Die Anwendung von Technologien zur Emissionsreduzierung an einem Niedrigemissionsmotor zur Potenzialbeurteilung zukünftiger Systeme für Europäische und weltweit harmonisierte Richtlinien

The Application of Emissions Control Technologies to a Low-Emissions Engine to Evaluate the Capabilities of Future Systems for European and World-Harmonised Regulations.

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Abstract

An existing medium heavy-duty “world” engine with low engine-out NOx emissions was fitted with an emissions control system comprising a diesel oxidation catalyst (DOC) and catalysed diesel particulate filter (C-DPF), an airless urea dosing system, a Selective Catalytic Reduction (SCR) catalyst and an Ammonia Slip Catalyst (ASC).

The urea dosing system was calibrated to provide good performance over the European steady-state and transient emissions test cycles (ESC and ETC) as well as the World Harmonised Transient Cycle (WHTC) without modification of the existing engine calibration.

Regulated emissions (Carbon Monoxide, Hydrocarbons, Nitrogen Oxides, and Particulate Mass) were measured over the European and World harmonised steady-state and transient cycles to evaluate the capabilities if the system. Unregulated emissions, including nitrogenous species and particle numbers by the PMP method, were also measured.

1 Introduction

Ongoing concern about exhaust emissions has lead to progressively tighter regulations being promulgated in the European Union. The current Euro IV regulations were initially set out in European Directive 1999/96/EC[1] and subsequently updated in later Directives [2,3,4,5]. Euro V regulations were set out in the same Directives and will apply to new type approvals after 1 October 2008. Exhaust emissions limits from these Directives are listed in *Fig. 1*. Developments in exhaust emissions reduction technology have enabled European truck manufacturers to offer Euro V versions of their products in advance of this date. In view of this it is now appropriate to consider whether there is scope for further reduction of exhaust emissions limits towards Euro VI.

	Test Cycles	CO g/kW.h	THC g/kW.h	NOx g/kW.h	PM g/kW.h	ELR test m^{-1}
Euro IV from 2005	ESC	1.5	0.46	3.5	0.02	0.5
	ETC	4.0	0.55		0.03	
Euro V from 2008	ESC	1.5	0.46	2.0	0.02	0.5
	ETC	4.0	0.55		0.03	

Fig. 1: European Heavy-Duty Diesel Exhaust Emissions Limits

In a previous programme[6], AECC and Ricardo demonstrated the potential of a Euro III engine to meet 50% of Euro V emissions limits by the addition of urea-SCR and DPF (Diesel Particulate Filter). The purpose of the current programme was to evaluate the potential of an engine having low engine-out NOx levels combined with an advanced emissions control system. The target was to demonstrate tailpipe NOx levels below 0.4 g/kW.h on the ETC test.

There is increasing interest[7] in the adoption of Worldwide Harmonised test procedures[8], possibly at the same time as the Euro VI emissions limits. Therefore it was appropriate to investigate the implications of a change from the current European test procedures (ESC and ETC) to the Worldwide Harmonised test procedures (WHTC) as part of the work reported here.

The legislative limits for particulate mass emissions have reduced substantially since the procedures set out in the European Directives[1,2,3,4] for measuring diesel particulate matter were devised. Alternative metrics for particle emissions, which provide greater accuracy and sensitivity and might also be more appropriate for quantifying the effect of these emissions on human health, have been proposed. This led to the establishment of the Particle Measurement Programme (PMP) under the auspices of UNECE/GRPE, and the subsequent development of particle number and revised mass measurement methods [9,11,12]. It is understood that particle number limits are under consideration for Euro VI. Therefore, in this programme, particle numbers were measured so that the effects of the exhaust aftertreatment system on emissions could be assessed.

2 Test Engine and Aftertreatment Equipment

2.1 Test Engine

A pre-requisite for the programme was an appropriate heavy-duty engine equipped with cooled EGR and an engine-out NOx emissions level below the Euro V limit of 2.0 g/kW.h. At the time that the project was initiated all European Euro V engines used SCR systems, without EGR. For this reason a medium heavy-duty engine, equipped with cooled EGR and developed to meet US2007 was selected for the programme. Engine details are listed in *Fig. 2*.

Test Engine	
Displacement	7.5 litre
Number of cylinders	6
Valves/cylinder	4
Fuel injection equipment	Common Rail System
Maximum injection pressure	180 MPa
Aspiration	Turbocharged and aftercooled
Turbocharger	Wastegated, fixed geometry
NOx control	Cooled EGR
PM control	Ceramic DPF

Fig. 2: Details of the Base Engine used in the Test Programme

For this project, the DPF fitted to the US2007 production version was replaced by a new DPF suited to expected Euro VI requirements.

2.2 Catalyst System

The catalyst system consisted of an oxidation catalyst (DOC), a catalysed DPF, followed by an SCR system and a second oxidation, or Ammonia Slip Catalyst.

Catalyst Type	Subtrate Material	Catalyst Volume [litres]	% of Engine Displacement
DOC	Metallic	3.8	51
Catalysed DPF	Ceramic	14	186
SCR	Ceramic	14	186
ASC	Ceramic	3.5	47

Fig. 3: Details of Catalysts

Prior to installation in the test cell, all catalysts were oven-aged for 200 hours at 600°C (without H_2O).

2.3 Urea Dosing System

The engine out NOx level was around 1.1 to 1.5 g/kW.h, depending on test cycle, with a tailpipe target of below 0.4 g/kW.h. Consequently the NOx reduction rate required from the SCR catalyst was 0.7 to 1.1 g/kW.h, which would require a relatively low urea dosing rate, in the order of 1% of the fuel consumption rate. For this purpose, Bosch provided a prototype DNOX airless urea-injection system with a Dosing Control Unit[13].

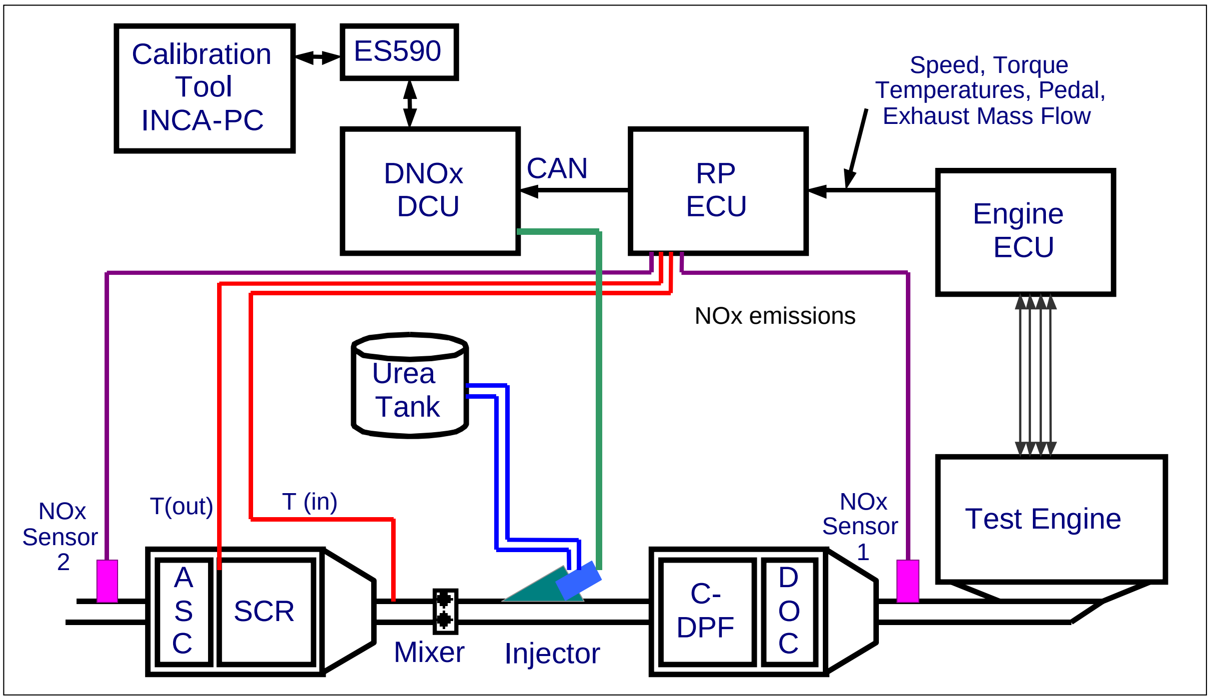


Fig. 4: Block Diagram of Emissions Control System

AdBlue® aqueous urea to DIN 70070 specification was injected at ~5 bar into the exhaust stream, upstream of a mixer plate. The mixer plate had a series of vanes and was designed to encourage entrainment of the injected urea into the exhaust stream. The urea injector and the mixer were placed approximately 1 metre ahead of the front face of the SCR catalyst to provide scope for mixing of the urea into the exhaust gas. A block diagram of the various components required for the correct functioning of the DCU is shown in *Fig. 4*. A Rapid Prototyping ECU was used for communication between the engine ECU and the DCU.

The DCU required a number of signals from the engine ECU, including engine speed, torque (fuelling), pedal position, and exhaust mass flow. NOx emissions were recorded and signals passed to the ECU by the NOx sensor 1. Data taken from the engine ECU was processed by the Rapid Prototyping ECU, which passed the signals in the required format to the Bosch DCU. An Inca calibration tool was linked to the DCU to enable calibration of the DCU maps. A second NOx sensor was fitted downstream of the SCR/ASC for recording tailpipe emissions, but this was not used for closed loop control.

It should be noted that no re-calibration of the base engine was undertaken during the programme.

2.4 Test Installation

The engine and the catalyst system were installed on a transient testbed. It was instrumented to measure the usual parameters (speed, load, air and fuel consumption, temperatures and pressures).

Additional instrumentation was used to measure exhaust emissions and catalyst performance data. *Fig. 5* shows sampling positions for the equipment described below:

- Temperatures and pressures before and after each of the catalysts (see *Fig. 5* for sampling positions)
- Horiba MEXA-7100DEGR to sample raw gaseous emissions sampled upstream of the catalysts to provide engine out emissions results for all tests
- CVS emissions system, with Horiba MEXA dilute gaseous emissions sampling system, and particulate mass sampling via a secondary dilution tunnel
- FTIR (Fourier Transform Infra-Red) analyser (Nicolet Magna IR) with REGA sampling trolley. The FTIR was used primarily for the analysis of NOx species (nitrous oxide, nitric oxide, nitrogen dioxide and ammonia). The FTIR was also used for the analysis of small hydrocarbons (methane, ethane, ethane, ethyne, propane, propene) and carbonyls (formaldehyde, acetaldehyde). A single instrument was used throughout the test programme. There were

four sampling points at strategic positions along the exhaust system. A single position was used for each emissions test, and data were recorded at 1Hz.

- Partial flow dilution tunnel (Horiba MDLT) for measurement of particulate mass

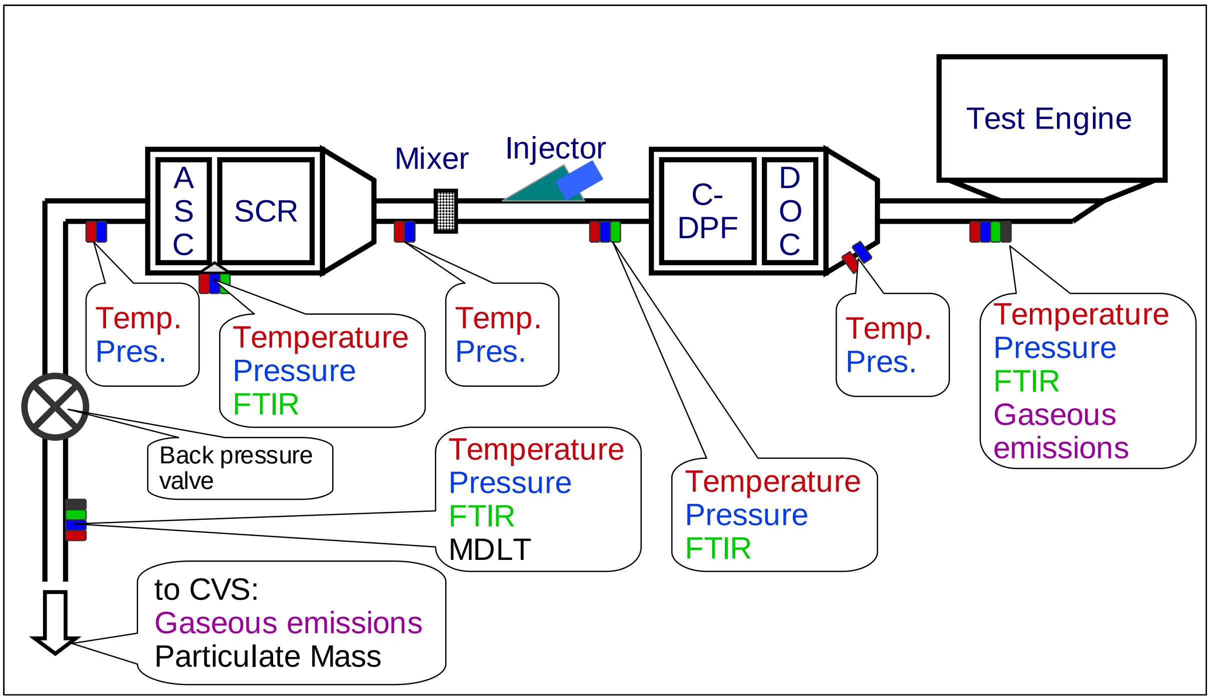


Fig. 5: Exhaust System instrumentation and sampling positions

2.5 Particle Number Measurement System

In the PMP programme, the development philosophy of the particle number measurement system was to enable the accurate, repeatable and reproducible sampling of a well-defined particle from a very low background environment. It was also considered desirable to minimise required changes to the current type approval facilities, to employ an understandable metric and for the system to be simple to operate. The system was developed with an objective for the lowest possible particle losses – to avoid the possible requirement for correction factors.

The particles measured – 'PMP Solid Particles' are defined by upper and lower limits (d50) on particle sizes of approximately 25nm and 2.5µm and by their volatility: they must survive the heating and evaporation processes experienced by the sample at or above 300°C.

2.5.1 Full Flow Measurements

Particle number measurements were undertaken according to the PMP's heavy-duty inter-laboratory correlation exercise guide[9] with sampling from the primary CVS dilution system. The sampling system comprises several components, which together define the particle measured. A schematic is given in *Fig. 6*.

2.5.2 Partial Flow Measurements

From selected engine-out tests, the PMP particle number measurement equipment was employed to sample from the partial flow dilution system.

Samples were drawn, simultaneously with mass samples, from the partial flow system above the filter holder but after the dilution tunnel. Drawing extra flow results in reduced dilution ratios at all conditions, with the differences in dilution ratio varying depending on operating condition. The MDLT software includes a function to permit an additional flow to be drawn and the mass flow corrected. This function was employed in all tests.

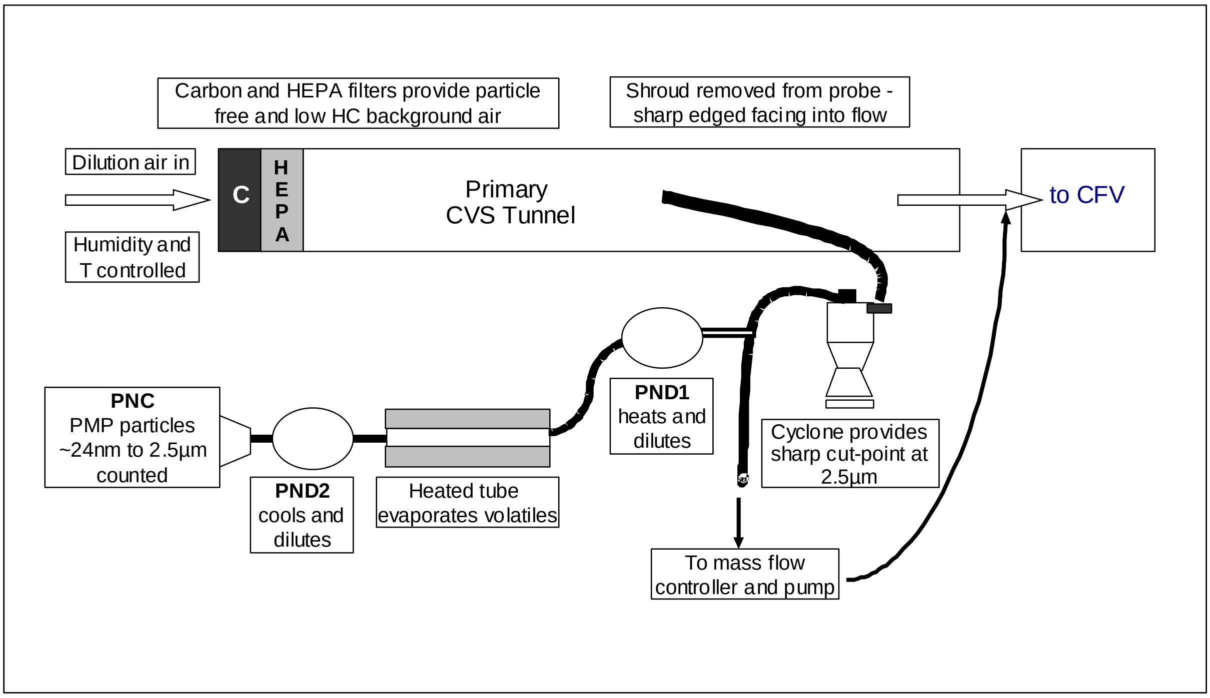


Fig. 6: Particle Number Measurement System

3 Test Programme

The test programme included test cycles used for exhaust emissions certification in major world markets and new test cycles under consideration. Only the results over test cycles relevant to Europe are reported here; that is: ESC, ETC, WHTC and WHSC. The WHTC test has two parts, a cold start and a warm start test. Hot start WHTC tests were carried out with hot soak intervals of 5, 10 and 20 minutes.

Engine-out and tailpipe regulated gaseous exhaust emissions were measured simultaneously for all tests. In order to ensure consistent results, at least three tests of each type were carried out. Additional tests were carried out with the catalysts removed to measure engine-out particulates via the CVS and MDLT systems.

The engine and exhaust system was pre-conditioned before each test, in order to achieve consistent ammonia storage and soot loading.

4 Results and Discussion

4.1 Regulated Emissions Results over European Certification Cycles

The results of regulated emissions tests over the European and World Harmonised Cycles are tabulated in *Fig. 7*, and compared in *Fig. 8*.

The tailpipe NOx level over both the ETC and the ESC tests was 0.15 g/kW.h, below the project target of 0.4 g/kW.h, and well within the lowest scenario being considered for Euro VI. The NOx conversion efficiency was over 85%, and was achieved without ammonia slip. PM emissions were very low, especially over the ETC test. During the course of the test programme the engine was operated over a wide range of test cycles and in most cases, the tailpipe PM levels were similar to background levels.

The engine-out (pre-catalysts) CO emissions were very high over the ETC and the WHTC transient test cycles, probably due to the high levels of EGR used to control NOx emissions. However the catalyst controlled tailpipe CO and HC emissions well within the Euro V CO limit.

Test Procedure		**Emissions [g/kW.h]**											
		THC			**NOx**			**CO**			**PM**		
		Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.
Current European Test Cycles													
ETC	hot transient	0.43	**0.16**	63%	1.10	**0.15**	86%	8.59	**0.87**	90%	0.581	**0.001**	99.8%
ESC	steady state	0.15	**0.06**	63%	1.54	**0.15**	90%	1.10	**0.00**	100%	0.151	**0.009**	94.3%
Worldwide Harmonised Cycles													
WHTC	cold, +5min, +hot trans.	0.63	**0.20**	69%	1.25	**0.30**	76%	9.09	**1.92**	79%	0.721	**0.002**	99.7%
WHSC	steady state	0.19	**0.01**	95%	1.33	**0.18**	87%	1.00	**0.02**	98%	0.128	**0.001**	99.3%

Fig. 7: Summary of regulated exhaust emissions results

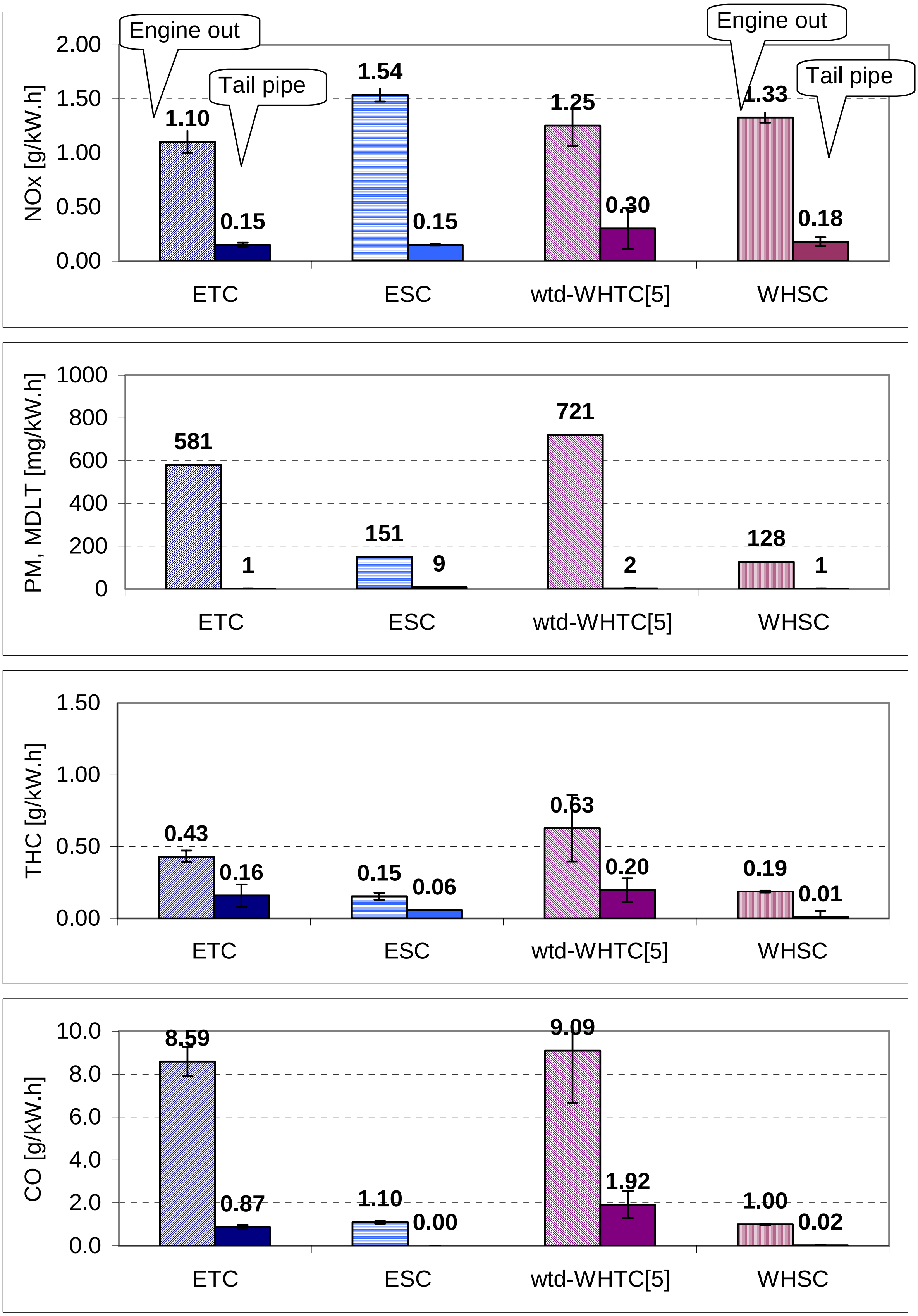


Fig. 8: Comparison of emissions over European and World Harmonised tests

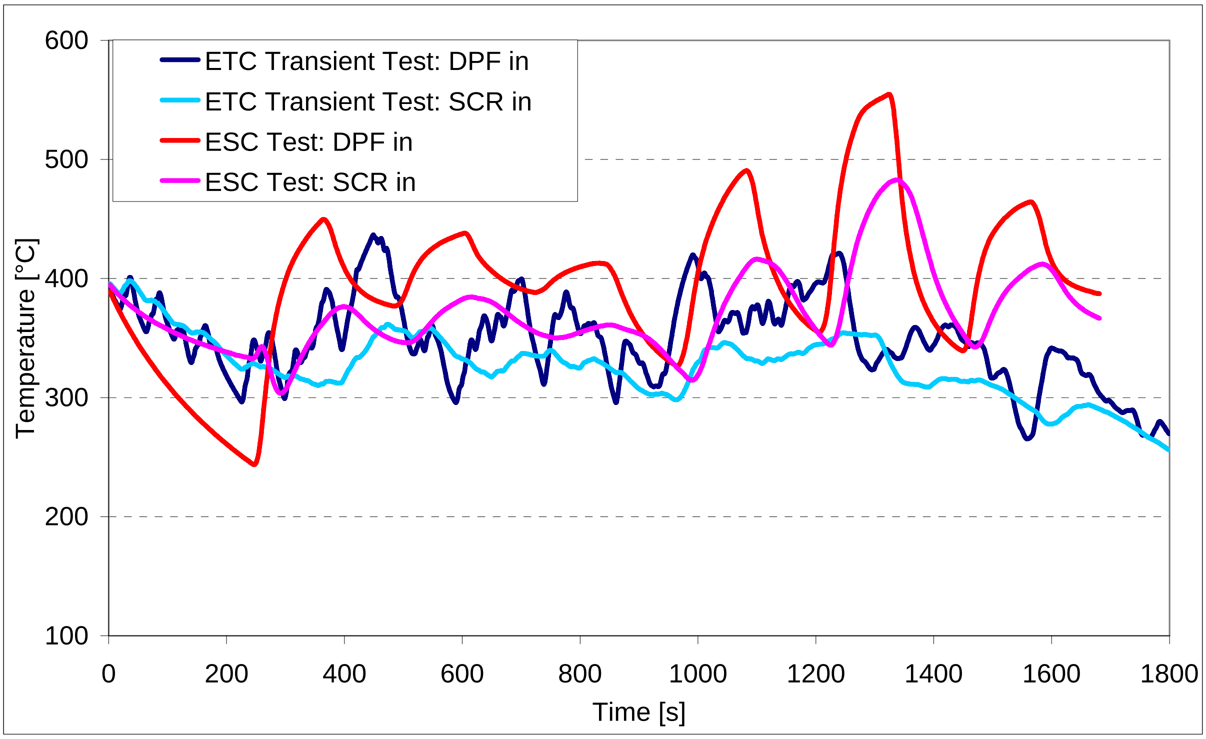


Fig. 9: Exhaust temperatures over the ETC and ESC tests

The exhaust temperatures over the ETC and ESC tests are compared in *Fig. 9*. Both tests start with a pre-warmed engine and exhaust system, and the temperature of the catalysts does not fall below 250°C throughout the tests. To ensure thermal decomposition, the dosing strategy was calibrated so that urea was injected only when the SCR catalyst exceeded a temperature of 200°C. As a result the catalysts operated at high conversion efficiencies throughout the test cycles.

4.2 Comparison of European and World Harmonised Test Results

The WHTC test includes a cold start test from an ambient temperature of 25°C. For the data presented in this Section, the hot tests commenced 5 minutes after the cold test completed (referred to as '5 min soak'), and the results were weighted 10% cold and 90% hot.

When the same engine and catalyst system was operated over the WHTC cycle, without re-calibration, the tailpipe NOx emissions doubled from 0.15 g/kW.h for the ETC test to 0.30 g/kW.h over the WHTC test (see Table in *Fig. 11*). The increase in NOx emissions over the WHTC test was due to two reasons. Firstly no EGR was used until the coolant temperature had reached about 60°C, in the interests of avoiding engine wear and condensation in the EGR cooler. Secondly, the lower exhaust temperatures over the cold test (see *Fig. 10*) also meant that there was no urea injection for the first 750 s of the WHTC test until the temperature at the SCR inlet reached 200°C.

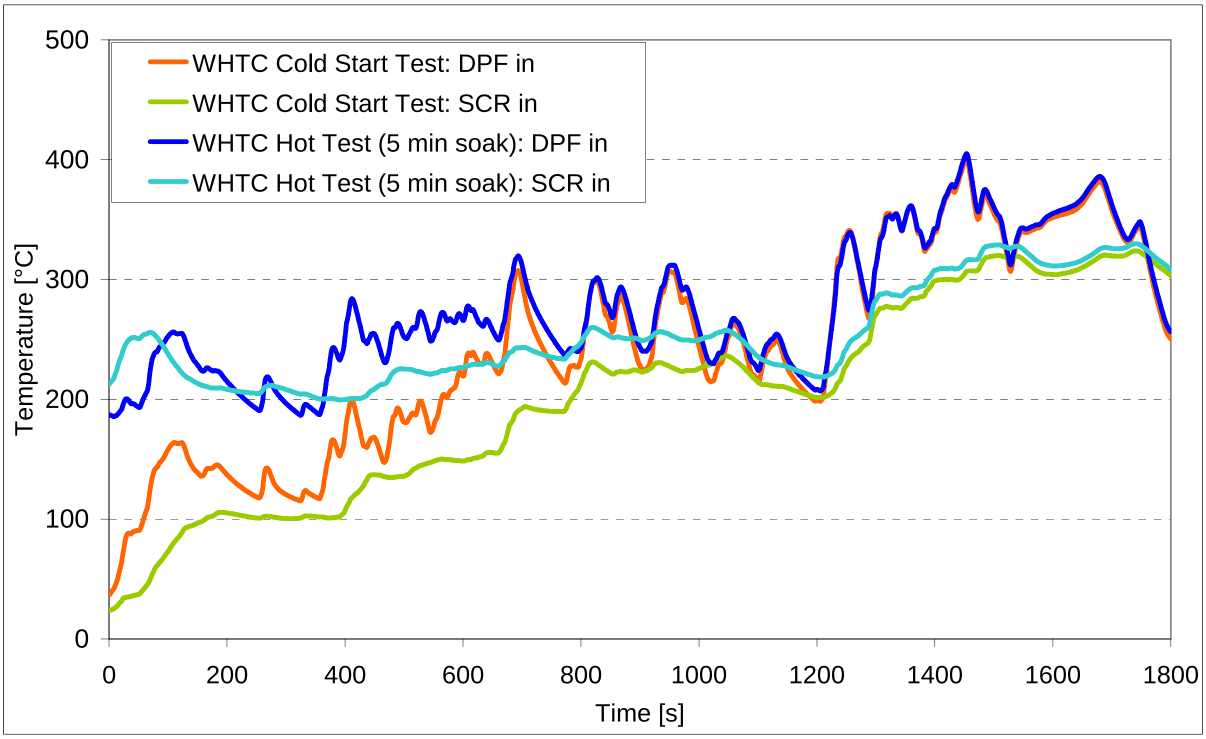


Fig. 10: Exhaust temperatures over the cold and hot WHTC tests

The lack of EGR during the early part of the cold test may explain the lower engine-out CO and PM for the cold start test. Also of note was that the HC, CO and PM conversion efficiencies over the cold WHTC test were almost equal to the levels observed over the hot WHTC tests.

The potential of thermal management to improve the efficiency of the SCR system during the cold start and warm up phase of the test cycle will be the focus of further development. The key will be to achieve higher efficiencies without sacrificing fuel consumption.

If the Euro VI test procedure is to be changed to WHTC, then it is important that corresponding emissions limits are set at an appropriate level, considering the effects of adding a cold start procedure.

4.3 Effects of Hot Soak Period for the WHTC

There has been some debate about the time interval that should be used between the cold and hot tests on the WHTC. In order to test the effects, cold and hot WHTC tests were run with soak intervals of 5, 10 and 20 minutes. The results, tabulated in *Fig. 11* and shown graphically in *Fig. 12*, show that the soak period had no significant effect on emissions. The catalyst temperatures did reduce during the soak period (see *Fig. 13*), but the overall effect is small.

Test Procedure		**Emissions [g/kW.h]**											
		THC			**NOx**			**CO**			**PM**		
		Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.
Hot Soak Period = 5 minutes													
cWHTC	cold	0.66	0.16	76%	2.34	1.69	28%	6.31	1.57	75%	0.594	0.002	99.6%
hWHTC(5)	hot (5min)	0.62	0.20	68%	1.13	0.15	87%	9.40	1.96	79%	0.735	0.002	99.7%
WHTC [5]	Weighted	0.63	**0.20**	69%	1.25	**0.30**	76%	9.09	**1.92**	79%	0.721	**0.002**	99.7%
Hot Soak Period = 10 minutes													
cWHTC	cold	0.66	0.16	76%	2.34	1.69	28%	6.31	1.57	75%	0.594	0.002	99.6%
hWHTC(10)	hot(10min)	0.57	0.20	64%	1.23	0.19	84%	8.04	1.79	78%	0.735	0.002	99.8%
WHTC [10]	Weighted	0.58	**0.20**	66%	1.34	**0.34**	75%	7.87	**1.77**	77%	0.721	**0.002**	99.8%
Hot Soak Period = 20 minutes													
cWHTC	cold	0.66	0.16	76%	2.34	1.69	28%	6.31	1.57	75%	0.594	0.002	99.6%
hWHTC(20)	hot(20min)	0.57	0.16	72%	1.19	0.18	85%	8.32	1.99	76%	0.735	0.002	99.8%
WHTC [20]	Weighted	0.58	**0.16**	72%	1.31	**0.33**	75%	8.12	**1.95**	76%	0.721	**0.002**	99.8%

Fig. 11: Table of WHTC tests with alternative hot soak periods (10% cold weighting)

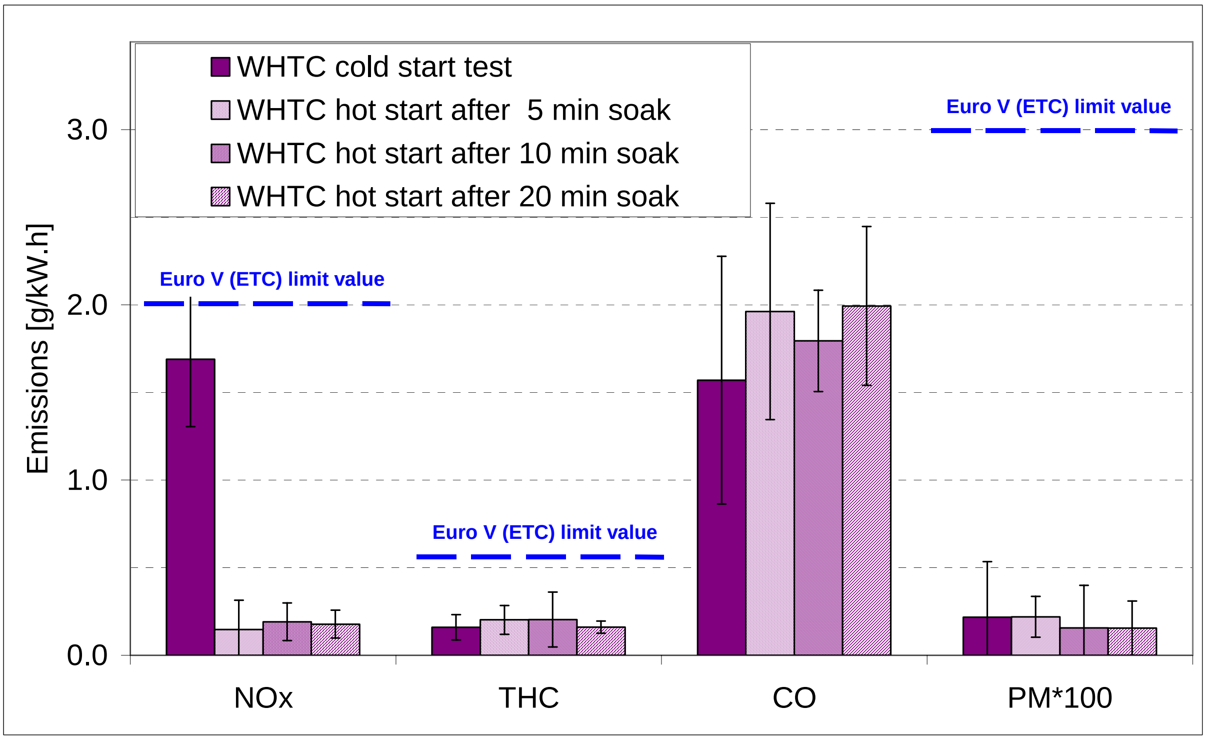


Fig. 12: Effects of soak period on weighted exhaust emissions over the WHTC test

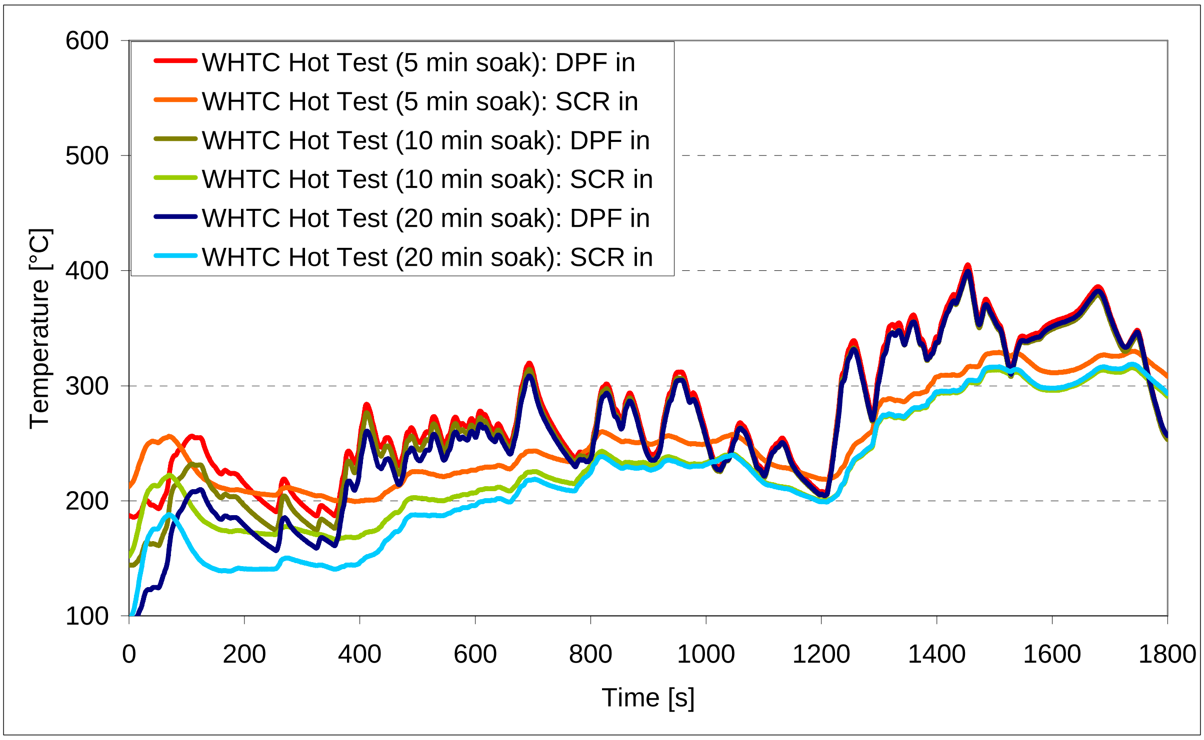


Fig. 13: Effects of soak period on exhaust temperatures over the hot WHTC test

4.4 Emissions of Oxides of Nitrogen and Ammonia

Recent atmospheric studies have identified increases in ambient nitrogen dioxide levels, especially in Germany. The increases apparently coincide with the introduction of oxidation catalysts on diesel-engined road vehicles, especially passenger cars and light duty vans. Nitrogen dioxide is an air-toxic of which elevated levels are associated with airway inflammation and increased risk of respiratory infection[10]. On this basis, the effects of future catalyst aftertreatment systems on nitrogen dioxide emissions are a concern, especially where the system includes strong oxidative functionality. Data from the FTIR analyser recorded over ETC and WHTC tests have been plotted in *Fig. 14* and *Fig. 15* respectively. Over the ETC test about 13% of the engine-out NOx was NO_2. After the C-DPF the proportion of NO_2 increased to around 65%, due to oxidation. However, the NO_2 conversion rate over the SCR system was very high at around 80%, such that tailpipe NO_2 was reduced by about 60% from the initial engine out level. Similar trends were observed over the WHTC cycle, with the tailpipe fraction of NO_2 showing an even higher reduction.

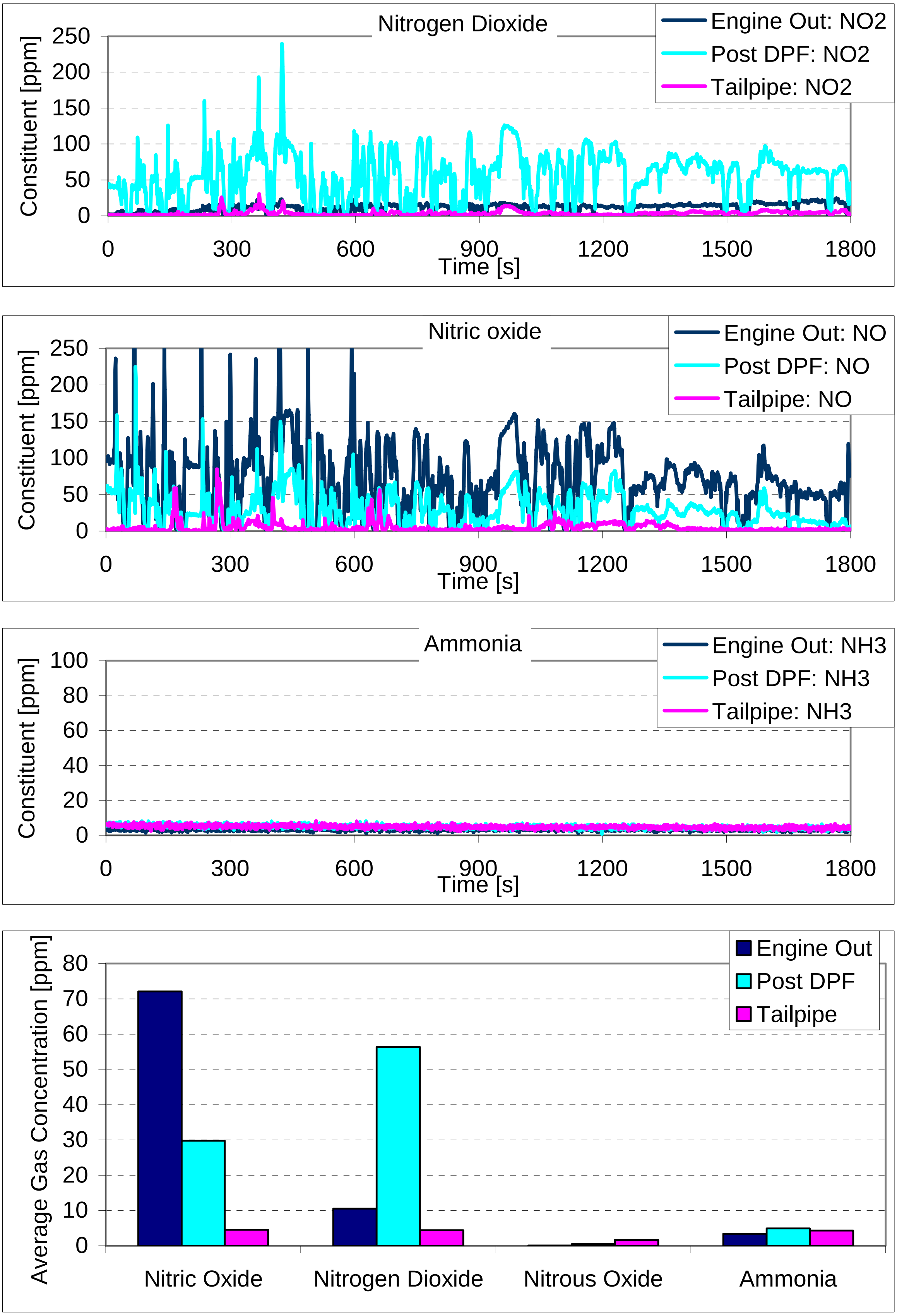


Fig. 14: Oxides of Nitrogen and ammonia in the catalyst system over the ETC test

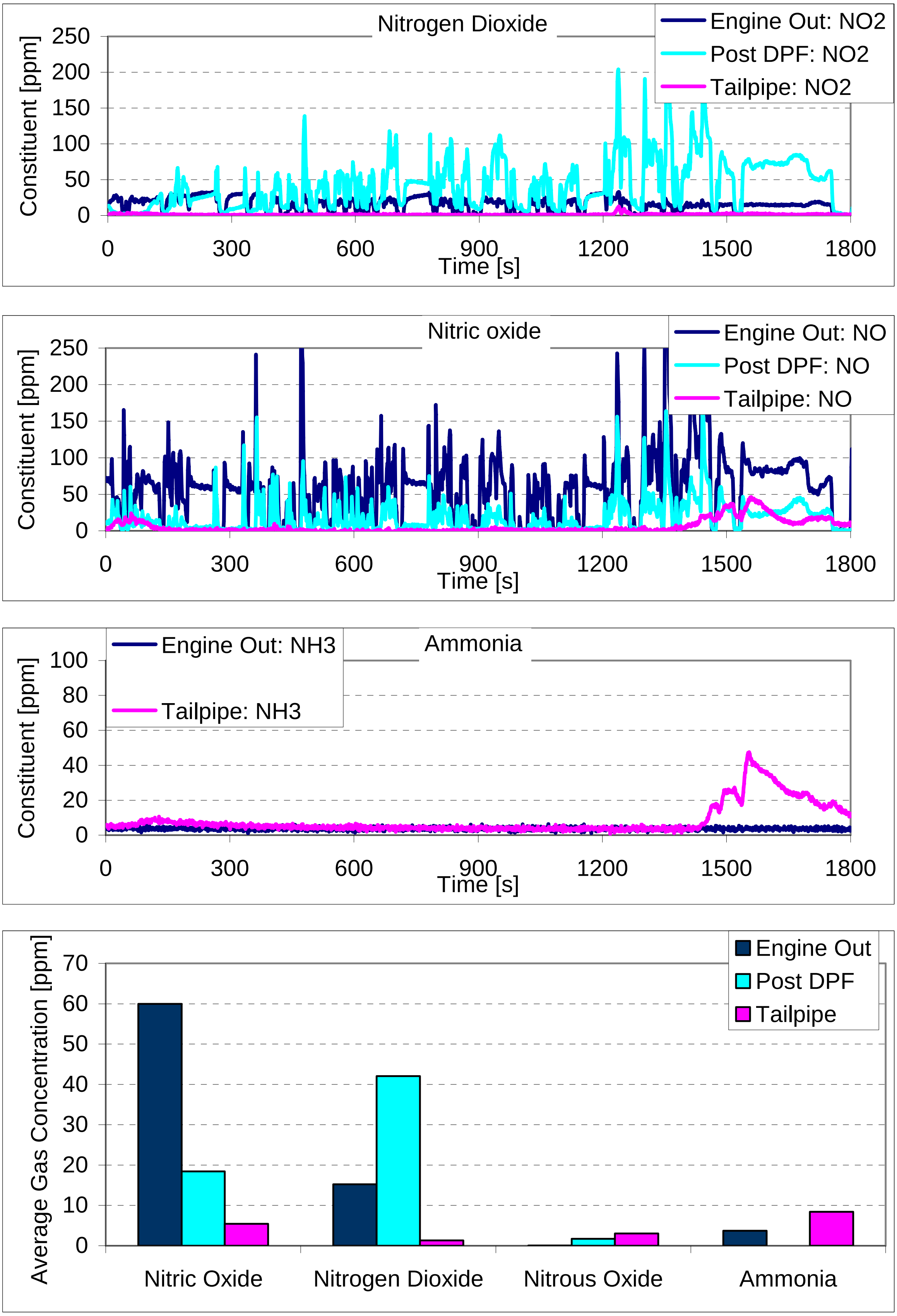


Fig. 15: Oxides of Nitrogen and ammonia in the catalyst system over the WHTC test

The data shown in *Fig. 14* confirms that there was no ammonia slip throughout the ETC tests (the FTIR measurements have an offset of ~3 ppm). Over the WHTC cycle (*Fig. 15*), there was some ammonia slip, with a peak of ~40 ppm and mean level < 10ppm. A key issue was finding a balance between the ammonia storage capacity of the SCR catalysts, and the rate of desorption of ammonia. The time available for the urea dosing calibration was relatively short and the WHTC data indicates that there is scope for further optimisation of the ammonia storage strategy.

4.5 Unregulated Gaseous Emissions

In addition to the nitrogenous species (NO, NO_2, N_2O and NH_3), selected additional unregulated gases were measured using the FTIR. As *Fig. 16* shows for the ETC, emissions of formaldehyde, acetaldehyde and SO_2 were either not present or completely eliminated by the emissions control system. An approximate doubling of the methane emissions between engine-out and tailpipe can be attributed to cracking of heavier hydrocarbon molecules over the DPF. Similar results were observed for both hot and cold start WHTC cycles.

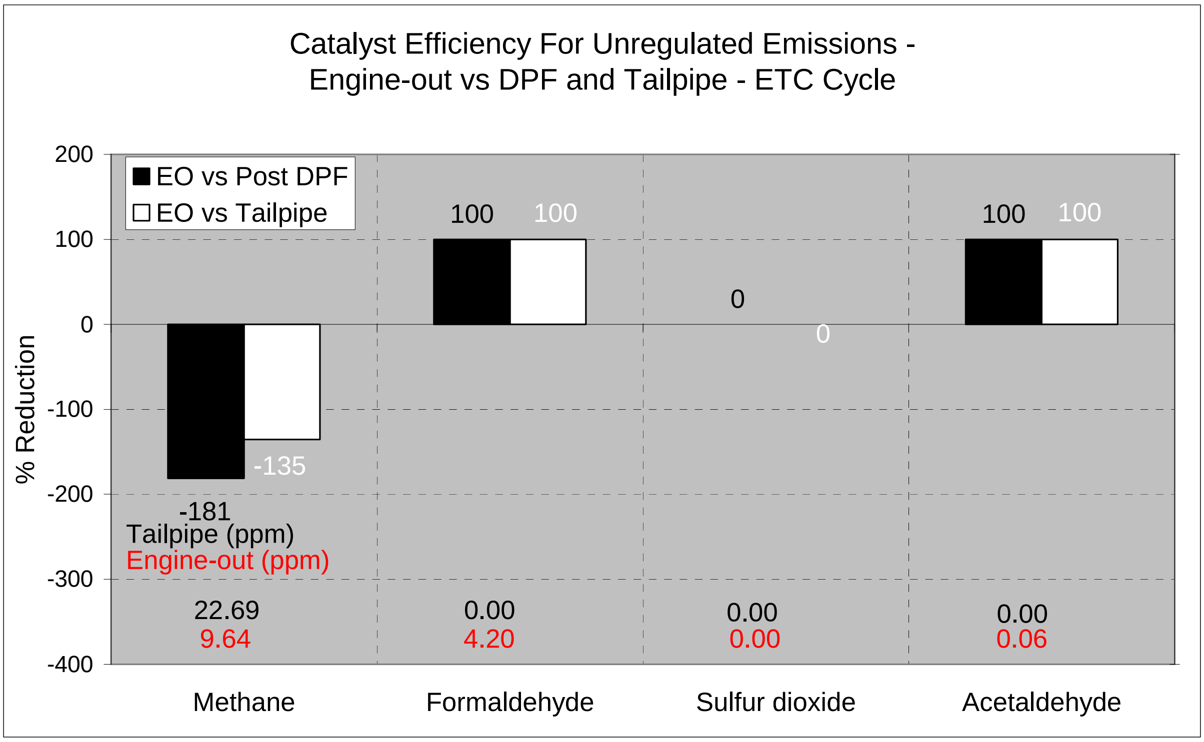


Fig. 16: Unregulated gases emitted during the ETC cycle

4.6 Elemental Carbon

Elemental carbon emissions, determined from PM filters by thermogravimetric analyses, showed that this PM constituent dominated the engine-out particulate mass, comprising ~85% of the measured total. Tailpipe emissions levels of elemental carbon were typically <4mg/kW.h from the ETC and WHTC and did not exceed 10mg/kW.h from the ESC (*Fig. 17*). These levels corresponded to a few milligrams of soot collected on the filter.

DPF filtration of elemental carbon exceeded 95% for the ESC where some passive regeneration may have led to short-term reductions in efficiency, and exceeded 99% for the lower temperature ETC and WHTC.

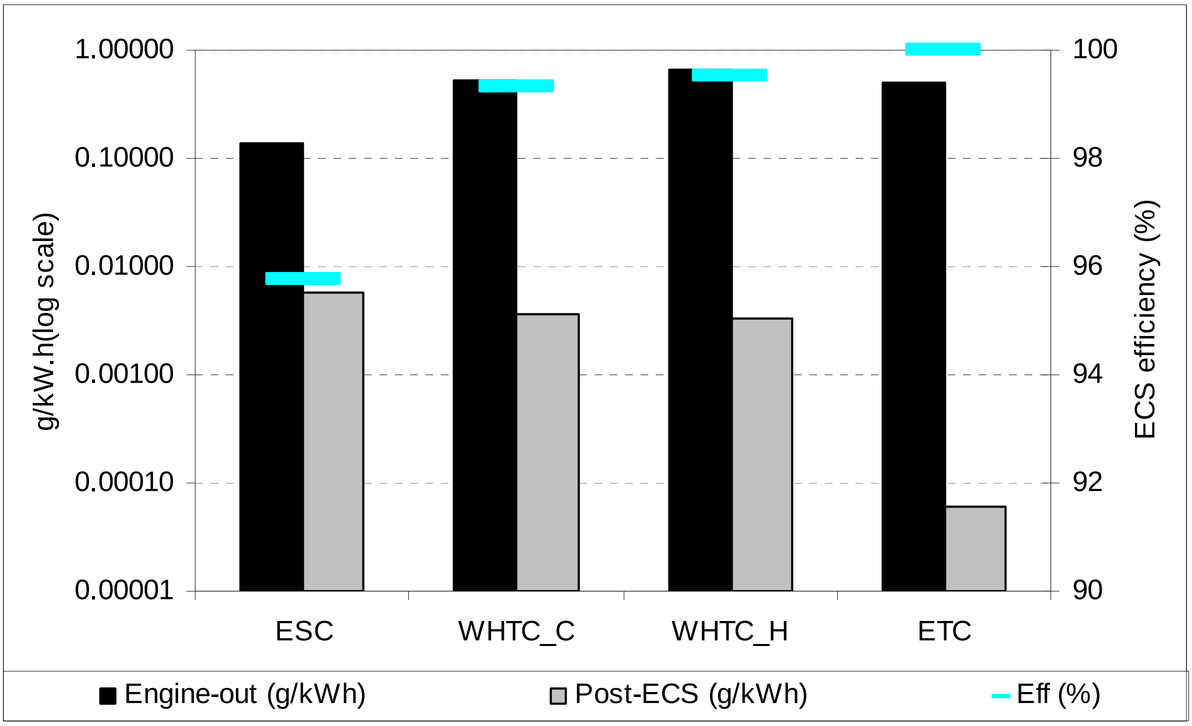


Fig. 17 Elemental Carbon Levels and Filtration Efficiencies - Regulatory Cycles

4.7 Particle Numbers

Solid particle number measurements showed engine-out emissions levels to be between 2.3 and 4.4 x 10^{14}/kW.h (*Fig. 18*). These levels are consistent with emissions previously observed in European studies[14].

Highest engine-out emissions were observed from the ETC and WHTC, with lower levels from the steady state cycles – this was consistent with the predominantly elemental carbon nature of these particles.

Tailpipe particle numbers showed a greater range of emissions: from 2.25 to 7.35 x 10^{11}/kW.h. Highest emissions were seen from the ESC cycle. This is believed to be due to contributions from (a) elemental carbon emissions breaking through the DPF following passive regeneration at the highest temperature modes and (b) solid HC particles of low volatility being released from the exhaust system downstream of the

DPF during sustained operation with exhaust temperatures above 500°C[15]. Particle number levels were similar for the WHTC, ETC and WHSC tests.

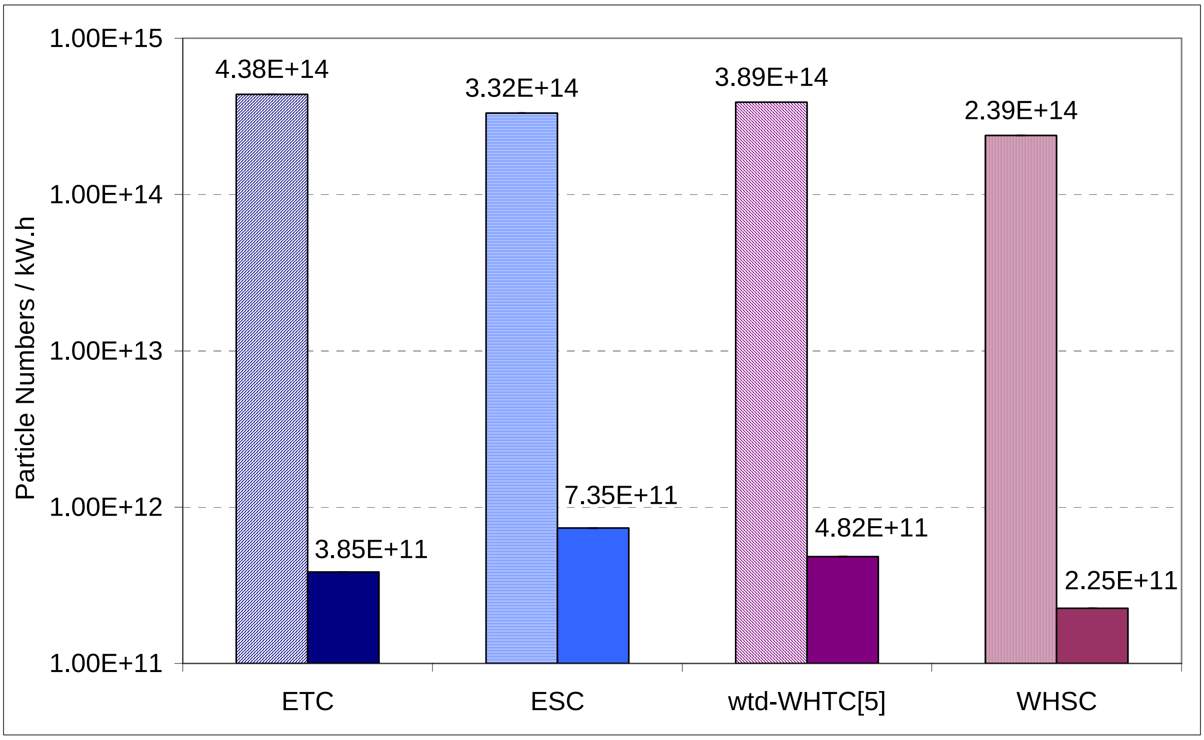


Fig. 18 Solid Particle Number Emissions - Regulatory Cycles

Particle numbers in this study were almost 10 times lower than post-DPF particle numbers measured at the same facility previously [16, 17] – though it should be noted that previous measurements featured only hot dilution and not the full PMP thermal preconditioning process.

DPF efficiency levels ranged from 99.78% (ESC) to 99.91% (WHSC) – showing that the DPF was capable of reducing solid particles in the size range 25nm to 2.5µm by more than 1000 times.

4.8 Emissions of Cyanide Compounds

Several intermediates and possible byproducts in the thermolysis of urea and its eventual conversion to urea have been shown to contain the cyanide functional group (-CN)[18]. These include hydrogen cyanide, HCN and other organic cyanides. Analyses were perfomed using the standard method (soda-lime chemisorption tube with spectrophotometric analysis) for workplace total cyanides[19]. As *Fig. 19* shows, no cyanides were detected from any tests. Cyanide emissions, if present, were below the limit of detection and less than 50% of the workplace exposure limit.

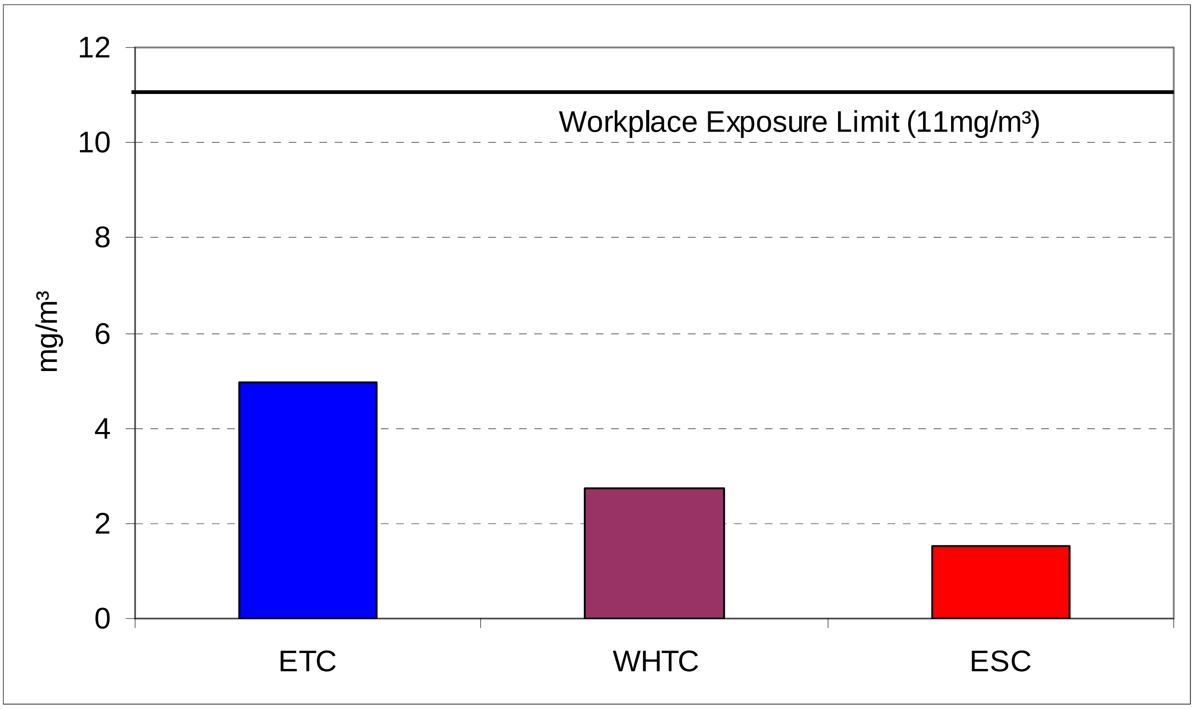


Fig. 19: No cyanide emissions detected above limit of detection -Regulatory Cycles

4.9 Tests using a Biodiesel (30% bio-fuel content)

There is increasing interest in bio-fuels. Most biofuels are blended with standard fuel in various concentrations, up to a maximum of ~30%. Therefore a biodiesel fuel (30% RME, 70% standard Diesel fuel) was procured for a limited number of tests at the end of the main programme. The results for ESC tests with B30 biodiesel are compared with tests on standard European diesel fuel in *Fig. 20* and *Fig. 21*.

Test Procedure	**Emissions [g/kW.h]**											
		THC			**NOx**			**CO**			**PM**	
	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.	Engine Out	**Tail pipe**	Conv. Effy.
Tests on Standard European Diesel Fuel												
ESC (RF06 fuel)	0.15	**0.06**	63%	1.54	**0.15**	90%	1.10	**0.00**	100%	0.151	**0.009**	94.3%
Tests on B30 Biodiesel Fuel												
ESC (B30 fuel)	0.13	**0.05**	58%	1.64	**0.27**	83%	0.87	**0.00**	100%	0.513	**0.002**	99.6%

Fig. 20: Comparison of ESC test results on B30 Biodiesel and standard diesel

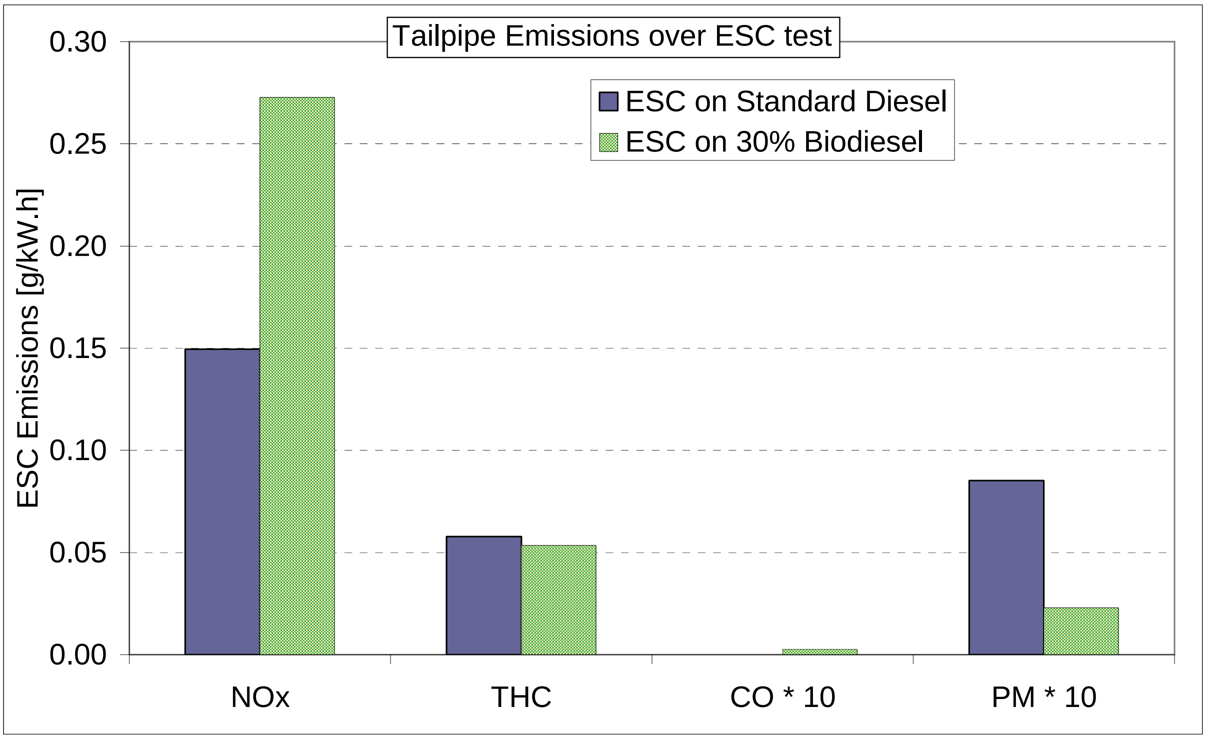


Fig. 21: Effects of a B30 Biodiesel on tailpipe emissions over the ESC test

The results showed that, on biodiesel, the NOx was reduced from 1.64 g/kW.h at engine out to 0.27 g/kW.h at the tailpipe, a difference of 1.37 g/kW.h. The difference was almost identical to that measured on the standard fuel (1.54 g/kW.h engine out to 0.15 g/kW.h tailpipe). As the urea dosing strategy was unchanged, the urea injection rate was similar for both tests, and the implication is that the catalysts were just as effective.

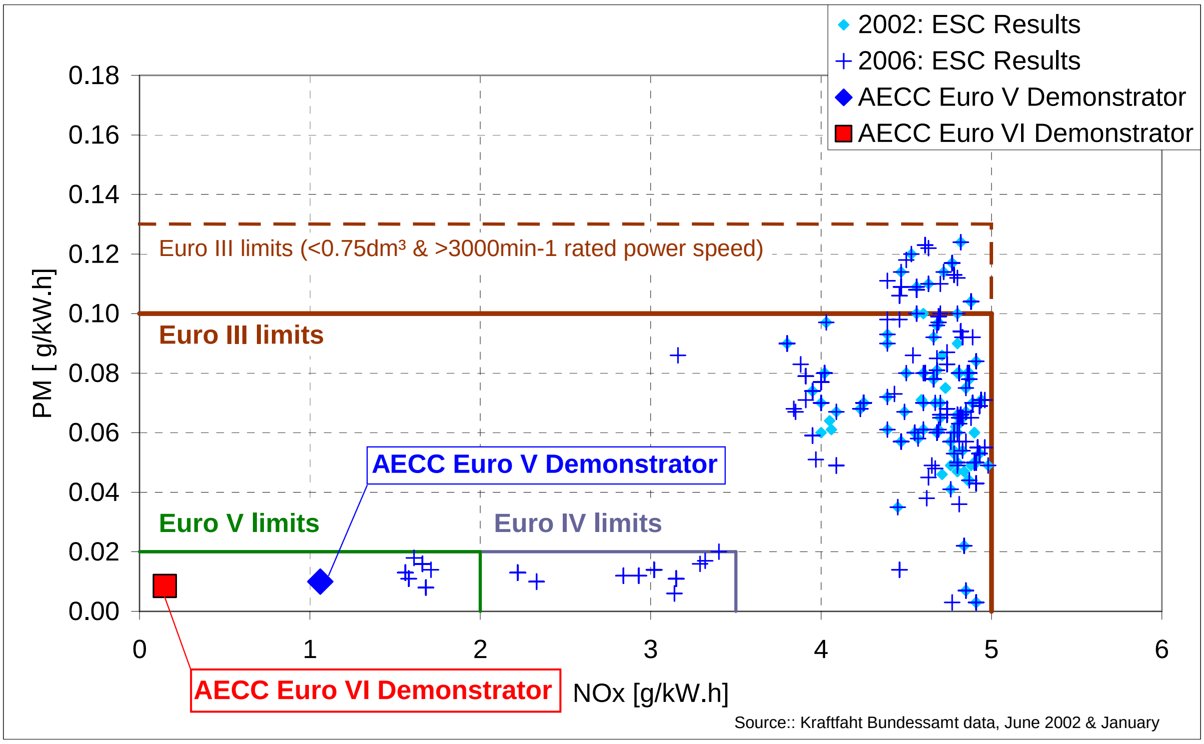
5 Summary and Conclusions

An existing medium heavy-duty "world" engine with low engine-out NOx emissions was fitted with an emissions control system comprising a diesel oxidation catalyst (DOC) and catalysed diesel particulate filter (C-DPF), an airless urea dosing system, a Selective Catalytic Reduction (SCR) catalyst and an Ammonia Slip Catalyst (ASC).

The urea dosing system was calibrated to provide good performance over the European steady-state and transient emissions test cycles (ESC and ETC) as well as the World Harmonised Transient Cycle (WHTC) without modification of the existing engine calibration.

NOx conversion efficiencies were 86% and 76% over the ETC and EU-composite WHTC respectively, resulting in tailpipe levels of 0.15 and 0.30 g/kW.h. The results over the ESC Test are compared with certification data for Euro IV and V and the results of an earlier demonstration project in *Fig. 22*.

Fast warm-up of the catalysts will be essential to minimise tailpipe emissions after cold start. In a real world application, further work would have been carried out to integrate catalyst warm-up strategies into the engine control strategy. This would have enabled better optimisation of the emissions control system in terms of packaging, volume and performance.



Source:: Kraftfaht Bundessamt data, June 2002 & January

Fig. 22: Comparison of AECC Demonstrator projecst with Certification Data

PM conversion efficiencies were more than 99.5% over the ETC and EU-composite WHTC, resulting in PM tailpipe levels of 1 to 2 mg/kW.h when measured with the partial flow method.

The PMP particle number method proved very reliable even at near-ambient particle emissions levels. Engine-out particle number data were in the range of 2.5 to 5×10^{14}/kWh. Particle numbers were essentially cycle-independent. All transient cycle data showed tailpipe particle number emissions below 10^{12}/kW.h. The catalyst system reduced elemental carbon emissions by more than 99%.

Various WHTC options were evaluated. The effect of hot soak time was investigated for 5, 10 and 20 minutes soak intervals. Tailpipe composite NOx with 10% cold weighting were 0.30 g/kW.h (EU-composite - 5 minutes), 0.34 g/kW.h (10 minutes) and 0.33 g/kW.h (20 minutes). Soak time had no significant effect on tailpipe PM or on particle numbers.

The integrated SCR system reduced all nitrogen species to low levels over the various cycles tested. NO_2 reduction efficiency of the SCR was over 80%.

The emissions control system reduced non-regulated emissions (that is, particulate PAHs, air toxics) to below detection levels. Cyanide levels were below detection limits for all tests and well below the workplace exposure limit.

Measurements of emissions over the ESC test were made using B30 biodiesel. Compared with diesel, the catalyst efficiencies on B30 biodiesel were the same for CO, slightly reduced for NOx and HC, and slightly higher for PM. Comparing B30 and diesel, there was no significant difference in particle numbers.

The combined engine and emissions control system met the most stringent scenarios from the European Commission's Euro VI validation exercise (referred to the ETC test). Compared with the existing engine population, the tailpipe results achieved in this demonstration project point the way to future low emissions solutions.

Regarding the WHTC test and other cold start tests, there is potential for further improvement of emissions by means of thermal management, optimised emission control system design, and engine and urea dosing calibration.

If the Euro VI test procedure is to be changed to WHTC, then it is important that corresponding emissions limits are set at an appropriate level, considering the effects of adding the cold start procedure.

6 Definitions, Acronyms, Abbreviations

ASC	Ammonia Slip Catalyst
B30	Diesel/Bio-fuel blend with 30% RME content
C-DPF	Catalysed Diesel Particulate Filter
CVS	Constant Volume Sampling System (for emissions measurement)
DOC	Diesel Oxidation Catalyst
DCU	(Bosch) Dosing Control Unit (for urea injection system)
ECS	Exhaust Catalysts System (or Emissions Control System)
EGR	Exhaust Gas Recirculation (in engine)
ESC	European Steady-state Cycle (for Heavy Duty Engines)
ETC	European Transient Cycle (for Heavy Duty Engines)
FTIR	Fourier Transform Infra-Red analyser (chemical species)
IC	Ion Chromatography

MDLT	(Horiba) Mini-Dilution Tunnel (Partial Flow Dilution System)
PM	Particulate Matter
PMP	UN-ECE Europe Particle Measurement Programme
PN	Particle Number
RF06	(Standard Diesel) Reference Fuel
RME	Rapeseed Methyl Ester
SCR	Selective Catalytic Reduction (of NOx)
Wtd	weighted (reported result from combination of cold & hot start tests)
WHSC	World-wide Harmonised Steady-state Cycle (for Heavy Duty Engines)
WHTC	World-wide Harmonised Transient Cycle (for Heavy Duty Engines)

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