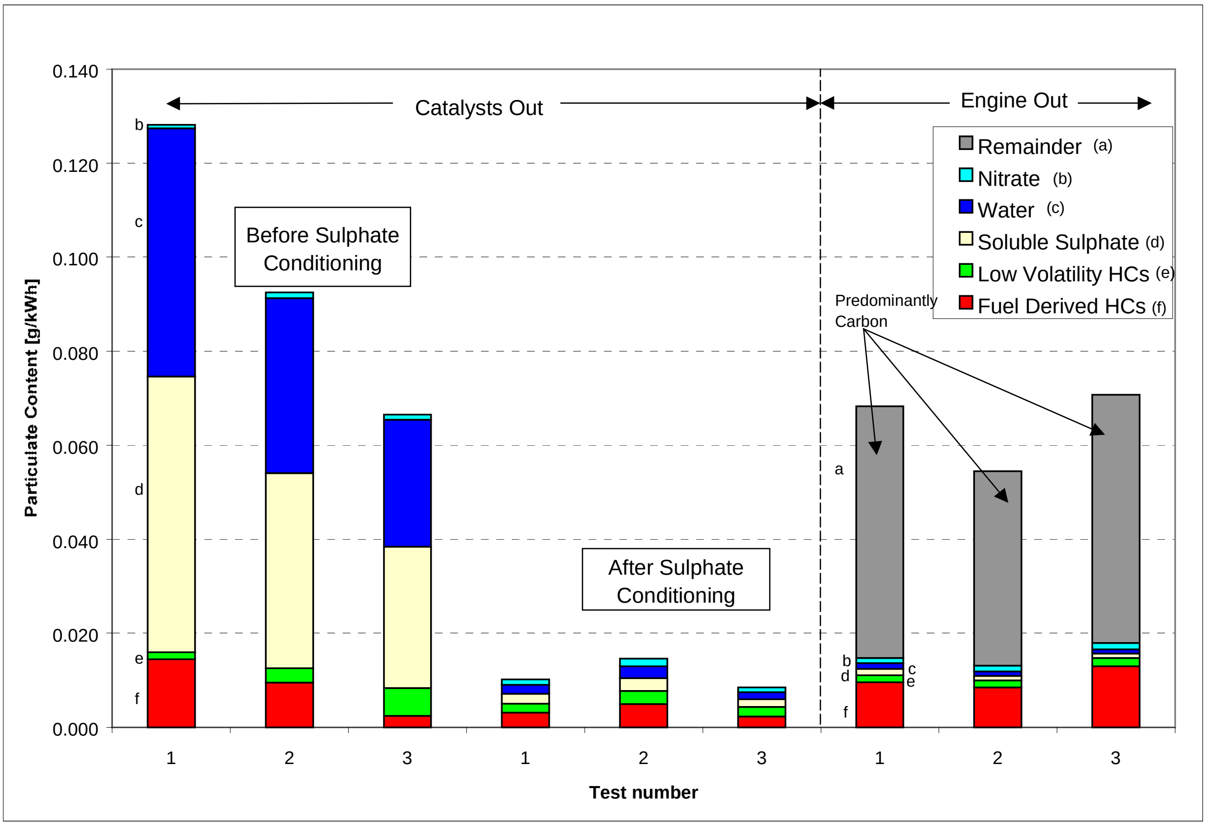
Emission measurements made at intervals during the ageing test were made using 8ppm sulphur fuel, about 2h after switching from the 40ppm sulphur fuel and about 300h after misfuelling with the 250ppm sulphur fuel.

There is evidence that prolonged conditioning on the new fuel is needed to clear the effect of sulphur [17], consequently some evidence of increase in sulphate in the particulates was expected. The particulate emissions from the first three ESC tests after ageing were very high due to the release of stored sulphate, as can be seen in Figure 14. The sulphate storage in the catalysts was due to the prevailing exhaust temperatures during the ageing test (300-400°C) and the fuels used. The sulphate was released during the initial emission tests at 500h and 1000h when higher exhaust temperatures (450°C at CB-DPF inlet) were experienced, resulting in high levels of sulphate in the particulate.

Conditioning the catalysts at high load with a CB-DPF inlet temperature of 510°C for 8h released most of the remaining sulphate and restored measured particulates to very low levels. The sulphate storage and release process will be minimised by the introduction of the <10ppm sulphur diesel fuel being introduced across the EU from 2005. This fuel quality will be necessary if the full potential of emission control systems for heavy-duty engines, as demonstrated in this programme, is to be realised.

The particulate analyses after ageing confirm that carbon emissions are virtually eliminated by the CB-DPF.

Figure 14: ESC Tests at 1000h: Particulate Analysis Before and After Desulphation

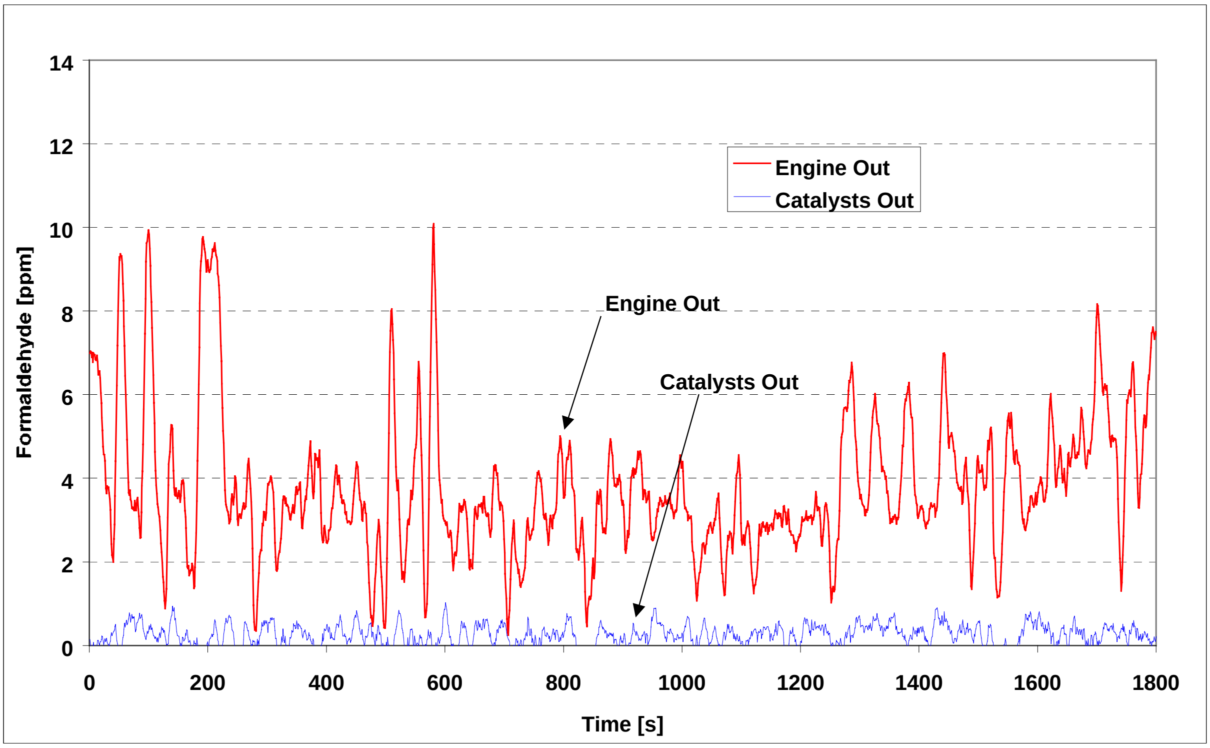


7.3 Non Regulated Emissions

7.3.1 Aldehydes

Emissions of formaldehyde and acetaldehyde over ESC and ETC tests were at a low level from the baseline engine (<10ppm). The catalysts reduced these compounds to below the detectable levels of ca. 2ppm.

Figure 15: ETC Tests at 0h: Formaldehyde Engine Out versus Catalysts Out



7.3.2 Nitro Polycyclic Aromatic Hydrocarbons

Concern has been expressed over the possible formation of nitro polyaromatic hydrocarbons (NitroPAH) when the particulate collected in DPFs is exposed to the NO_2 in the exhaust gas. This was investigated by varying the dilution ratio in the secondary dilution tunnel to give NO_2 levels in the range 1ppm to 30ppm. The particulate samples were analysed for the compounds shown in Figure 16, which also gives the estimated limits of detection, and no NitroPAH emissions were detected either engine out or catalysts out.

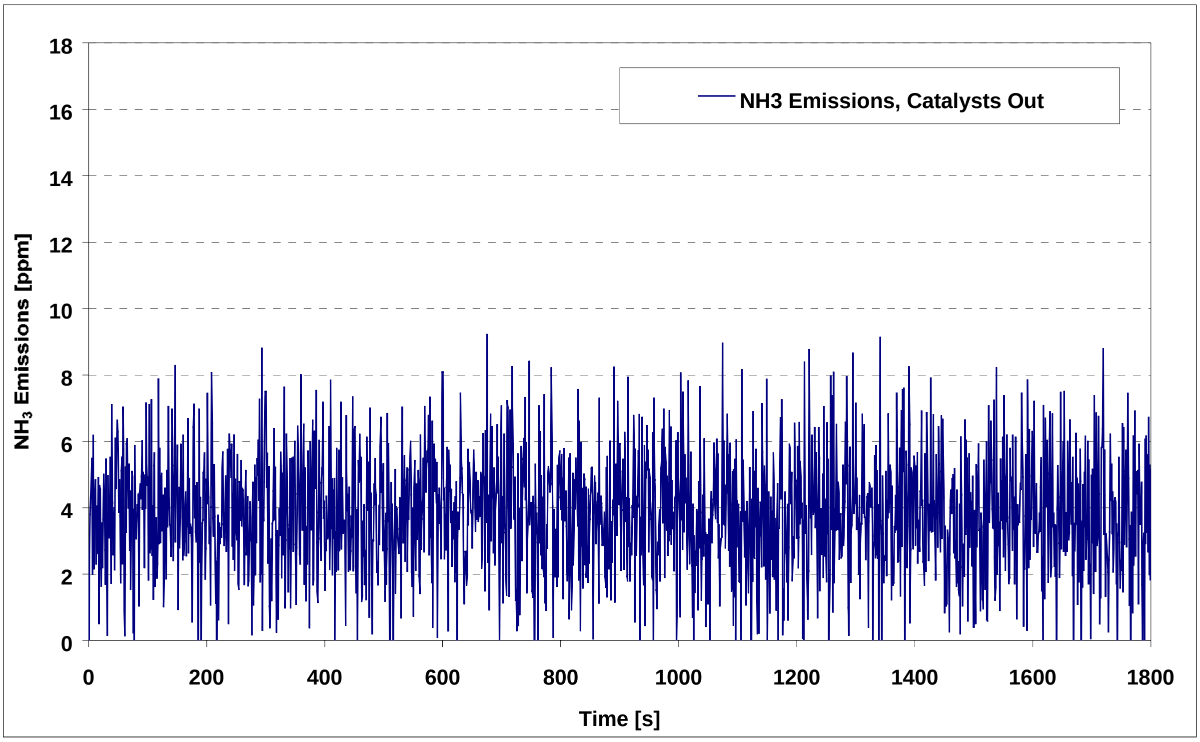
Figure 16: NitroPAH Emissions

Compounds analysed for	Quantity detected	
	Engine Out	**Catalysts Out**
1-nitropyrene	Below detectable limit (<2ng)	Below detectable limit (<2ng)
1,3-dinitropyrene	Below detectable limit (<6ng)	Below detectable limit (<6ng)
1,6-dinitropyrene	Below detectable limit (<2ng)	Below detectable limit (<2ng)
1,8-dinitropyrene	Below detectable limit (<10ng)	Below detectable limit (<10ng)

7.3.3 Ammonia

Catalysts out ammonia levels were well below 10ppm, as shown in Figure 17.

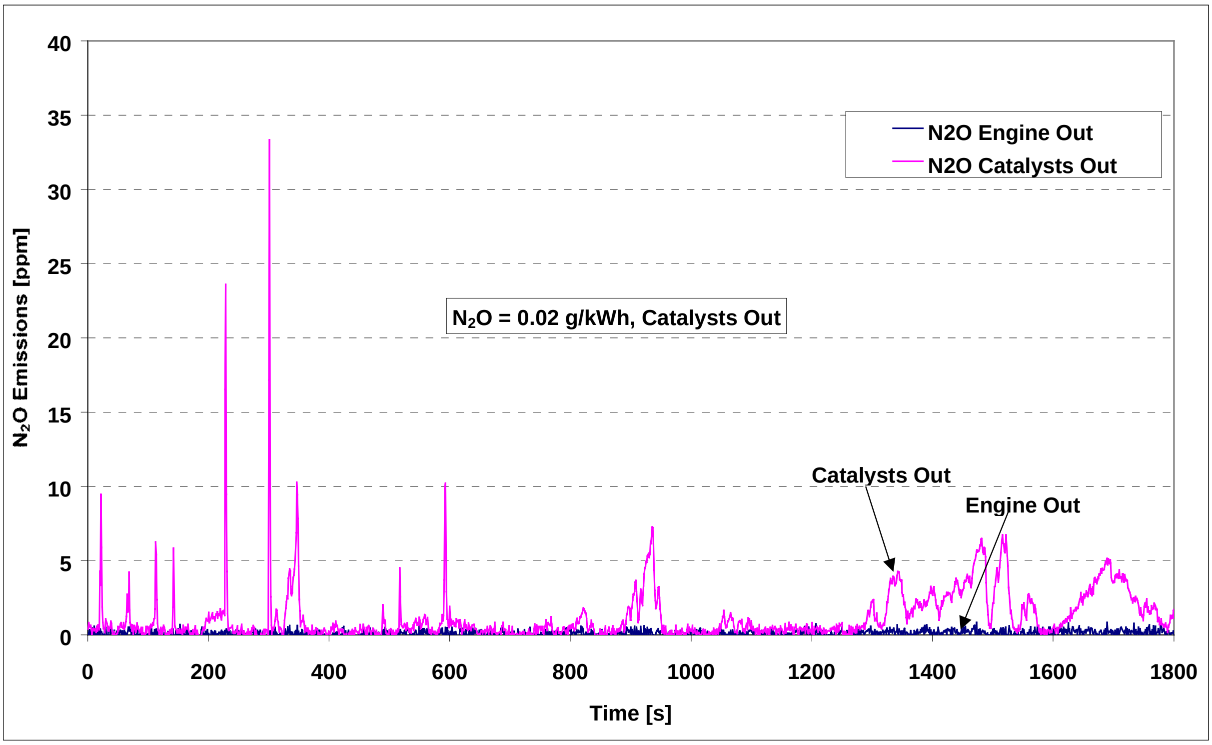
Figure 17: ETC Test at 1000h: NH_3 Catalysts Out



7.3.4 Nitrous Oxide

Compared with the NOx levels catalysts out shown in Figures 7 and 8, the nitrous oxide (N_2O) barely register on the same scale. The trace of N_2O emissions over the ETC test is shown in Figure 18. Apart from some instantaneous peaks in the early part of the cycle, the N_2O emissions showed no significant change over the catalyst system. Both before and after ageing the N_2O emissions were measured at 0.02 g/kWh over the ETC test.

Figure 18: ETC Tests at 0h: N_2O Engine Out versus Catalysts Out



7.4 Proposed WHDC Test Results Compared to the Results on ESC and ETC Tests

The engine was run over the Worldwide Harmonised Diesel Cycle (WHDC), which was still under development and validation at the time of the programme. The results of post-ageing tests are shown in Figures 19 and 20. The emission levels over the proposed WHDC are slightly higher than over the ESC and ETC due to the lower cycle power and lower exhaust temperatures, which results in a slightly reduced conversion efficiency of gaseous emissions over the catalysts. However, the fact that the catalyst system is able to provide substantial emission reduction over the ETC, ESC and WHDC without recalibrating or any other modifications to the urea injection calibration is an indication of the robustness of the emission control systems.

Figure 19: NOx and PM over ESC, ETC and Proposed WHDC at 1000h

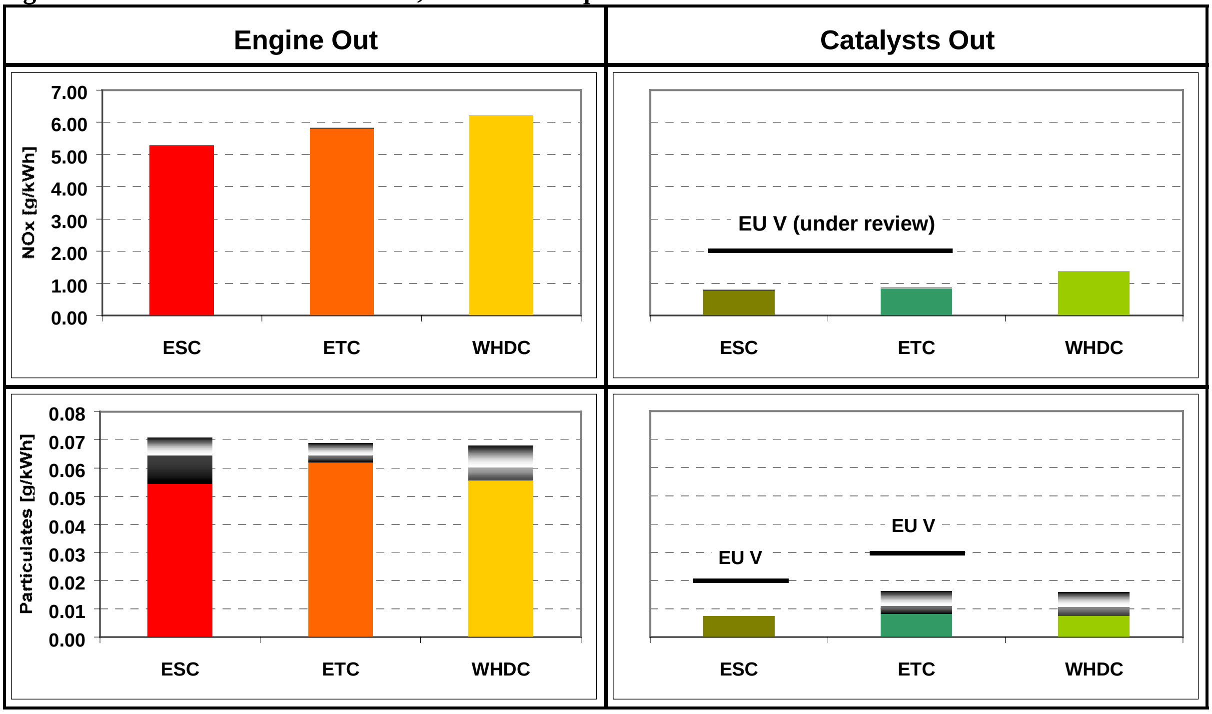
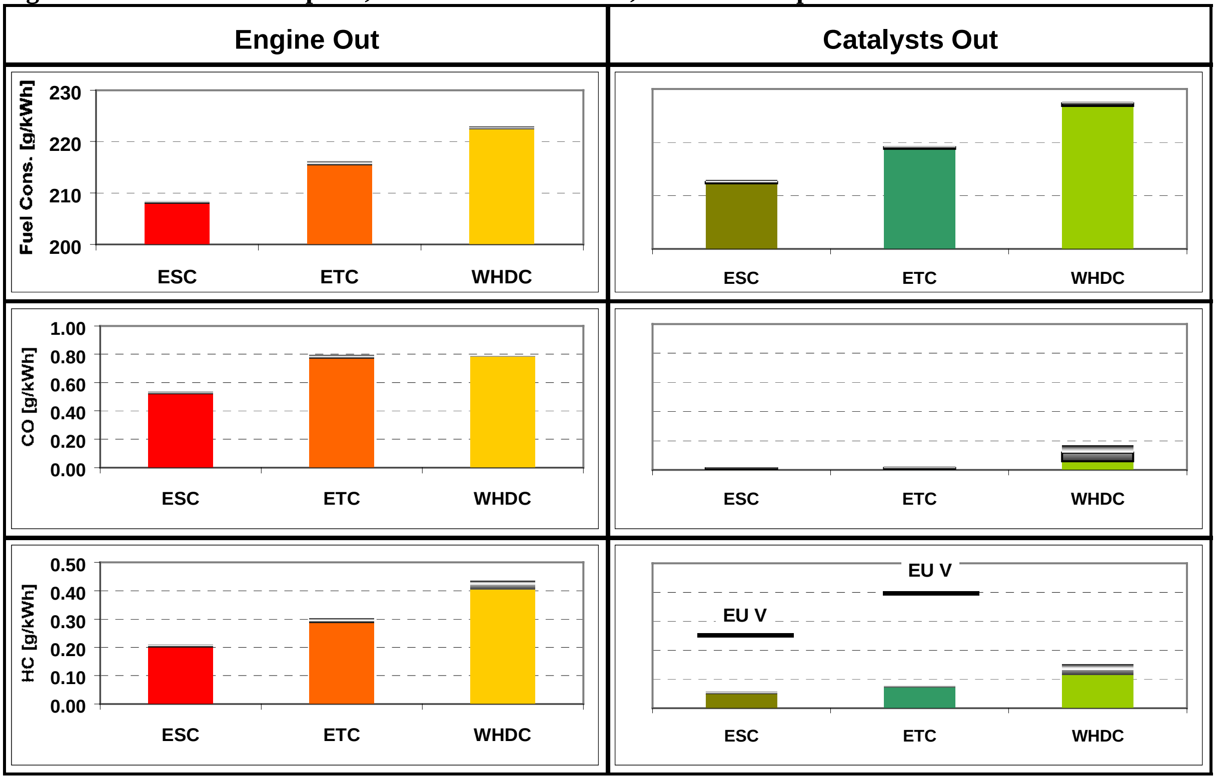


Figure 20: Fuel Consumption, CO and HC over ESC, ETC and Proposed WHDC at 1000h



8 CONCLUSIONS

- The emissions control system (CB-DPF + SCR + clean-up catalyst) applied to an unmodified heavy-duty Euro III series production engine enabled the 2008 (Euro V) emissions limits to be achieved with a margin of more than 50% after 1000h ageing.

- There was no deterioration in emissions after ageing for 1000h using a cycle typical of severe continuous on-road operation with some high sulphur fuel misfuelling.

- The emission control system gave a catalyst out NOx level of below 1.0 g/kWh on ETC and ESC tests, corresponding to a reduction of 85% after 1000h ageing. NH_3 emissions were well below 10ppm throughout the 1000h.

- The urea consumption was about 4.4% of the diesel fuel consumption over the durability test and 4.8% in the ESC and ETC tests.

- Particulate emissions were reduced by about 85% on both ETC and ESC tests after 1000h ageing. Exhaust back pressure remained constant throughout the ageing test, in spite of deliberate misfuelling with 250ppm sulphur fuel for 100h. Particulate emissions contained virtually no carbon.

- Total particulate numbers were reduced by about two orders of magnitude over a size range from 10 to >100nm.

- CO emissions were virtually eliminated by the catalysts, HC emissions were reduced by 75% and aldehydes to undetectable levels (by FTIR). Nitro-polyaromatic compounds were below the limits of detection, both engine out and catalysts out.

- There was storage of sulphate in the catalysts during the ageing test due to the prevailing exhaust temperatures and the fuels used.

  The planned reduction in fuel sulphur to 10ppm in Europe will minimise the storage and release of sulphates.

- Adding the catalyst system without recalibrating the engine resulted in a fuel consumption penalty of up to 2% due to the increased exhaust back pressure. There is potential for combined engine and emissions control system optimisation to reduce fuel consumption while still achieving Euro V limits.

ACKNOWLEDGEMENTS

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